



**Met Office**

**Optimising the accuracy of radar  
products with dual polarisation :  
Project benefits**

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## **Introduction**

**This project was initiated with the aim of realising some of the many potential benefits of upgrading the UK Weather Radars to dual polarisation capability. This report aims to bring together a summary of the improvements made to the quality of the radar products as a result of this project.**

**The three year project was a funded collaboration with the Met Office (50%), the Environment Agency led Incident Management and Modelling Theme Advisory Group (25%), and Flood Forecasting Centre (25%) and in total cost £414k to implement and completed in Spring 2016.**

**The Met Office has developed new methods to improve the quality and accuracy of weather radar products which are critical for forecasting river levels in fast-responding catchments in intense rainfall. The new dual polarisation algorithms increase the accuracy of the precipitation nowcast (out to 6 hours) and NWP forecasts, particularly in very intense events, allowing for more accurate and timely warnings, which will give emergency responders and the public better and earlier information to help protect lives, livelihoods and property.**

### **What is dual polarisation?**

The Met Office and the Environment Agency are currently rolling out the largest upgrade to the UK radar network in its 30 year history. Unlike conventional and Doppler radars, dual polarisation radars transmit and receive signals in both vertical and horizontal polarisations (Figure 1). Small differences between the two received signals tell us about the shape of the target and its composition (ice or water). The dual polarisation technology upgrade to the radars was developed in-house by Met Office staff, which allows for unprecedented access and control over the hardware and signal processing. This has enabled some of the more novel developments described later in this report.

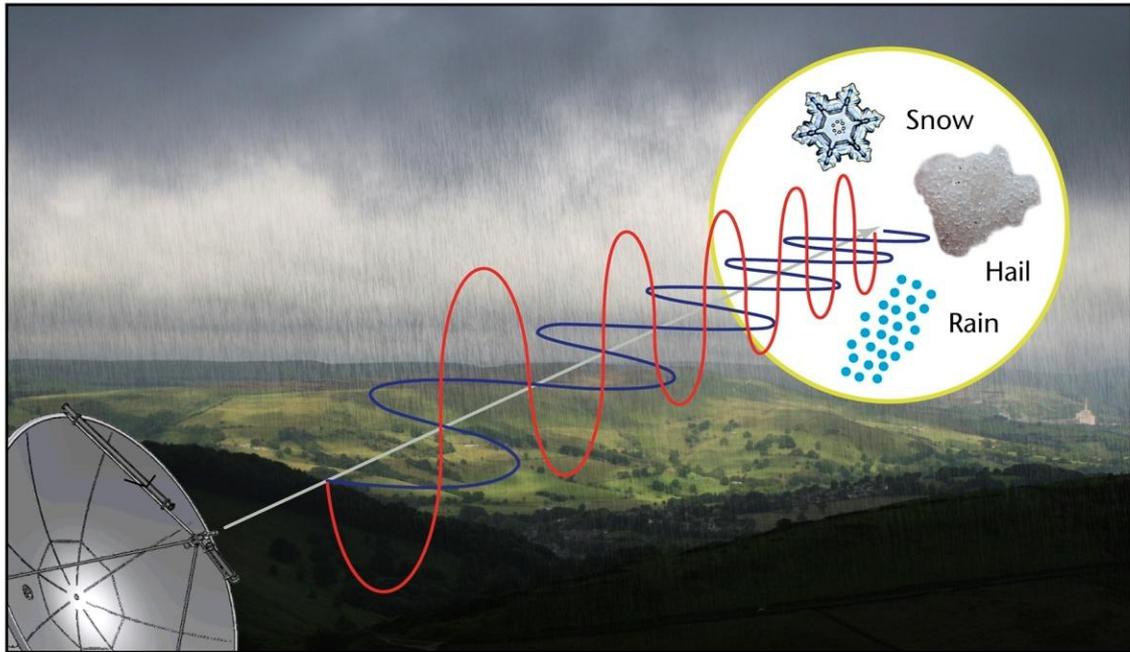


Figure 1 Schematic of dual polarisation measurement

The project was broken down into three work packages:

- **WP 1. “Focusing on the weather” (Improved Spurious echoes detection)**
- **WP 2. “Seeing through the storm” (Improved Radar reflectivity measurement)**
- **WP 3. “More accurate rain rate products when it really matters” (Hybrid Z/KDP/R relationship)**

The aim of the “Focusing on the weather” work package was to improve our ability to distinguish between precipitation and non-meteorological returns which can cause large data “spikes” and large biases in the rainfall estimates. This was done using both the new dual polarisation capabilities and by the improved signal processing capacity at the radar site to implement Doppler clutter filtering techniques.

The aim of the “Seeing through the storm” work package was to improve our ability to accurately calibrate the radars and also to correct for attenuation caused by both wetting of the radome and by the storms themselves. It is primarily this work package that has benefitted from the in-house design of the radar. Specifically, the fact that we are able to use the radars to make radiometric measurements of the total attenuation, a facility not available on commercially available radars.

The aim of the “More accurate rain rate products when it really matters” work package was to use the dual polarisation measurements to better estimate the rain rates in high intensity events. This work makes use of information about the relative phase of the two polarised waves, which are delayed relative to one another when passing through the liquid medium, giving an intensity independent estimate of the precipitation.

As the upgrade of the radars is an ongoing project it is not possible at this time to quantify the total benefit to the whole UK radar network as a result of this work, and so the benefits shown are qualified on single radar site basis.

## WP 1 “Focusing on the weather” (Improved Spurious echoes detection)

One of the key benefits of dual polarisation radars is their ability to provide information on the type of targets that are being observed, be it rain, ice, insects, the ground, planes, etc. It is this ability that is used in this work package to improve the removal of non-meteorological echoes. Improvements to the quality control are essential if the radar data are to be used in hydrological models and NWP, where even a low intensity persistent pixel of clutter breaking through can result in significant accumulations over time.

### *Dual polarisation non-metrological echo removal*

The new dual polarisation classification scheme makes use of a Naive Bayes Classifier to classify radar echoes similar to that described in Rico-Ramirez and Cluckie (2008); a probabilistic way of combining information from each of the dual polarisation measurements. The new dual polarisation scheme was compared to the previous operational scheme, and the results were very encouraging. As a result, the dual polarisation scheme went operational in September 2014 and has resulted in a composite with fewer spurious echoes from that time onwards.

It should be noted that a satellite image based cloud mask would often, but not always, compensate for deficiencies in the old scheme. The new scheme is similarly helped by the satellite constraint and so any residual spurious echoes are still often deleted. As such, it is very difficult to qualify the true benefits of the improved quality control as there are many different aspects which will perform differently in different situations and so the approach taken has been to determine the improvement seen in each of the situations known to cause issues in the original classification scheme.

The highlights of the new scheme are as follows.

1. The **sensitivity** of the radars to light rainfall has increased by about 2–5%, and the average reflectivity over a month has dropped by 2–5 dBZ, indicating that we are keeping echoes with lower intensity. Indeed, in a case study of light rainfall, we noted an increase of nearly four times the number of pixels kept as precipitation.
2. We are no longer dependent on climatology probability of detection maps and thresholds to filter **ground clutter** — the new scheme is skilled at deleting ground clutter, and yet keeps precipitation when the signal from the latter is strong enough to overwhelm the clutter signal. This reduces the loss of good data and give us more flexibility to alter the radar scanning strategy without needing to built up climatological maps of clutter. Tests on cloud-free, dry days show that the new scheme deletes between 82 and 94% more clutter relative to the conventional scheme (Figure 2).

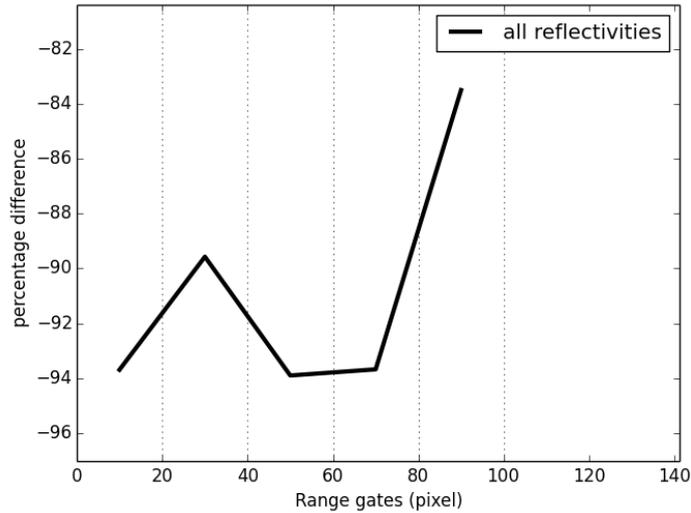


Figure 2 Percentage difference in deletion of clutter on a dry day between old and new schemes, plotted against the range from the radar

3. In the case of **sea clutter**, the old scheme used a “sea mask” which was applied in all conditions but which had to account for the worst case of sea-clutter leading to large areas of data being un-necessarily deleted. The new scheme does away with this mask, and retains strong signals from precipitation, saving up to about half of the radar image within 60km of Predannack (Figure 3) – equivalent to an increase of ~ 5500 km<sup>2</sup> in the availability of high quality lowest elevation data at this site. While this will primarily give improved quality over the sea and so will not be reflected in improved rain gauge comparisons, this will improve the quality of the nowcast rain estimates over Cornwall.

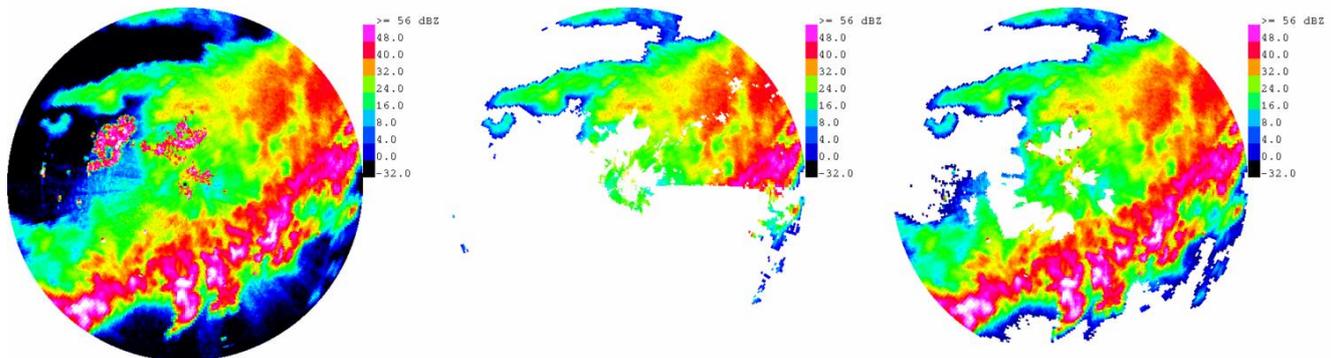


Figure 3 Effect of removal of sea clutter mask at Predannack in the first 60km range. Left image is raw unprocessed reflectivity, middle image is the convention processing with sea clutter mask, the right hand images is new dual pol. processing.

- Anomalous propagation (**anaprop**) occurs in certain atmospheric conditions that bend the radar beam back towards the ground. The single polarisation radars were entirely dependent on satellite imagery to delete anaprop (no clouds indicating no rain). With the introduction of dual polarisation we are able to deal with anaprop even in cases where satellite data shows clouds. This can lead to about 20–50% decrease in the count of false positives.

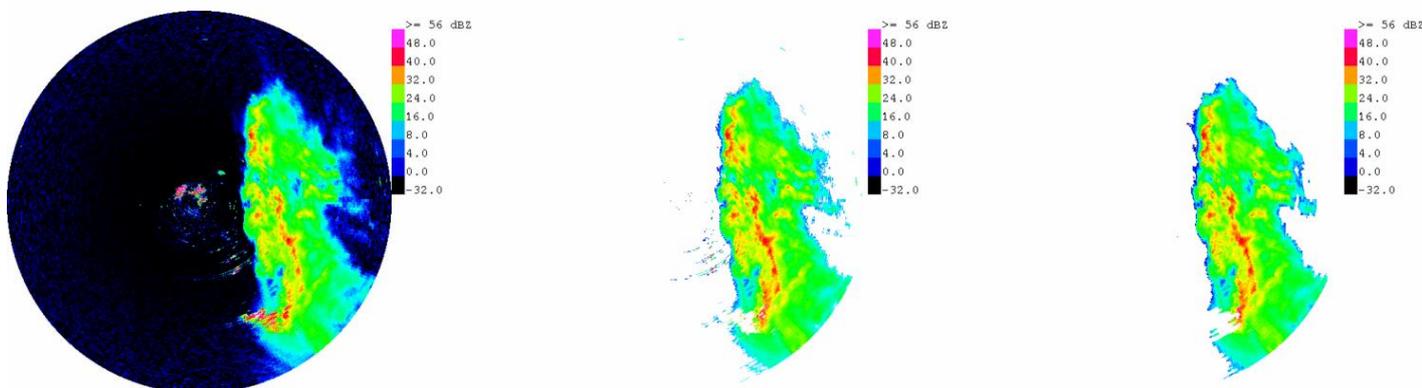


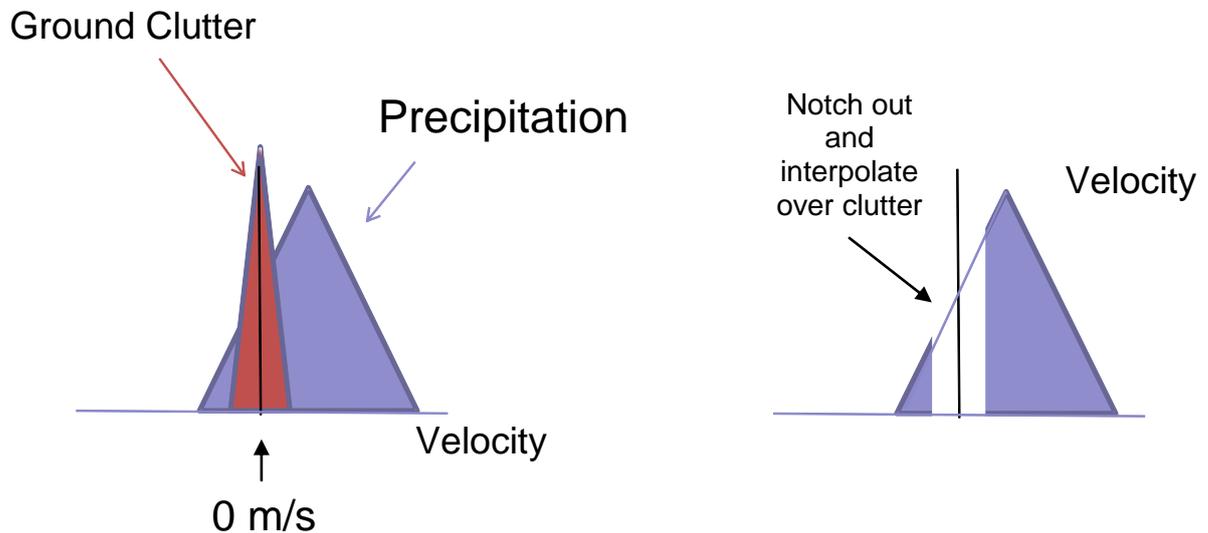
Figure 4 Improvement in quality control in anomalous propagation conditions, left image is the raw reflectivity, the middle image uses single polarisation only, and the right hand image uses the new dual polarisation filtering.

- The old scheme relied on the speckle filter and the satellite data to delete echoes from **ships and aircraft**, but often this was overwhelmed by the particularly intense returns. The new scheme shows some improvement, with up to 90–98% of aircraft echoes being deleted. The benefits of this improvement are particularly significant in areas with high volumes of air or sea traffic, such as the south east of England and over the Channel.
- The current scheme has no way of dealing with insects, other than to treat them as noise. The new scheme is better able delete the insects to a large extent (20–90% of counts in a case study), although some remain.
- The single polarisation scheme relied on a “spokes correction” filter to delete and report rays that are contaminated with **interference** from radio networks (RLANs). The dual polarisation scheme is able to delete the RLAN rays that get past the spokes correction in most cases. For example, around 20 such events are seen per hour at Chenies and Castor Bay, and about 60 such events are seen at Ingham. A separate scheme for detecting RLANs (termed the FMI code here), has been developed, which uses output from the “rack” executable from the Finnish Meteorological Institute, coupled with dual polarisation parameters. The new code accurately detects around 25 true positives/hour at Chenies as compared to around 15 true positives/hour. Similar results are seen at other radars.

## **CLEAN-AP ground clutter removal**

The **C**lutter **E**nvironment **A**nalysis using **A**daptive **P**rocessing (CLEAN-AP) Doppler clutter filter is a technique developed by the **A**dvanced **R**adar **T**echniques (ART) team, who are part of the National Severe Storms Lab (NSSL) in the US. As part of a collaboration on signal processing between the Met Office Radar Systems and the ART teams, they have kindly provided a detailed algorithm description of the CLEAN-AP technique and allowed an implementation in Cyclops-D - the UK Weather Radar site signal processing and control system.

Doppler clutter filters take advantage of the fact that the ground clutter is known to have zero velocity and a very narrow spectral width. The CLEAN-AP clutter filter makes use of advanced signal processing techniques (Torres, S. and D. Warde, 2014), specifically the auto-correlation spectral density (ASD), to examine the velocity components at every radar pixel, determine how much of the velocity spectrum is due to ground clutter or weather, then notch out the clutter component and interpolate the spectrum to restore the precipitation signal (Figure 5).



**Figure 5 CLEAN-AP Clutter Filtering schematic**

The radar signal for a single pixel is broken down into its velocity components (left). The ground clutter appears at zero velocity (shown in red). Its extent can be determined and its contribution to the signal removed (Right). The weather signal can then be reconstructed over this notch.

The effect of the CLEAN-AP filter can be seen in Figure 6. After applying CLEAN-AP the intensity of the clutter signal is significantly reduced and in some cases is removed entirely, whereas the precipitation signal is not visibly affected.

While the availability of this algorithm at a late stage in the project has meant that it has not been possible to fully evaluate its effect on precipitation estimates it is expected that the ability to make more use of lower altitude measurements will lead to less dependency on the corrections for the vertical profile of reflectivity and so lead to an improvement in the quality of the precipitation estimates. The decreased dependence on making higher elevation scans to in-fill for cluttered regions could also be used to increase the time available to scan at lower elevations, leading to either faster updates or higher quality data. The work to make optimal use of the data forms part of the ongoing collaboration.

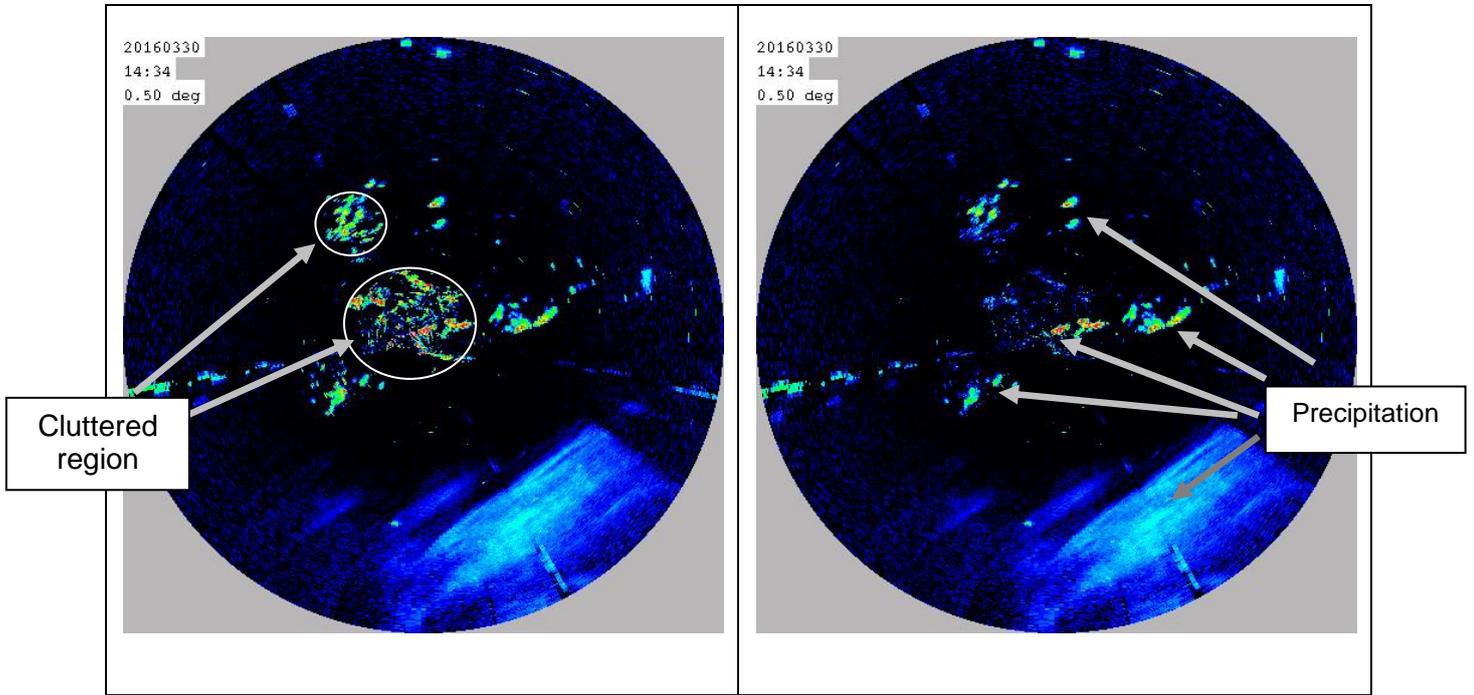


Figure 6 The effect of the CLEAN-AP Clutter filter on ground clutter and precipitation at Warden Hill, the left hand image is unfiltered, whereas the right hand image has the CLEAN-AP filter applied, leading to a significant reduction in the level of the clutter with little or no impact on the precipitation.

## WP 2. “Seeing through the storm” (Improved Radar reflectivity measurement)

### *Dual polarisation based reflectivity calibration*

The dual polarisation radars return additional measurements which are based on the relative phase of the differently polarised signals ( $\phi_{dp}$ ) and the difference in power levels between the two received polarisation channels ( $Z_{dr}$ ). As such these parameters are unaffected by the absolute calibration level of the radar. In carefully chosen conditions, these parameters can be used to determine the expected reflectivity value and by comparison with the observed reflectivity, a calibration offset can be obtained.

Figure 7 shows the effect on the instantaneous gauge adjustment value of applying the calculated offset to data from Chenies radar. The gauge adjustment value shown is a multiplicative factor applied to rain rates to account for calibration errors and changes in the rain drop size distribution. Values closer to one represent a smaller adjustment, with values greater than one suggesting under reading by the radar and values less than one representing over reading. As can be seen, Chenies radar is already well calibrated but there is a reduction in the required gauge adjustment value when the calculated offset is applied.

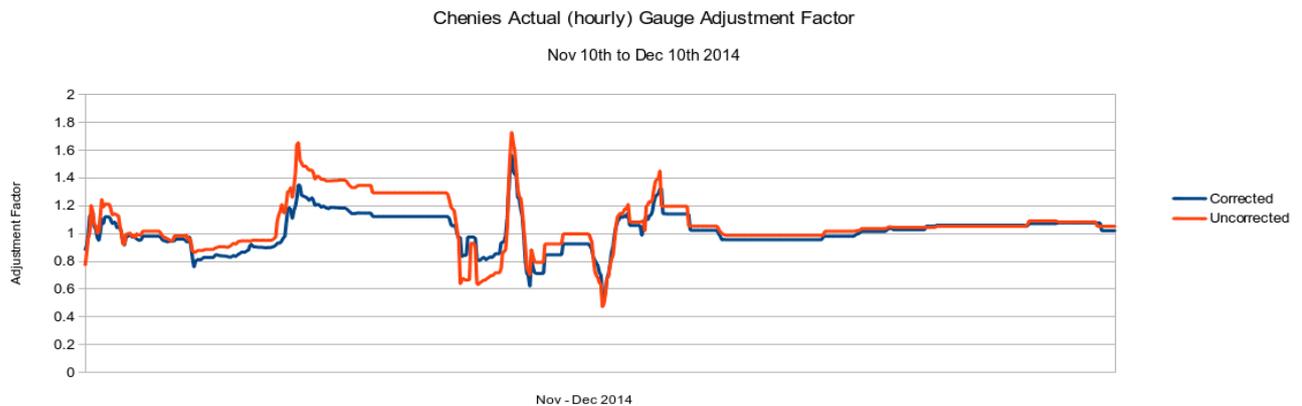


Figure 7 Effect on instantaneous gauge adjustment value of applying calculated calibration offset

## ***Improved Attenuation Corrections***

### *Radome attenuation correction*

The initial focus of the attenuation correction strand of this work package was on improving our ability to measure the attenuation caused when the radome, which protects the radar hardware from the elements, gets wet. It has been observed that with the original radomes, significant attenuation of the radar power can occur. A technique was developed in collaboration with Reading University which allows this attenuation to be detected and corrected for.

It was found that the new radomes cause significantly less attenuation when wet, compared to the old, pre-renewal ones, as would have been hoped. As such at this time no correction for wet radome attenuation is made, but a system has been developed to monitor the radomes for degradation with time.

### Improved correction of attenuation due to storms

The current single polarisation attenuation correction scheme, known as the Hitschfeld and Borden approach (H&B), only has the measured reflectivity from which to estimate the attenuation due to storms. As the attenuation correction is a cumulative value which is added to subsequent range gates before the correction for those gates is calculated, it is unstable and can grow to unrealistically high values if incorrectly calibrated or contaminated by non-rain returns – a highly undesirable feature. To prevent this from happening, the current correction used by the Met Office is capped at a factor of 3, or ~5dB. This can lead to under reading when high levels of attenuation are present.

The introduction of dual polarisation gives access to parameters which are known to be related to the amount of attenuation present, specifically  $\phi_{dp}$  - the differential phase shift, however, it is known (Carey et al. 2000) that this parameter varies in its sensitivity to attenuation by a factor of around 2, depending on the drop size distribution of the precipitation. The Met Office weather radars are thought to be unique in that they have an additional means of measuring the total attenuation along a given path by making use of the radiometric emissions from attenuating storms. This provides a valuable additional constraint on the attenuation. By making use of that fact that we now have three independent measurements of the total attenuation along a given ray (Figure 8 Upper), we can use the consistency between the measurements to recalibrate the  $\phi_{dp}$  based estimate, detect contamination and calibration issues with H&B, and detect when the radiometric measurement has been contaminated by interference, to get a “best” estimate of the true attenuation along the path (Figure 8 Lower).

While other met. services have had difficulties in making use of the dual polarisation data to correct for attenuation, it is thought that the unique three parameter approach adopted by the Met Office mitigates for the issues they have seen.

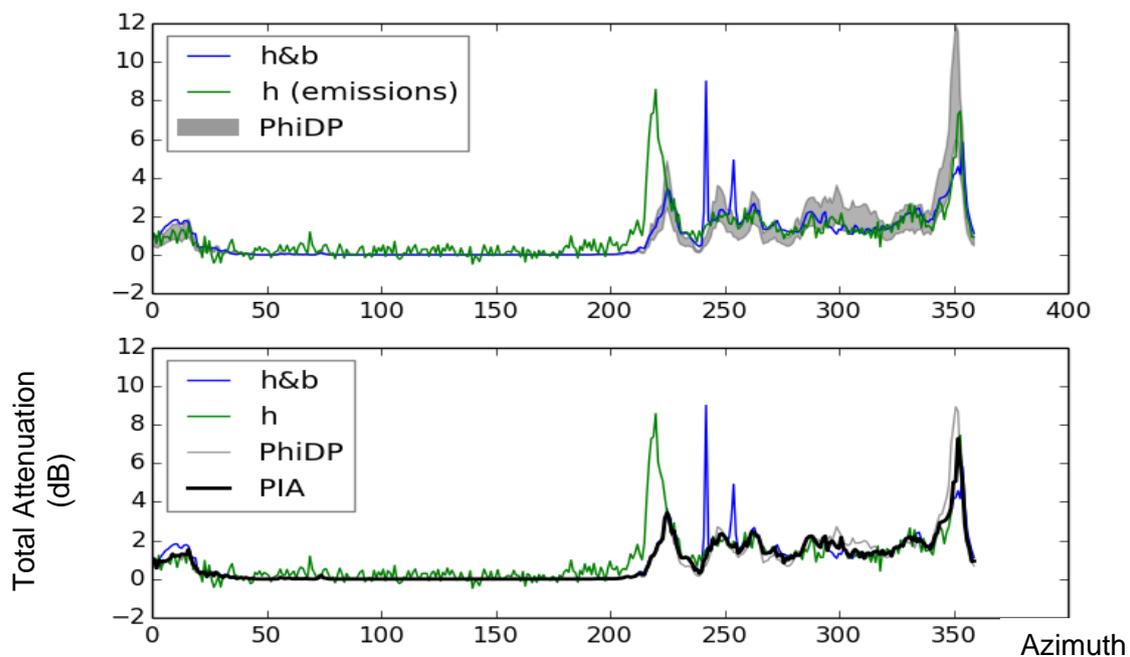
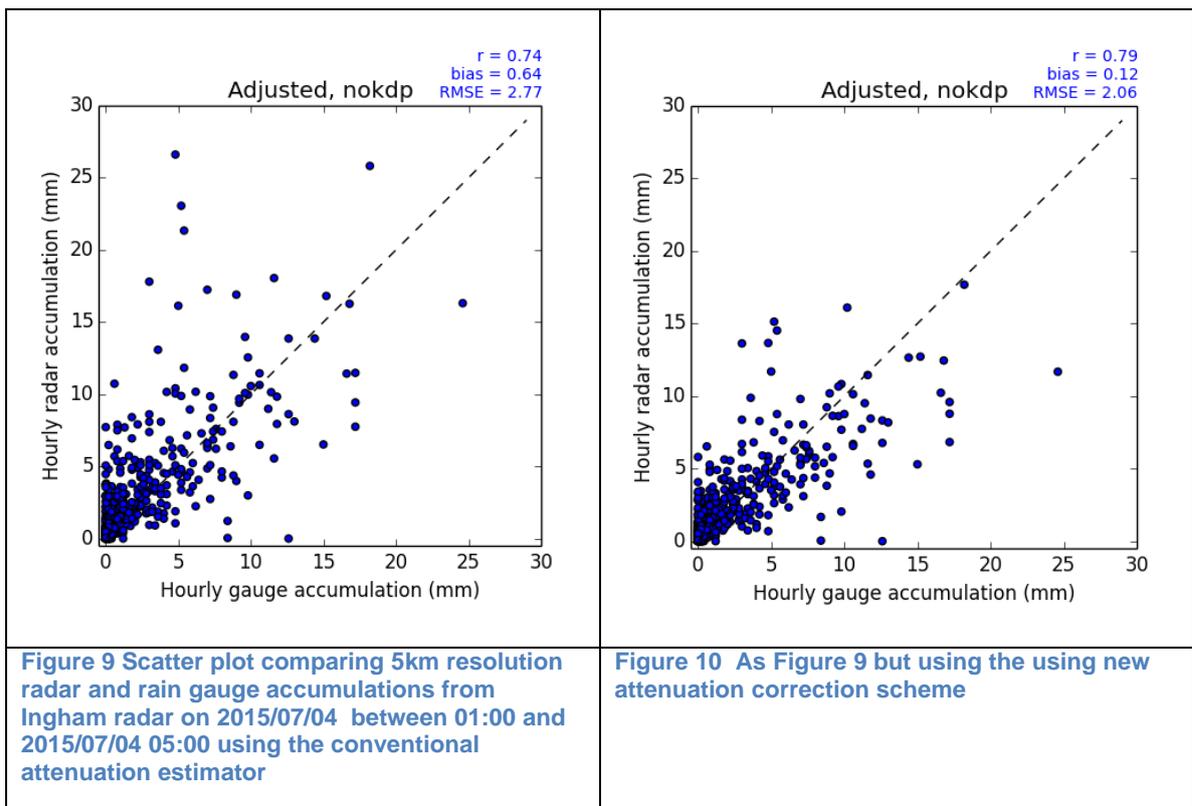


Figure 8 Upper: Total attenuation along a path estimated from the three available sources, the reflectivity based estimate (H&B) is shown in blue, the range of values that the  $\phi_{dp}$  based estimate can take is shown in grey, and the estimate based on radiometric emissions is shown in green. Lower: The  $\phi_{dp}$  based estimate is re-calibrated for the appropriate scaling and consistency used to remove outlying values to give a best estimate for the path integrated attenuation (Black).

It is difficult to quantify the improvement due to this new scheme, as fortunately, significantly attenuating storms do not occur very often in the UK, however they tend to have a significant impact when they do. Also, to demonstrate the benefits of the new scheme an alignment of radar, storm and rain gauges behind the path of the storm is required. A case study to investigate the benefits of the new scheme was carried out for an event which had these characteristics the results of which are shown in Figure 9 and Figure 10. In this case the introduction of the new scheme leads to an improvement in the correlation of the radar with the gauges (“r”), a reduction in bias and a significant reduction in root mean square error (RMSE). In this case reduction in the error is around 30%, with around a factor of 5 reduction in the positive bias.

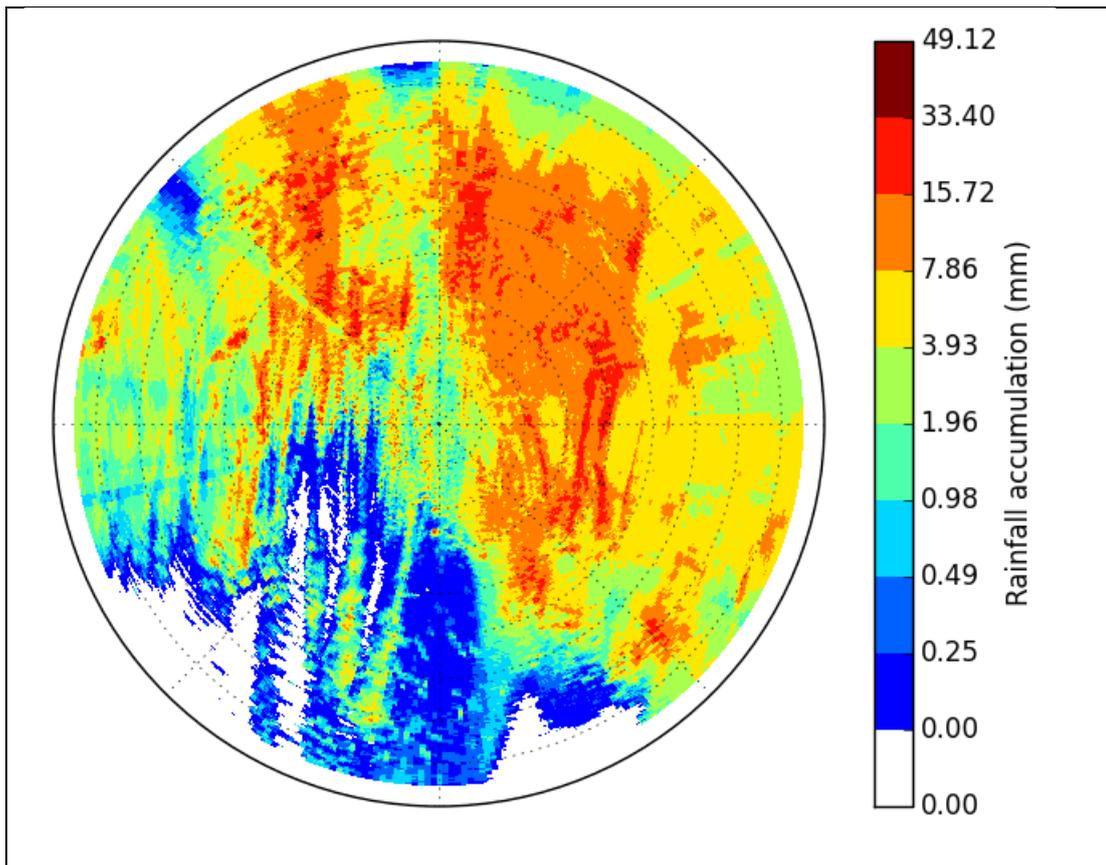


### **WP 3. “More accurate rainrate products when it really matters” (Hybrid Z/KDP/R relationship)**

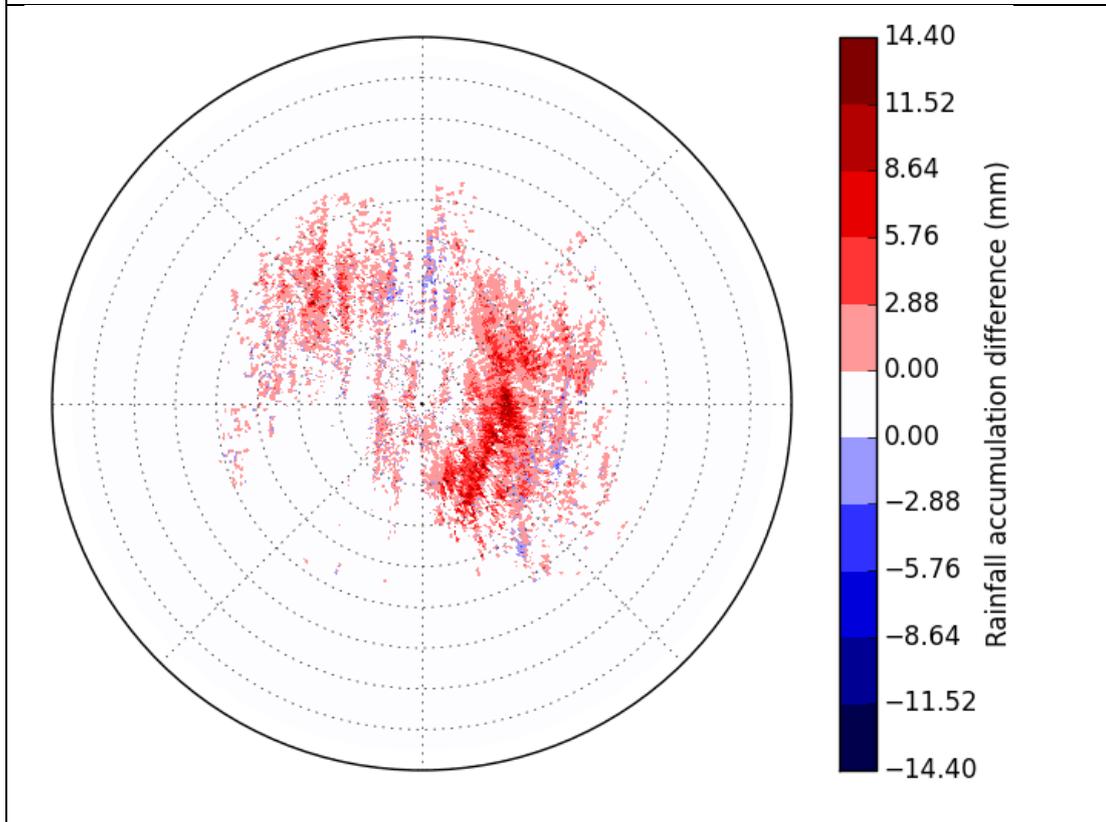
The current rain rate estimator is based on the reflected power measured by the radars. This has known deficiencies in that it is affected by radar miscalibration, attenuation, partial beam blocking, and is sensitive to Drop Size Distribution (DSD) variations – most of which cause underestimation of the rain rate at higher intensities. The upgraded dual polarisation radars can measure changes in the relative phases of polarised radar signals, known as the differential propagation phase ( $\phi_{dp}$ ), and its range derivative  $K_{dp}$ . As these are based on phase they are not affected by the aforementioned signal intensity-related issues. However, as  $K_{dp}$  is measured as the range derivative of  $\phi_{dp}$ , at low rain rates the noise on  $\phi_{dp}$  makes calculation of  $K_{dp}$  inaccurate. As such it is only suitable for use after filtering and at high rain rates, and so a hybrid reflectivity and Kdp approach has been developed.

A case study was carried out for an intense storm in the north of England (Figure 11). As can be seen in Figure 13 the introduction of the Kdp estimator leads to increased rainfall estimates which give improved correlation with gauge accumulations, reduced bias and decreased RMSE. As expected, the Kdp estimator has increased the estimated rain rates only where the most intense precipitation is occurring, suggesting that the increase in the accumulations shown by Figure 12 is the correct behaviour. As can be seen from Figure 12 the main effect of the hybrid scheme was to increase the rain rates, by as much as ~75% in some areas, particularly areas which saw higher accumulations. This was associated decrease in RMS error by ~ 25% suggesting that this increase was the correct behaviour.

The research phase of this work showed such promise that Met Office, Environment Agency and Flood Forecasting centre agreed to prioritise this work to bring it from the research phase in to operational use ahead of schedule.



**Figure 11. Five-hour control rainfall accumulation for Hameldon Hill between 2015/07/04 01:00 and 2015/07/04 06:00**



**Figure 12. Five-hour rainfall accumulation difference (test-control) for Hameldon Hill between 2015/07/04 01:00 and 2015/07/04 06:00**

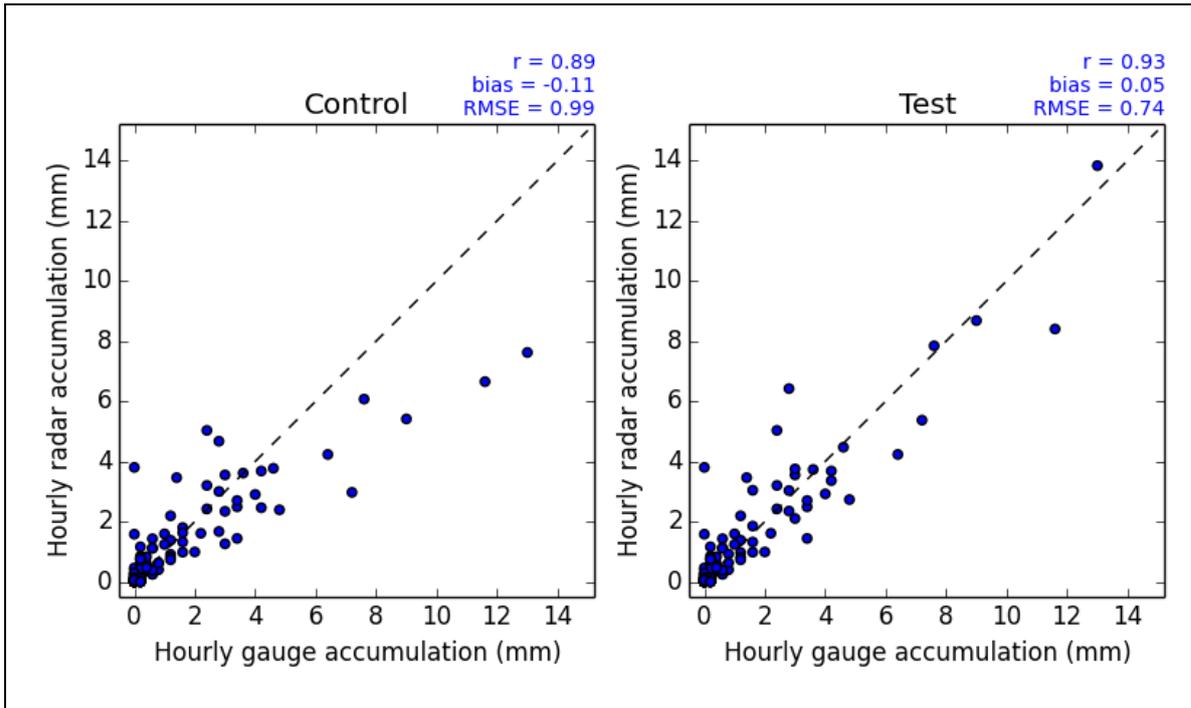


Figure 13. Scatter plots showing hourly rainfall accumulations from rain gauges and 1km resolution radar products from Hameldon Hill between 2015/07/04 01:00 and 2015/07/04 06:00. 'r' represents the Pearson correlation coefficient. Control (Left) is the conventional estimator and Test (Right) uses Kdp at higher intensities.

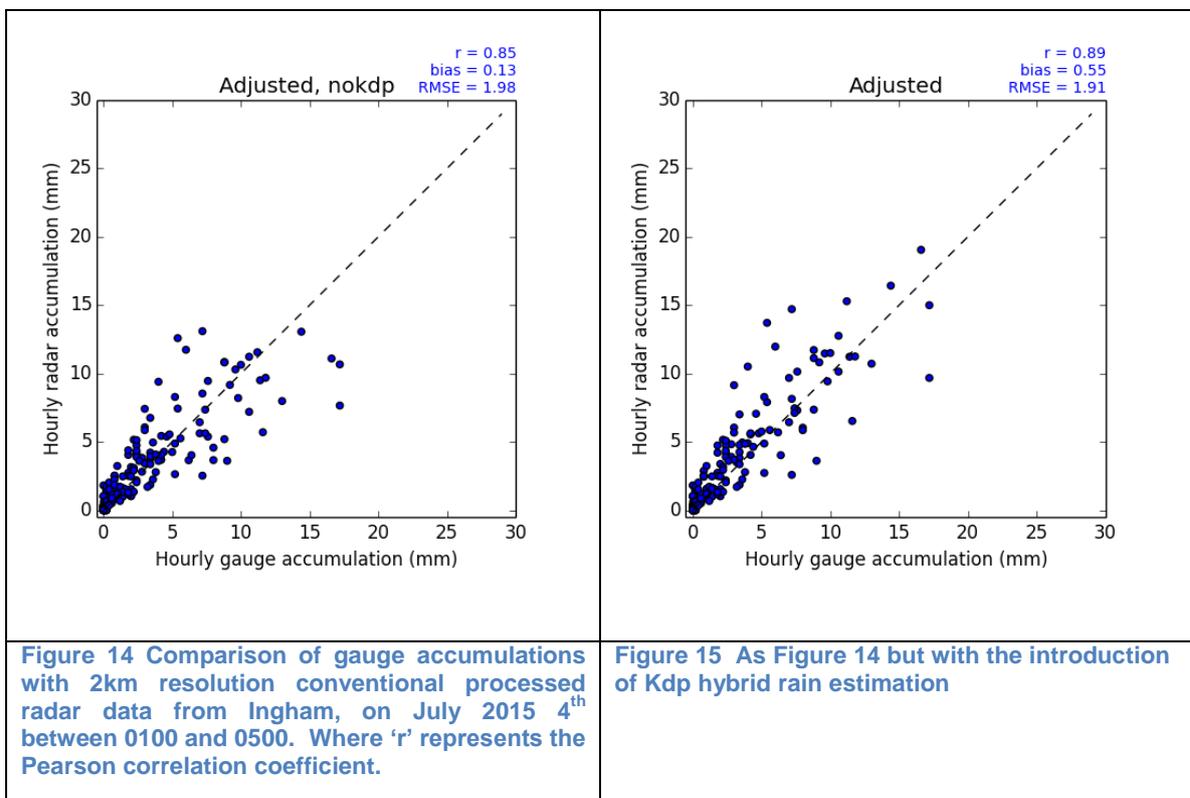
## Combined benefits of WP2 and WP3

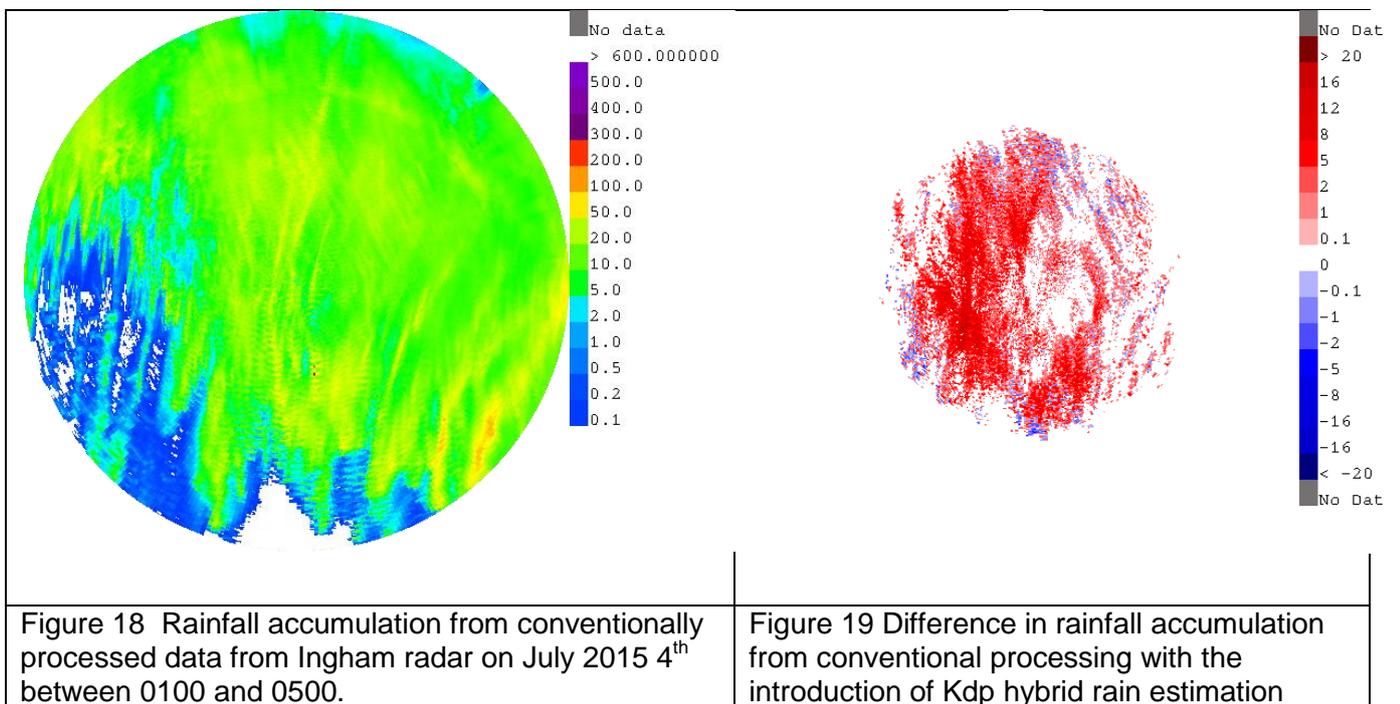
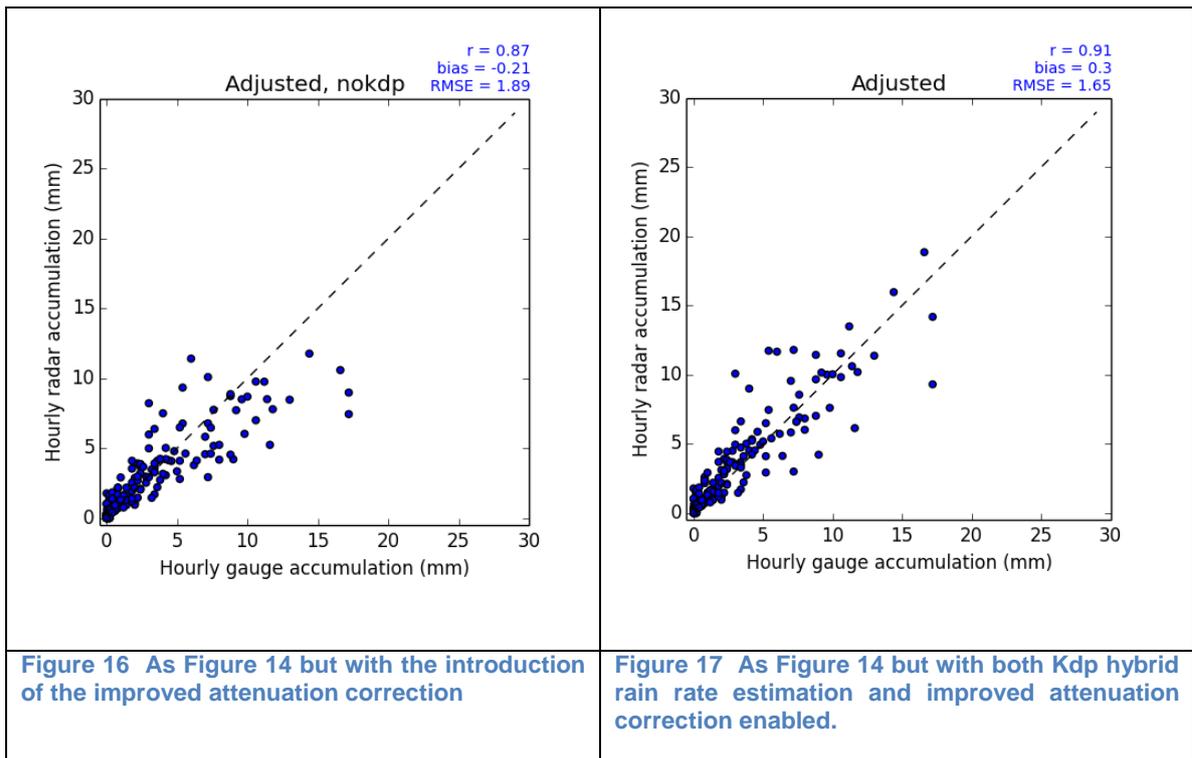
A case study was carried out to verify the benefits of combining the outputs of WP2 and WP3 using Ingham radar on July 4<sup>th</sup> 2015 between 0100 and 0500: A time and location where significant attenuating storms were observed. This is the same storm as shown for WP3, but now using a different radar with a different view of the storm to highlight the benefits of the improved attenuation correction.

Gauge-Radar comparisons for conventionally processed data following bias adjustment are shown in Figure 14 and act as a control. The gauge-radar accumulation comparisons shown in Figure 15 demonstrate that the introduction of the Kdp estimator (WP3) gives improved correlation and reduced RMS error; primarily due to increases in radar estimates at higher accumulations (Figure 19).

Figure 16 shows the effect of introducing the improved attenuation estimator (WP2), and again we see an improvement in correlation with gauge accumulations and a reduction in RMS error, this time primarily due to a decrease in the over correction for attenuation by the conventional scheme at lower accumulations (Figure 20).

As would be hoped, it is the combination of both these developments, shown in Figure 17, which give the most significant gains; both correctly increasing the estimates when the appropriate at the same time as reducing the inappropriate overcorrection from the conventional attenuation correction (Figure 21).





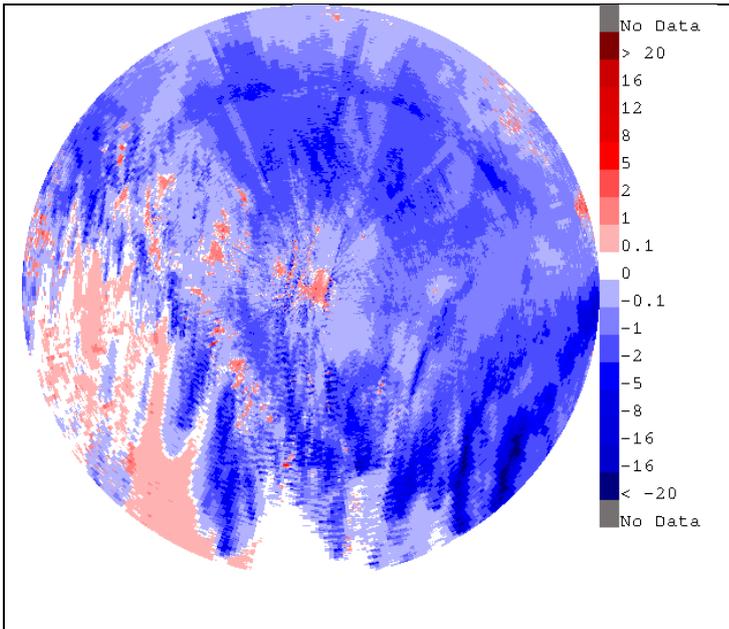


Figure 20 Difference in rainfall accumulation from conventional processing with the introduction of the improved attenuation correction

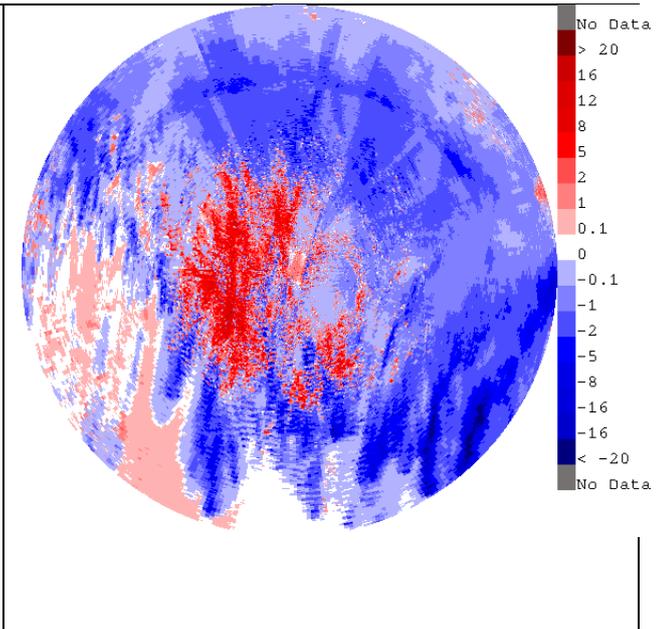


Figure 21 Difference in the rainfall accumulation with both Kdp hybrid rain rate estimation and improved attenuation correction enabled.

## Summary

With the roll out of these new algorithms we have begun to realise the benefits of the upgrade of the UK weather radar network to dual polarisation technology. For sites which have been upgraded we see a reduction in non-meteorological echoes breaking through in to the UK rain rate composite, an increase in data availability from low altitudes where quality is higher, and an increase in high quality data from sites that were previously affected by sea clutter.

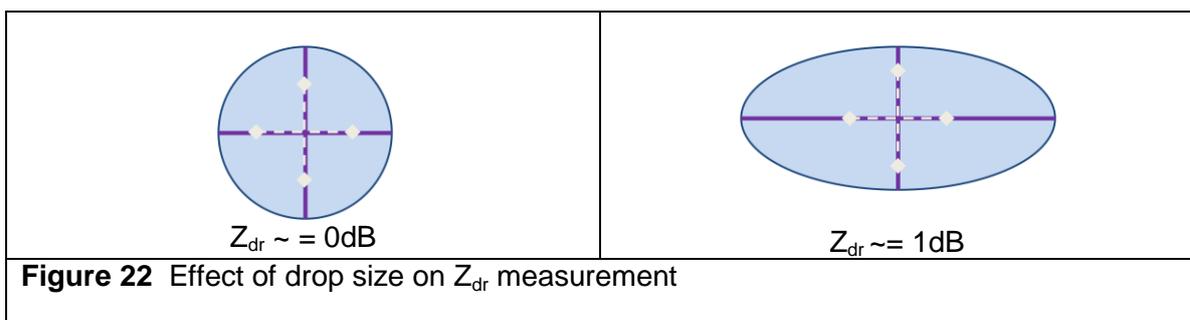
We are now able to more closely monitor and correct for error in radar calibrations, which in addition to improving the accuracy of the reflectivity measurements should lead to a reduction in unnecessary site visits by engineers, and so reduce system down-time. The introduction of a world leading attenuation correction making use of the unique features of the Met Office in-house designed radars will give improved rain rate estimates at lower rain rate, whereas the introduction of the hybrid Kdp estimator will lead to better rainfall estimates in the more intense storms.

The benefits of this work will only increase as the number of upgraded sites increases.

## Future work

While this work has led to a number of significant improvements in radar rain rate estimation, there is still significant potential further improvement from dual polarisation measurements. Perhaps the most obvious example of this comes from one of the more reliable parameters measured by dual polarisation radars –  $Z_{dr}$ .

This parameter measures the difference in power returned in the horizontal and vertical planes. While small rain drops are nearly spherical, the larger the droplet, the more oblate it is, due to the effects of air resistance as it falls (**Figure 22**). This leads to a larger return in the horizontal plane than the vertical. This difference can be used to improve the conversion from radar measurements to rain rates but requires careful calibration.



Another area in which the dual polarisation measurements can be used improve rain rate estimates is through hydrometeor type identification. It is known for example that snow has a different conversion from measured reflectivity to liquid water equivalent, something that is not accounted for at the moment. In a similar way hail can strongly contaminate rainfall estimates.

## Timeline of Developments

<b>Date</b>	<b>Development</b>
August 2014	Operational release of Dual polarisation quality control
November 2014	Operational release of hybrid RF interference flagging
November 2015	Operational release of calibration monitoring by dual polarisation self-consistency
November 2015	Operational release of hybrid $K_{dp}$ based estimates
March 2016	Release of improved attenuation estimation scheme to development / test system
November 2016	Operational release of improved attenuation estimation scheme

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