Reply to comments of Miguel Rico-Ramirez on Close-range radar rainfall estimation and error analysis

The paper attempts to quantify some of the error sources in weather radar observations (such as ground clutter, radome attenuation and Z-R variability) by comparing radar observations at very short range (1-2 km) with raingauge and disdrometer measurements. The paper is very interesting and AMT readers would benefit from this paper. The paper is well written and it should be published after the authors address some minor issues as discussed below.

The authors would like to thank Miguel Rico Ramirez for the positive comments, and the valuable suggestions for improving the paper.

1- An important source of "error" between radar and raingauge measurements is due to the fact that radar observations are areal (in fact volume) rainfall measurements whereas raingauges provide point rainfall measurements (Kitchen and Blackall, 1992; Ciach & Krajewski, 1999; Bringi et al, 2011). This produces some differences when comparing both sets of observations even at short range because the radar spatial resolution is relatively large (1km along-range in your case) compared to the raingauge sampling area. Please comment on this and give an indication of how much of the observed difference between radar and gauge measurements is due to the point to area variance.

The large differences in sampling volumes is indeed a cause for differences between radar and rain gauge measurements of rain. The fact that we're using data close to the radar limits the size of the radar measurement volume (in azimuth and elevation directions anyway), but it is still orders of magnitude larger than a rain gauge orifice. However, we think that the differences between the two is compensated by the fact that rain gauges integrate in time (see comment 2), whereas radars provide instantaneous measurements. If we assume that Taylor's hypothesis of frozen turbulence holds for rain over a 5-minute period (similar to the assumptions behind the interpolation techniques to correct for advection) the effective scale of a rain gauge, translated to an instantaneous measurement, is much closer to that of a radar pixel (depending on the advection speed of the event, see Fabry et al., 1994). There are of course still differences, as we state on line 24 of p.15. We believe that a more thorough discussion of these differences is outside the scope of this paper.

2 - Another source of error in radar measurements is due to the fact that the radar provides instantaneous measurements whereas raingauges provide measurements integrated in time. Operational weather radars usually perform volume scans (i.e. several PPI scans at different elevations) and therefore the sampling time interval of the surface radar rainfall measurements is relatively large (5min in your case). Errors due to the sampling time interval can be large especially in convective situations (see e.g. Fabry et al, 1994). Interpolation techniques can help to mitigate this (e.g. using nowcasting). How much of the observed difference between radar and gauge measurements is due to the radar temporal sampling? Please comment on this.

See also our reply to comment 1. We fully agree with this comment that for advection speeds greater than 1 km per 5 minutes (i.e., 3.3 m/s) the temporal resolution of the radar is too coarse to capture the temporal variability of rain. For this event, the advection speed is indeed greater than 3.3 m/s. However, the space-time structure of the precipitation for this event was such that this had only a minor effect on our results. We will state this in the Discussions section, along with a reference to Fabry et al. (1994).

3 – Radome attenuation. The correction for the radome attenuation was performed using a fixed clutter target, but ignoring the effect of wetting of the clutter target and precipitation at the clutter location. The authors also highlighted the fact that radome attenuation depends on wind speed and direction. Please give an indication on how reliable is the proposed radome attenuation correction, perhaps by making reference to other papers.

The quality of our wet radome correction method is indeed uncertain due to the effects mentioned by the reviewer. The most uncertain part is the effect of the wetting of the clutter target. We don't know how this affects the reflectivity. Rain in the same pixel as the clutter target is not likely to influence results because the clutter target generates reflectivities (60 dBZ) that far exceed those generated by rain in this event. Because the method we use is not intended to be used in an operational setting (as stated on lines 2-5 on p.17) we feel that a further discussion of the quality of this correction method is not needed for the purpose of this paper.

4 – Z-R variability. The study concludes that applying an event-based Z–R relationship obtained from disdrometer observations improves the radar rainfall estimation. Although this is true for the location under consideration, it is well known that the Z-R equation changes in space and time. Please comment on this.

We have already included a discussion on this on lines 6-15 on p.17. With respect to the spatial variability of the drop see distribution, the applicability of disdrometers is limited when the inter-disdrometer distance is greater than the scale on which the DSD varies. However, the temporal variability of the DSD at the location of the disdrometer is well-captured on time scales of 5 minutes.

5 – The study was performed on a limited data set (only 3 days), but it is likely that the radar errors will depend on the precipitation type (e.g. stratiform rain, convective rain, winter storms, etc). Please comment on this.

We agree with the fact that errors can be different for different precipitation types. The nice thing about this event is that it contained both convective and stratiform rain. Of course, there are more types of events that could occur (we had no hail or other solid precipitation on the ground during this event). We will note this in the conclusions section of the paper.

Minor Comments:
Fig 3. Please be consistent with the use of colours in fig 3 (radar measurements were shown in red in top panel and in black in bottom panel). Similarly for gauge measurements.

We will change the colours used in the top panel of Figure 3 so that they are consistent with the bottom panel and other figures in the paper.

Page 8 "zero-isoDop"?

We've explained "zero-isoDop" on lines 8-9 of p.8, right after we first mention this term.

Section 4.1. It is unclear which azimuthal angle is used for the comparisons.

In Section 4.1 we do not use a given azimuth, but we use all measured sun interferences over that day to obtain a robust estimate of the receiver calibration and possible offsets in antenna pointing angles. More details on this method can be found in Holleman et al. (2010).

References.

Ciach, G. J., and W. F. Krajewski, (1999): On the estimation of radar rainfall error variance. Adv. Water Resour., 22, 585–595.

Fabry, F et al (1994): "High resolution rainfall measurements by radar for very small basins: the sampling problem reexamined," Journal of Hydrology , vol. 161, pp. 415– 428.

Bringi, VN, et al (2011): 'Rainfall Estimation with an Operational Polarimetric C-band Radar in the UK: Comparison with a Gauge Network and Error Analysis' Journal of Hydrometeorology, vol 12, pp. 935 – 954.

Kitchen, M., and R. M. Blackall, 1992: Representativeness errors in comparisons be- tween radar and gage measurements of rainfall. J. Hydrol., 134, 13–33.