14B.2 THE EVOLUTION OF THE MET OFFICE RADAR DATA QUALITY CONTROL AND PRODUCT GENERATION SYSTEM: RADARNET

Dawn Harrison*, Katie Norman, Tim Darlington, Donal Adams, Nawal Husnoo, Caroline Sandford and Steven Best

Met Office, Exeter, United Kingdom

1. INTRODUCTION

The Met Office's weather radar network is currently in the middle of a renewal programme which is seeing the introduction of new, in-house designed, C-band dual-polarisation Doppler radars. The first of these new radars was introduced in early 2013 and the final upgrade is expected to be completed in 2017. With a prolonged period of operating a mixed network of both single and dual-polarisation radars, the Met Office's centralised radar data quality control and product generation system (Radarnet) needs to be robustly designed to handle different data.

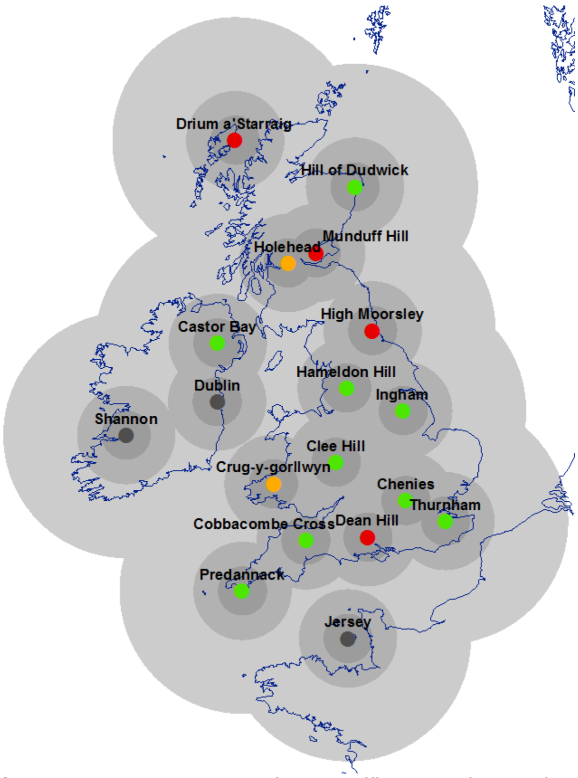

Figure 1: Latest status of Met Office weather radar network.
- Dual-polarisation radars
- Upgrade in progress
- Single polarisation
- Radars operated by other agencies

The availability of the polarimetric variables provides an opportunity to make significant improvements to quality control and correction of radar data, in particular in the identification of clutter, classification of hydrometeors and correction for attenuation. It is expected that improvements to the quality of quantitative precipitation estimates (QPE) will be possible through the use of specific differential phase (KDP) and differential reflectivity (ZDR). There is also the potential for better characterisation of the melting layer using the linear depolarisation ratio (LDR) and the correlation coefficient (ρHV). Such improvements will help meet demanding and evolving user requirements across a number of applications, including nowcasting, NWP, hydrology and aviation.

2. MET OFFICE RADAR NETWORK RENEWAL

The Met Office's network of 15 single-polarisation Plessey 45C/D C-band radars evolved over several decades, with the first radars dating back to the late 1970s. A weather radar network renewal (WRNR) programme is in progress, which is seeing these radars replaced by C-band dual-polarisation Doppler radars. As of September 2015, 9 of the 15 radars operated by the Met Office are fully operational dual-polarisation radars; 2 sites are in the process of being upgraded and a further 4 sites are scheduled for upgrade in 2016 and 2017 (see figure 1).

2.1. Radar system architecture

Rather than opt for a complete radar system from an established radar manufacturer, the Met Office instead took the decision to develop a solution in-house, with radar sub-systems sourced from a number of suppliers. To minimise environmental impacts, the large alloy castings in the radar pedestals have been re-used in the new design. The benefits of an in-house design are considered to be the ability to tailor the system to meet requirements at reduced costs. The radar engineering and signal-processing expertise developed through this process also means the skills exist in-house to maintain the systems over their life-time.

Following replacement of each radar, a 3 month reliability and data quality assessment phase takes place. The new radar is then introduced to the operational network once it has been demonstrated that acceptance criteria have been met. The overall radar performance to date has exceeded expectations with typical mode values of ρHV and LDR of 0.997 and -34dB respectively within light rain (Darlington et al., 2015). Figure 2 shows an example of LDR in light rain (reflectivity between 20 – 25 dBZ), within 30km of the Predannack radar. The lower peak is in rain, and the higher one is where the signal is dominated by clutter.

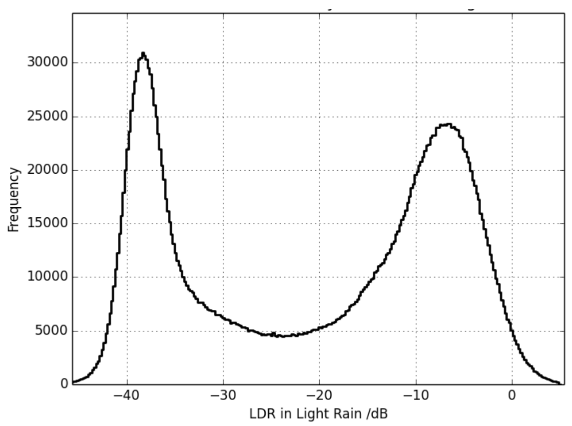

Figure 2: Sample LDR histogram from the Predannack radar in Cornwall, SW England

2.2. Radar scan strategy

The radars operate a scan strategy (table 1) which seeks to satisfy diverse requirements, including Doppler radial winds for assimilation in numerical weather prediction (NWP) models and low elevation scans for QPE. The scan strategy enables QPE estimates every 5 minutes, but also has Doppler scans and a vertical scan (for ZDR calibration) every 10 minutes. Two scans in LDR mode are completed at the lowest two elevations every 10 minutes, to help characterise the melting layer and hence improve QPE.

scan	low prf	high prf	elevation	rpm	mode
1	300		4.0	2.8	zdr
2	300		3.0	2.8	zdr
3	300		2.0	2.8	zdr
4	300		1.0	1.4	zdr
5	300		1.0	1.4	ldr
6	300		0.5	1.4	ldr
7	300		0.5	1.4	zdr
8	900	1200	9.0	3.4	zdr
9	900	1200	6.0	3.4	zdr
10	900	1200	4.0	3.4	zdr
11	900	1200	2.0	3.4	zdr
12	900	1200	1.0	3.4	zdr
13	300		4.0	2.8	zdr
14	300		3.0	2.8	zdr
15	300		2.0	2.8	zdr
16	300		1.0	1.4	zdr
17	300		0.5	1.4	zdr
18	900	1200	89.9	3.4	zdr

Table 1: Typical scan strategy operated by Met Office dual-polarisation radars

3. RADARNET IV

The current Met Office radar data quality control and product generation system (Radarnet 4) was introduced in 2005. It receives polar reflectivity data, from long pulse (2 µs), low-PRF (300 Hz) scans, at 1° x 600 m resolution, from up to 8 different antenna elevations, with a volume repeat frequency of 5 minutes. Doppler radial velocity and a spectrum quality indicator are also received from interspersed dual PRF (900 and 1200 Hz) short-pulse scans (0.5 µs).

3.1. *Quality control and correction of reflectivity*

The main quality control and correction steps associated with Radarnet 4 are summarised in Harrison et al., 2011):

- Clutter filtering using clutter phase alignment (CPA) (Hubbert et al. (2009); Nicol et al (2011)) in conjunction with a dynamic clutter map

- Identification of partial beam blocking (PBB) and correction using knowledge of terrain and climatological variation in probability of detection with azimuth
- Correction of reflectivity for attenuation in precipitation using the gate-by-gate algorithm proposed by Gunn and East (1954).

3.2. *Quantitative precipitation estimation (QPE)*

For QPE, the key features of Radarnet 4 are:

- Accounting for variation in the vertical profile of reflectivity (VPR) using the method proposed by Kitchen et al (1994), with a modification in deep convection using a reflectivity threshold of 30 dBZ at 1.5 km above the wet-bulb freezing level (Smyth and Illingworth (1998))
- Marshall-Palmer (1948) relationship $Z=200R^{1.6}$ to convert surface-equivalent reflectivity to precipitation rate
- Orographic enhancement of precipitation below the radar sampling height using the method of Alpert and Shafir (1989), tuned as described by Georgiou and Gaussiat (2010)
- Mean field bias adjustment using rain gauges using a variation of the method proposed by Seo et al. (1999) (Gibson, 2000).

4. CURRENT USE OF DUAL POLARISATION CAPABILITY

4.1. *Non-hydrometeor target identification using dual-polarisation data*

For the 9 dual-polarisation radars, a non-hydrometeor identification scheme has been implemented. This is a naive Bayesian classifier (Rico-Ramirez and Cluckie, 2008) which uses the texture of differential phase (ϕDP)$_{)}$, texture of ZDR and ρHV, as well as CPA. This new scheme shows significant improvements in non-hydrometeor identification, especially for sea clutter, ships and aircraft.

In addition, the use of dual polarisation for quality control has facilitated the retirement of an ad-hoc distance-based noise threshold, leading to a higher sensitivity to lighter rainfall at long range.

5. PLANNED USE OF DUAL-POLARISATION DATA

As well as the identification of non-hydrometeors, there are several uses of the dual polarisation data that are already under development and testing and are planned for operational implementation within the next 12 months.

5.1. *Radar calibration*

The method proposed by Gourley et al (2009), which uses the consistency between ZH, ZDR, and the path integral of KDP to calibrate ZH, with adjusted constraints, is being tested and is showing encouraging results. This is scheduled for implementation in November 2015. Initially the calibration will be semi-automated, with the final decision, as to whether to apply the derived calibration, lying with the Radar Network Manager. If the method proves robust over time, a fully automated implementation will be considered. It is hoped that improved initial calibration will reduce the reliance on the gauge-based mean field bias adjustment for radar QPEs – or even make its use redundant.

5.2. *Correction for attenuation in precipitation*

There are several approaches that have been developed which utilise dual-polarisation parameters to improve the correction of ZH and ZDR for attenuation in precipitation (e.g. Bringi et al. (2001); Testud et al. (2000) and Tabary et al. (2009)). The path-integrated attenuation (PIA) in precipitation is considered to be linearly proportional to ϕDP. However, the coefficient of proportionality can vary by up to a factor of two, depending on temperature, hydrometeor shape, and size distribution (Carey et al., 2000).

An alternative proposed technique is to use the principle that absorbers in thermal equilibrium will also emit electromagnetic radiation. This can be measured as an increase in the noise level at long range, which can then be converted into PIA (Thompson et al., 2011; Darlington, 2013). A scheme, which uses this technique, along with the ϕDP technique of Hubbert and Bringi (1995) and the gate-by-gate technique of Hitschfield and Bordan (1954); is being tested (Husnoo et al, 2015) – see figure 3 for an example. The use of the three techniques facilitates a better estimate of the PIA, by cross-comparison. The information in the emissions-based PIA is then used to calibrate the ϕDP-based estimation along the ray and to re-calculate the attenuation from reflectivity with a constraint on the PIA. The approach is yielding promising results and is expected to be implemented in Radarnet in early 2016. Where the three techniques closely match (e.g. within 0.5dB), there is increased confidence that attenuation has been well estimated. Divergence between the techniques could feed into the quality estimate subsequently used as the basis for radar compositing (Sandford and Gaussiat, 2012).

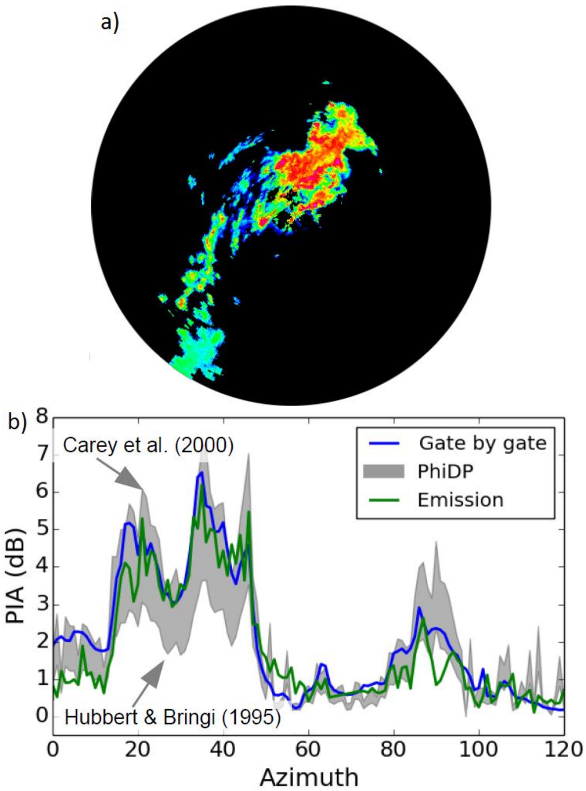

Figure 3: a) Reflectivity scan image b) corresponding path integrated attenuation from the Predannack radar, 10th July 2015.

5.3. *Convective/stratiform delineation*

In convective conditions, assuming a VPR with a bright band – and correcting for this - can cause significant underestimation of surface rainfall rates. The use of peak LDR to identify the most appropriate VPR model to apply is described in Sandford et al. (2015). Three distinct VPRs are suggested, representing stratiform, weak convective and strong convective conditions. Initial analysis of a large dataset of range-height indicator scans from the Met Office radar at Wardon Hill suggests that peak LDR has significantly more skill than a reflectivity threshold in identifying the appropriate VPR to use. These findings are consistent with Illingworth and Thompson (2012). Implementing this method should significantly improve QPE in high intensity, high impact events.

5.4. *Precipitation estimation*

The Marshall-Palmer relationship $Z=200R^{1.6}$ (Marshall and Palmer, 1948) is most applicable for moderate stratiform rain. The use of KDP to improve the estimation of precipitation at high intensities has been proposed by many authors (see Figueras i Ventura et al. (2012) for a summary).

A method, which utilises the Beard and Chuang (1987) drop shape for KDP > 0.5° has been trialled using data from operational Met Office dual-polarisation radars. It has been found to significantly reduce precipitation underestimation at high intensities (figure 4). It is planned to implement this method in the November 2015 Radarnet software release.

6. FURTHER EXPECTED USE OF DUAL POLARISATION CAPABILITY

The following two sub-sections outline applications for which it is expected, based on published literature, that the additional dual-polarisation data can be utilised to deliver additional products or improve the quality of existing radar products. To date, evaluation of published methods has not been progressed using data from the new Met Office dual-polarisation radars. There are, however, plans to make progress in these areas within the next 12-18 months.

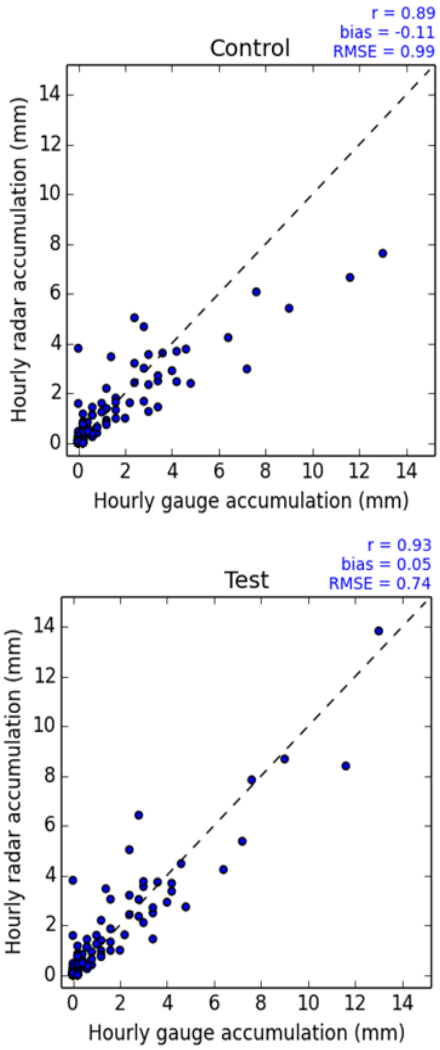

Figure 4: One hour rain gauge and radar precipitation accumulation for a) Z-R only and b) KDP-R for KDP>0.5° from the Hameldon Hill radar, 4th July 2015.

6.1. *Hydrometeor classification*

The ability to identify characteristics of hydrometeor shape is seen as one of the main benefits of dual-polarisation. Being able to distinguish between liquid water, ice and the melting layer is useful supporting information for the assimilation of reflectivity in NWP models. Surface precipitation type, derived from hydrometeor type along with NWP and/or other observational information (to account for changes in phase below the radar sampling height) is useful for identifying hazardous weather. This can be used to improve existing severe weather warning services, for example for the general public, transport operators and emergency responders.

Chandrasekar et al. (2013) provide a summary of how each of the dual-polarisation parameters relate to hydrometeor microphysical properties. Most of the numerous proposed hydrometeor classification schemes take a fuzzy logic approach (e.g. Park et al., 2009). Baysian and decision tree approaches have also been suggested (Marzano et al. (2008); Schuur et al., (2012)). Benefit has been demonstrated by additionally incorporating temperature information from NWP models, which is quantified in Al-Sakka et al (2013). It is clear from the literature that initial quality control is of paramount importance for successful hydrometeor classification. ZH, ZDR need to be well calibrated and ϕDP offsets applied. Gill et al (2012) suggest ZDR needs to be accurate to less than 0.2 dB and ϕDP within 1°. Also ZH and ZDR need to be pre-corrected for attenuation (radome and precipitation) and any partial beam blocking. Development and testing of a hydrometeor classification scheme for Radarnet needs, therefore, to follow development and implementation of attenuation corrections. It is proposed to carry out an inter-comparison of several schemes in 2016 and/or tailor an existing scheme to better meet the requirements for the UK weather. There is a desire to retain the probabilistic information associated with each hydrometeor type, rather than just the most likely class, so as to facilitate the generation of a greater range of products (such as probability of hail, probability of snow).

6.2. *ZDR for precipitation estimation*

A number of composite estimators, which use Z-R, ZDR-R and KDP-R relationships, depending on specific criteria being met, have been proposed (e.g. Ryzhkov et al., 2005). This approach can capitalize on the relative merits of each parameter for different rain rate categories, and have been shown to outperform fixed Z-R and KDP-R only relationships (Bringi et al., 2011).

As with hydrometeor classification, algorithm performance is critically dependent on the initial quality control, calibration and correction for attenuation and partial beam blocking. Hence work to investigate any improvement that additionally utilising ZDR can make will be considered after work to ensure these pre-processing stages have been completed.

7. FUTURE RADAR DATA PROCESSING AND PRODUCT GENERATION ARCHITECTURE

The introduction of dual polarisation radars, and the associated new data means a step change in the complexity of the associated processing chain, if this new data is to be fully exploited. Hence, it is a good time to re-consider the architecture of this system, rather than simply let it evolve in a piecemeal way. So, although in the short-term, use of the dual-polarisation data is being made within the existing Radarnet 4 system, work will progress in parallel on the next-generation of Radarnet. This will also consider broader design considerations for processing many types of observations.

The Met Office has a number of observations data processing systems, each handling different observation types, e.g. Lidarnet for processing LIDAR data (Adam et al., 2015) and ATDNet for processing lightning data (Anderson and Klugmann, 2014). These systems vary significantly in complexity but all have some common elements, largely associated with file handling, monitoring reception, product generation and visualisation. There is a desire to achieve convergence of these systems into a common framework in order to minimise duplication of effort, increase resilience and flexibility and use standard data format for the different observation types (e.g. ODIM HDF5 for weather radar scan data (Michelson et al., 2014)). It is anticipated that this common framework, Hermes, will provide the “glue” and “business logic” around the science code associated with each observation type, using open-source technologies.

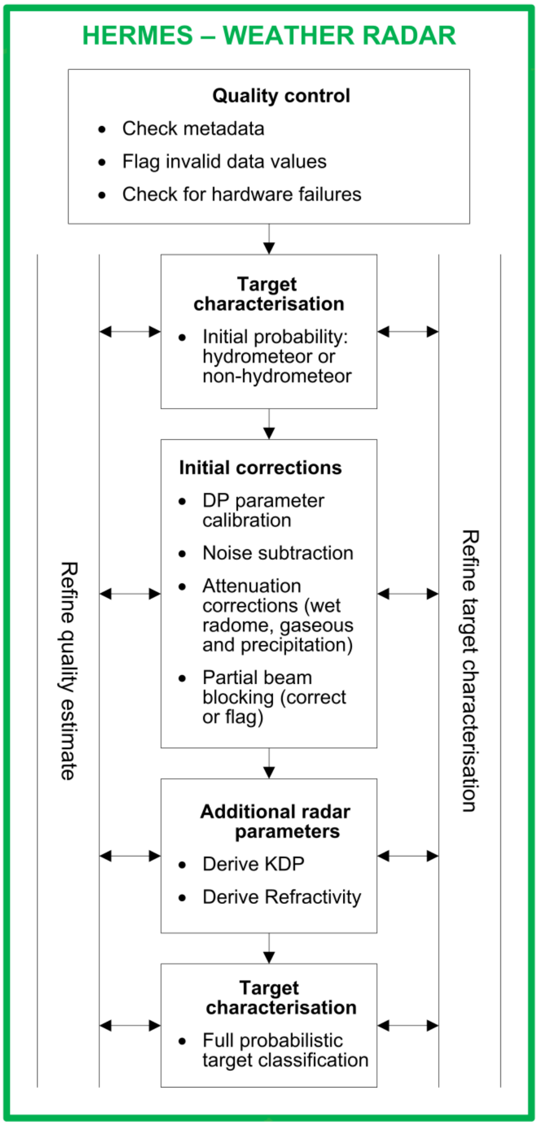

Figure 5: Schematic of Hermes–Radar, which will perform quality control and correction of radar volume data.

For the radar data processing chain specifically, there is a desire to decouple the three main aspects, i.e.:

- Radar system and site specific data processing
- Generation of 2D and 3D multi-radar products
- Packaging and user specific formatting

7.1. *Quality control and correction of radar scan data*

It is expected there will be a Hermes–Radar component in future that handles the radar data quality control and correction (see figure 5) and that this will be separated from the derivation of multi-radar products. This separation is more in terms of software and does not necessarily mean running on physically separate computer systems.

The main output from Hermes-Radar component will be quality controlled and corrected radar scan data, along with supporting quality information. A feature of the processing chain is envisaged to be a gradual refining of target characterisation and quality estimates with each processing stage, as illustrated in figure 5. There is also a desire to move away from using dimensionless quality indices towards quantitative error estimation (in units of dB etc.) - which are easier to interpret by users. The main use of the radar data at this stage of the processing chain will be for assimilation of reflectivity, refractivity and Doppler winds in high-resolution NWP models. Recent Met Office developments on radar data assimilation are described in Simonin et al. (2014) and Hawkness-Smith and Ballard (2013).

7.2. *Generation of 2D and 3D radar products*

The current range of radar products from Radarnet is quite limited, with the 1x1 km QPE composite being the primary product (Harrison et al., 2009). This is generated at 5 minute intervals, at 5 minutes after the nominal product validity time. Although this meets the timeliness and resolution demands of many users, the current system lacks flexibility. For example, if data for a limited domain is required at higher resolution, or data is required more quickly, accepting that data may be absent from some radar sites. It is envisaged that the next generation radar products system, Radarnet 5, will hold data within a 3D living point cloud, which will enable products to be derived at any point in time, using the latest data (see figure 6). The range of products that can be derived will also increase, with 3D wind hazard products and 2D probabilistic weather hazard information expected to be generated.

Composite QPE will still be a key product, and the process of deriving QPE an integral part of the Radarnet 5 system. However, it is expected that the process will have more of a multi-radar approach. So, instead of deriving QPE from each radar in the network and then compositing to form a network wide product, Radarnet 5 will more fully exploit the overlap between each radar's coverage to inform and improve the derivation of QPE. This is in line with evolution of other operational multi-radar data processing system.

7.3. *Re-formatting and packaging*

Radarnet 4 generates QPE products for a wide variety of customers in both standard and bespoke formats (e.g. BUFR, Nimrod) and many sub-domains. It is planned to move towards a single standard format – ODIM HDF5 (Michelson et al., 2014) – and a primary domain. The Met Office has down-stream product generation systems that handle a wide variety of meteorological gridded products which can handle these packaging tasks in a more efficient way. It is anticipated that this approach will minimise duplication of effort in product generation across the many observations processing systems.

8. SUMMARY AND CONCLUSIONS

This paper has summarized the status of the Met Office network of C-band radars and the centralized processing system, Radarnet. The rationale behind the future Radarnet architecture has been outlined, emphasising the expected distinction between quality control and correction of the basic radar scan data and the derivation of 2D and 3D products. The current use of the additional dual-polarisation data for improving the identification of non-hydrometeor echoes has been outlined. Ongoing developments for further utilising this additional capability to improve the correction of reflectivity scan data and the quality of derived QPEs have also been described.

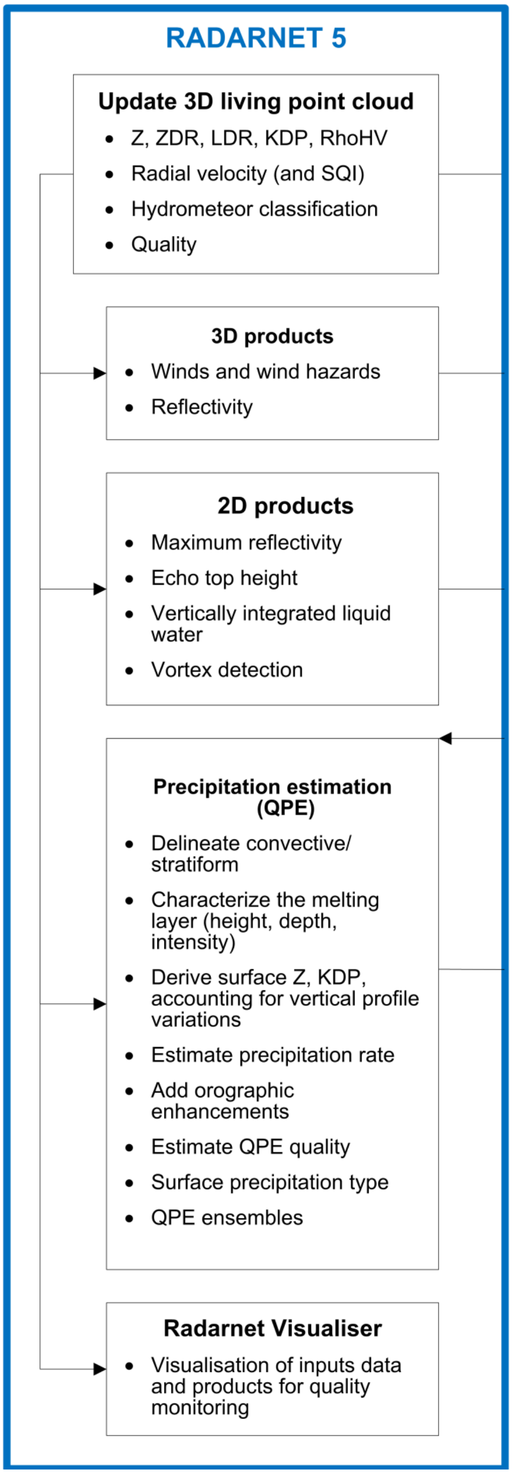

Figure 6: Radarnet 5: Radar product generation system

The re-design of the Radarnet system is still at a relatively early stage, but the basic requirements to improve product quality, increase flexibility, develop probabilistic products, engage new users and retire legacy formats have been established. Other desirables are to reduce the reliance on rain gauges and satellite data for calibration and non-hydrometeor target identification.

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