Quality Control Algorithms Applied on Weather Radar Reflectivity Data

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1. Introduction

Quality related issues are becoming more and more often one of the main research fields nowadays. This trend affects weather radar data as well. Radar-derived precipitation data are burdened with a number of errors from different sources (meteorological and technical). Due to the complexity of radar measurement and processing it is practically impossible to eliminate these errors completely or at least to evaluate each error separately (Villarini & Krajewski, 2010). On the other hand, precise information about the data reliability is important for the end user.

The estimation of radar data quality even as global quantity for single radar provides very useful and important information (e.g. Peura et al., 2006). However for some applications, such as flash flood prediction, more detailed quality information is expected by hydrologists (Sharif et al., 2004; Vivoni et al., 2007, Collier, 2009). A quality index approach for each radar pixel seems to be an appropriate way of quality characterization (Michelson et al., 2005; Friedrich et al., 2006; Szturc et al., 2006, 2008a, 2011). As a consequence a map of the quality index can be attached to the radar-based product.

2. Sources of radar data uncertainty

There are numerous sources of errors that affect radar measurements of reflectivity volumes or surface precipitation, which have been comprehensively discussed by many authors (e.g. Collier, 1996; Meischner 2004; Šálek et al., 2004; Michelson et al., 2005).

Hardware sources of errors are related to electronics stability, antenna accuracy, and signal processing accuracy (Gekat et al., 2004). Other non-meteorological errors are results of electromagnetic interference with the sun and other microwave emitters, attenuation due to a wet or snow (ice) covered radome, ground clutter (Germann & Joss, 2004), anomalous propagation of radar beam due to specific atmosphere temperature or moisture gradient (Bebbington et al., 2007), and biological echoes from birds, insects, etc. Next group of errors is associated with scan strategy, radar beam geometry and interpolation between sampling points, as well as the broadening of the beam width with increasing distance from the radar site. Moreover the beam may be blocked due to topography (Bech et al., 2007) and by nearby objects like trees and buildings, or not fully filled when the size of precipitation echo is relatively small or the precipitation is at low altitude in relation to the antenna elevation (so called overshooting).

Apart from the above-mentioned non-precipitation errors, meteorologically related factors influence precipitation estimation from weather radar measurements. Attenuation by hydrometeors, which depends on precipitation phase (rain, snow, melting snow, graupel or hail), intensity, and radar wavelength, particularly C and X-band, may cause the strong underestimation in precipitation, especially in case of hail. Another source of error is Z–R relation which expresses the dependence of precipitation intensity R on radar reflectivity Z. This empirical formula is influenced by drop size distribution, which varies for different precipitation phases, intensities, and types of precipitation: convective or non-convective (Šálek et al., 2004). The melting layer located at the altitude where ice melts to rain additionally introduces uncertainty into precipitation estimation. Since water is much more conductive than ice, a thin layer of water covering melting snowflakes causes strong overestimation in radar reflectivity. This effect is known as the bright band (Battan, 1973; Goltz et al., 2006). Moreover the non-uniform vertical profile of precipitation leads to problems with the estimation of surface precipitation from radar measurement (e.g. Franco et al., 2002; Germann & Joss, 2004; Einfalt & Michaelides, 2008), and these vertical profiles may strongly vary in space and time (Zawadzki, 2006).

Dual-polarization radars have the potential to provide additional information to overcome many of the uncertainties in contrast to situation when only the conventional reflectivity Z and Doppler information is available (Illingworth, 2004).

3. Methods for data quality characterization

3.1 Introduction

Characterization of the radar data quality is necessary to describe uncertainty in the data taking into account potential errors that can be quantified as well as the ones that can be estimated only qualitatively. Generally, values of many detailed "physical" quality descriptors are not readable for end users, so the following quality metrics are used as more suitable:

- total error level, i.e. measured value ± standard deviation expressed as measured physical quantity (radar reflectivity in dBZ, precipitation in mm h^{-1}, etc.),
- quality flag taking discrete value, in the simplest form 0 or 1 that means "bad" or "excellent" data,
- quality index as unitless quantity related to the data errors, which is expressed by numbers e.g. from 0 to 1.

Many national meteorological services provide quality information in form of flags to indicate where radar data is burdened with specific errors and if it is corrected by dedicated algorithms (Michelson et al., 2005; Norman et al., 2010). The flags are expressed as discrete numbers.

The quality index (QI) is a measure of data quality that gives a more detailed characteristic than a flag, providing quantitative assessment, for instance using numbers in a range from 0 (for bad data) to some value (e.g. 1, 100, or 255 for excellent data). The quality index concept is operationally applied to surface precipitation data in some national meteorological services (see review in Einfalt et al., 2010).

3.2 General description of *QI* scheme

An idea of quality index (*QI*) scheme is often employed to evaluate radar data quality. In this scheme the following quantities must be determined (Szturc et. al., 2011):

1. Quality factors, X_i (where i = 1, …n) – quantities that have impact on weather radar-based data quality. Their set should include the most important factors that can be measured or assessed.
2. Quality functions, f_i – formulas for transformation of each individual quality factor X_i into relevant quality index QI_i. The formulas can be linear, sigmoidal, etc.
3. Quality indices, QI_i – quantities that express the quality of data in terms of a specific quality factors X_i:

$$QI_i = \begin{cases} 0 & \text{bad data} \\ 1 & \text{good data} \\ f_i(X_i) \in (0,1) & \text{other cases} \end{cases} \tag{1}$$

4. Weights, W_i – weights of the QI_is. The optimal way of the weight determination seems to be an analysis of experimental relationships between proper quality factors X_i and radar data errors calculated from comparison with benchmark data (on historical data set).
5. Final quality index, *QI* – quantity that expresses quality of data in total, calculated using one of the formulae:
   - minimum value:

$$QI = \min\left(QI_i\right), \tag{2a}$$

   - additive scheme (weighted average):

$$QI = \sum_{i=1}^{n}\left(QI_i \cdot W_i\right), \tag{2b}$$

   - multiplicative scheme (multiplication):

$$QI = \prod_{i=1}^{n}\left(QI_i \cdot W_i\right) \text{ or } QI = \prod_{i=1}^{n} QI_i \,. \tag{2c}$$

The latter seems to be the most appropriate and its form is open (e.g. changes in set of quality indicators do not require the scheme parameterization).

4. Quality control algorithms for radar reflectivity volumes

Starting point in dealing with weather radar reflectivity data should be quality control of 3-D raw radar data. There are not many papers focused on quality characterization of such data. Fornasiero et al. (2005) presented a scheme employed in ARPA Bologna (Italy) for quality evaluation of radar data both raw and processed. The scheme developed in Institute of Meteorology and Water Management in Poland (IMGW) in the frame of BALTRAD project (Michelson et al., 2010) was described by Ośródka et al. (2010, 2012). Commonly employed groups of quality control algorithms are listed in Table 1.

Task	Correction algorithm	Quality factor	QC	QI
Evaluation of technical radar parameters	–	Set of technical radar parameters		x
Assessment of effects related to distance to radar site	–	Horizontal and vertical beam broadening		x
Ground clutter removal	Using Doppler filter or 3-D clutter map	Presence of ground clutter	x*	x
Removal of non-meteorological echoes	Analysis of 3-D reflectivity structure. Using dual-polarization parameters	Presence of the non-meteorological echoes	x	x
Beam blockage correction	Using topography map	Presence of beam blockage	x	x
Correction for attenuation in rain	Based on attenuation coefficient. Using dual-polarization parameters	Attenuation in rain along the beam path	x	x
Spatial variability evaluation	Analysis of 3-D reflectivity structure	Spatial variability of reflectivity field		x

* commonly the correction is made by built-in radar software.

Table 1. Groups of quality control algorithms (correction QC and characterization QI) for 3-D reflectivity (Z) data.

4.1 Technical radar parameters

This algorithm aims to deliver data quality metric only. A set of technical radar parameters that impact on data quality can be selected as quality factors. The parameters are for instance: operating frequency, beam width, pointing accuracy in elevation and azimuth, minimal detectable signal at 1000 m, antenna speed, date of last electronic calibration, etc. (Holleman et al., 2006). All the factors are static within the whole radar range and characterize quality of each particular radar so different radars can be compared in terms of their quality. The threshold values for which the quality index becomes lower than one should be set for all parameters according to the common standards.

4.2 Horizontal and vertical broadening of a radar beam

Radar measurements are performed along each beam at successive gates (measurement points in 3-D data space), which represent certain surrounding areas determined by the beam width and pulse length. Since the radar beam broadens with the distance to the radar site, the measurement comes from a larger volume and related errors increase as well. There is no possibility to correct this effect, however it can be quantitatively determined and taken into account in the total quality index.

The horizontal and vertical broadening of radar beam for each gate can be geometrically computed knowing its polar coordinates: elevation, azimuth, and radial distance to radar site, and two parameters of radar beam: beam width and radar pulse length. Related quality index may be determined from broadenings of the both beam cross section (Ośródka et al., 2012).

4.3 Ground clutter removal

The correction of radar data due to contamination by ground clutter is commonly made at a level of radar system software which uses statistical or Doppler filtering (e.g. Selex, 2010). In such situation the information about the correction is not available so generation of a ground clutter map for the lowest (and higher if necessary) scan elevation must be employed, e.g. using a digital terrain map (DTM). In order to determine areas contaminated by ground clutter a diagram of partial beam blockage values (*PBB*) is analysed. The *PBB* is defined as a ratio of blocked beam cross section area to the whole one.

Gates where ground clutter was detected should be characterized by lowered quality index. A simple formula for quality index QI_{GC} related to ground clutter presence can be written as:

$$QI_{GC} = \begin{cases} a & \text{ground clutter is detected} \\ 1 & \text{no clutter} \end{cases} \tag{3}$$

where a is the constant, e.g. between 0 and 1 in the case of $QI_i \in (0, 1)$. The quality index decreases in each gate with detected clutter even if it was removed.

4.4 Removal of non-meteorological echoes

Apart from ground clutter other phenomena like: specks, external interference signals (e.g. from sun and Wi-Fi emitters), biometeors (flock of birds, swarm of insects), anomalous propagation echoes (so called anaprop), sea clutter, clear-air echoes, chaff, etc., are considered as non-meteorological clutter. Since various types of non-precipitation echoes can be found in radar observations, in practice individual subalgorithms must be developed to address each of them. More effective removal of such echoes is possible using dual-polarization radars and relevant algorithms for echo classification.

Removal of external interference signals. Signals coming from external sources that interfere with radar signal have become source of non-meteorological echoes in radar data more and more often. Their effect is similar to a spike generated by sun, but they are observed in any azimuth at any time, mainly at lower elevations, and may reach very high reflectivity. The spurious spike-type echoes are characterized by their very specific spatial structure that clearly differs from precipitation field pattern (Peura, 2002; Ośródka et al., 2012): they are observed along the whole or large part of a single or a few neighbouring radar beams. Commonly reflectivity field structure is investigated to detect such echo on radar image (Zejdlik & Novak, 2010). Recognition of such echo is not very difficult task unless it interferes with a precipitation field: its variability is low along the beam and high across it. The algorithm removes it from the precipitation field and replaces by proper (e.g. interpolated) reflectivity values. In the algorithm of Ośródka et al. (2012) two stages of spike removal are introduced: for "wide" and "narrow" types of spikes.

Removal of "high" spurious echoes. "High" spurious echoes, not only spikes, are echoes detected at altitudes higher than 20 km where any meteorological echo is not possible to exist. All the "high" echoes are removed.

Removal of "low" spurious echoes. "Low" spurious echoes are all low-reflectivity echoes detected at low altitudes only. No meteorological echo can exist here. All the "low" echoes are removed. The algorithm can be treated as a simple method to deal with biometeor echoes (Peura, 2002).

Meteosat filtering. As a preliminary method for non-meteorological echo removal the filtering by Meteosat data on cloudiness can be used. A Cloud Type product, which is provided by EUMETSAT, distinguishes twenty classes of cloud type with the classes from 1 to 4 assigned to areas not covered by any cloud. All echoes within not clouded areas are treated as spurious ones and removed. Such simple technique can turn out to be quite efficient in the cases of anomalous propagation echoes (anaprop) over bigger areas without clouds (Michelson, 2006).

Speck removal. Generally, the specks are isolated radar gates with echo surrounded by non-precipitation gates. Number of echo gates in a grid around the given gate (e.g. of 3 x 3 gates) is calculated (Michelson et al., 2000). If a certain threshold is not achieved then the gate is classified as a speck, i.e. measurement noise, and the echo is removed. Algorithm of the reverse specks (i.e. isolated radar gates with no echo surrounded by precipitation gates) removal is analogous to the one used for specks.

Using artificial intelligence techniques. Artificial intelligence algorithms, such as neural network (NN), are based on analysis of reflectivity structure (Lakshmanan et al., 2007). The difference is that similarity of the given object pattern to non-meteorological one, on which the model was learned, is a criterion of spurious echo detection. For this reason NN-based algorithms are difficult to parameterize and control their running.

Using dual-polarization observations. The basis is the fact that different types of targets are characterized by different size, shape, fall mode and dielectric constant distribution. In general, different combinations of polarimetric parameters can be used to categorize the given echo into one of different types (classes). The fuzzy logic scheme is mostly employed for the combination. Such methods consider the overlap of the boundaries between meteorological and non-meteorological objects. For each polarimetric radar observable and for each class a membership function is identified basing on careful analysis of data. Finally, an object is assigned to the class with the highest value of membership function.

The most often horizontal reflectivity (Z_H), differential reflectivity (Z_{DR}), differential phase shift (Φ_{DP}), correlation coefficient (ρ_{HV}), and analyses of spatial pattern (by means of standard deviation) of the parameters are employed in fuzzy logic schemes. Radars operating in different frequencies (S-, C-, and X-band) may provide different values of polarimetric parameters as they are frequency-dependent. For that reason, different algorithms are developed for identification of non-meteorological echoes using different radar frequencies, see e.g. algorithms proposed by Schuur et al. (2003) for S-band radars and by Gourley et al. (2007b) for C-band. A significant disadvantage of such techniques is that they are parameterized on local data and conditions so they are not transportable to other locations.

Quality index. Quality index for the gates in which non-meteorological echoes are detected is decreased to a constant value using formula similar to Equation (3).

An example of algorithms running for spike- and speck-type echoes removal is depicted in Figure 2b (for Legionowo radar).

4.5 Beam blockage

Radar beam can be blocked by ground targets, i.e. places where the beam hits terrain. A geometrical approach is applied to calculate the degree of the beam blockage. This approach is based on calculation what part of radar beam cross section is blocked by any topographical object. For this purpose a degree of partial beam blocking (*PBB*) is computed from a digital terrain map (DTM). According to Bech et al. (2003, 2007), the *PBB* is calculated from the formula:

$$PBB = \frac{y\sqrt{a^2 - y^2} + a^2 \arcsin\frac{y}{a} + \frac{\pi a^2}{2}}{\pi a^2} \tag{4}$$

where a is the radius of radar beam cross section at the given distance from radar, y is the difference between the height of the terrain and the height of the radar beam centre. The partial blockage takes place when $-a < y < a$, and varies from 0 to 1 (see Figure 1).

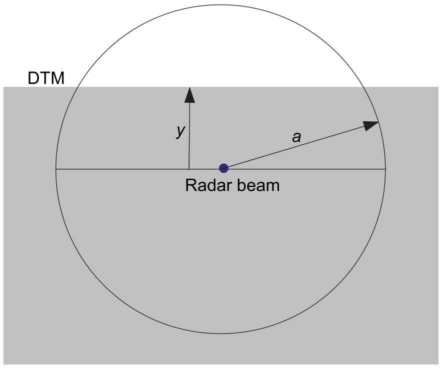

Fig. 1. Scheme of partial beam blockage *PBB* calculation using Bech et al. (2007) algorithm.

Quantity y in Equation 4 and Figure 1 is calculated as an altitude obtained from DTM for pixel located in radar beam centre taking into account altitude of radar antenna, the Earth curvature, and antenna elevation. Then the correction of partial beam blocking is made according to the formula (Bech et al., 2007):

$$Z_{cor} = Z + 10 \cdot \lg_{10}(1 - PBB)^{-1} \tag{5}$$

The correction is introduced if the *PBB* value is lower than 0.7. For higher *PBB* values "no data" (Bech et al., 2007) or reflectivity from neighbouring higher elevation (Ośródka et al., 2012) may be taken. A quality of blocked measurement dramatically decreases and can be expressed by:

$$QI_{PBB} = \begin{cases} 1 - PBB & PBB \le a \\ 0 & PBB > a \end{cases} \tag{6}$$

where coefficient a can be set as 0.5 (Fornasiero et al., 2005) or 0.7 (Bech et al., 2007; Ośródka et al., 2012). If reflectivity in a specific gate has been replaced by reflectivity from higher elevation then QI_{PBB} is taken from the higher one multiplied by factor b set as e.g. 0.3 (Ośródka et al., 2012). An example of the algorithm running is presented in Fig. 2 for Pastewnik radar which is located near mountains.

4.6 Attenuation in rain

Attenuation is defined as decrease in radar signal power after passing a meteorological object, that results in underestimation of the measured rain:

$$A = 10 \cdot \log_{10} \frac{Z_{corr}}{Z} \tag{7}$$

where A is the specific attenuation (dB km^{-1}), Z_{corr} is the non-attenuated rain and Z is the measured one (mm^6 m^{-3}). Especially at C- and X-band wavelength the attenuation can considerably degrade radar measurements. The aim of the algorithm is to calculate the non-attenuated rain. Empirical formulae for determination of specific attenuation can be found in literature. Using 5.7-cm radar wavelength (C-band radar) for rain rate the two-way attenuation A in 18°C can be estimated from the formula (Battan, 1973):

$$A = 0.0044 \cdot R^{1.17} \tag{8}$$

Reflectivity-based correction made iteratively ("gate by gate") is a common technique of correction for attenuation in rain (Friedrich et al., 2006; Ośródka et al., 2012). For a given gate i the attenuation at distance between gate i-1 and gate i can be calculated taking into account underestimations calculated for all gates along the beam from the radar site up to the i-1 gate (based on Equation 8). Finally, corrected rain rate in the gate i is computed from the attenuation and underestimations in all previous gates.

In case of dual-polarization radars specific attenuation for horizontal polarization A_H and specific differential attenuation A_{DP} (in dB km^{-1}) can be calculated using different methods. For C-band radar typically specific differential phase K_{DP} is applied using a nearly linear relation between the attenuation and K_{DP}, e.g. (Paulitsch et al., 2009):

$$A_H = 0.073 K_{DP}{}^{0.99}, \; A_{DP} = 0.013 K_{DP}{}^{1.23} \tag{9}$$

or a linear one.

The iterative approach can lead to unstable results because it is very sensitive to small errors in both measurement and specific attenuation. Therefore, in order to avoid the instability in the algorithm, certain threshold values must be set to limit the corrections. For dual-polarization radar a ZPHI algorithm is recommended, in which specific attenuation is stabilized by differential phase shift Φ_{DP} (Testud et al., 2000; Gourley et al., 2007a).

Magnitude of the correction in precipitation rate can be considered as a measure of quality due to radar beam attenuation (Ośródka et al., 2012).

4.7 Spatial variability of reflectivity field

Small-scale variability of precipitation field is directly connected with uncertainty because heavy precipitation is more variable in space and time, as it can be especially observed in the case of small-scale convective phenomena. Moreover non-precipitation echoes, such as ground clutter, are often characterized by high variability that differs from that for stratiform precipitation echoes. Spatial variability can be quantified as 3-D reflectivity gradient (Friedrich & Hagen, 2004) or standard deviation in a certain spatial grid (Szturc et al., 2011) and should be taken into account in quality index determination.

4.8 Total quality index

Computation of the total quality index QI is the final step in estimation of radar volume data quality. If the individual quality indices QI_i characterizing data quality are quantitatively determined, then the total quality index QI is a result of all the individual values QI_i employing one of the formulas 2a – 2c.

Each elevation of raw reflectivity volume can be compared with final corrected field. A set of such data for the lowest elevation is presented in Fig. 2. In this Figure a strong impact of spike echoes is observed for Legionowo radar whereas ground clutter and related blockage on data from Pastewnik radar is evident. Both radars are included in Polish radar network POLRAD (Szturc & Dziewit, 2005).

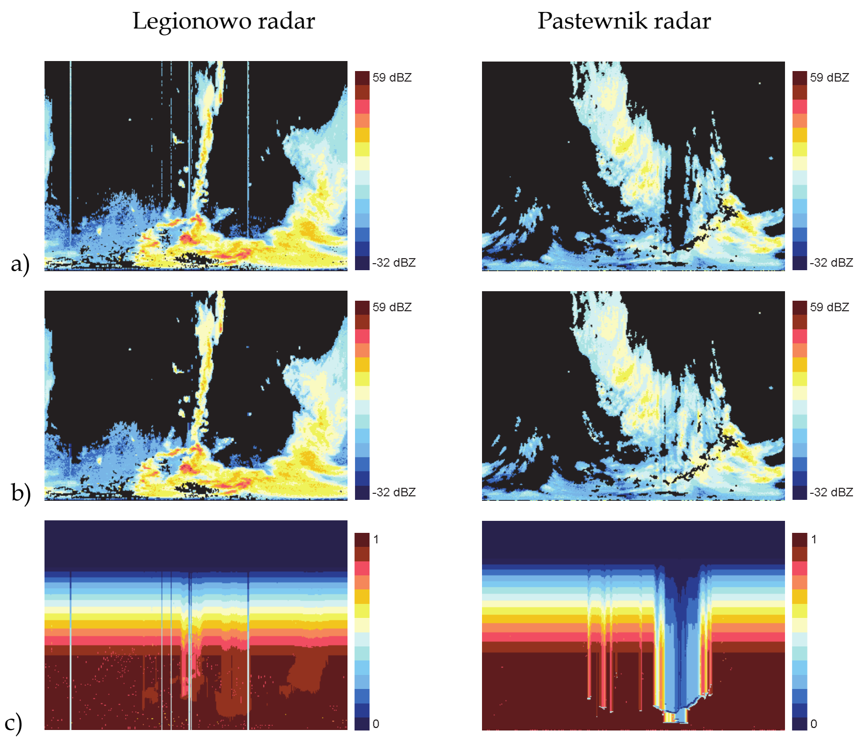

Fig. 2. Example of influence of all correction algorithms for the lowest elevation (0.5°): a) raw data Z (in dBZ); b) corrected data Z; c) total quality index QI (the left image for Legionowo radar, 10.05.2010, 15:30 UTC, the right for Pastewnik radar, 5.05.2010, 18:00 UTC; distance to radar up to 250 km). The panels represent range (y-axis) vs. azimuth (x-axis) displays.

5. Quality control algorithms for surface precipitation products

Corrections of 2-D radar data should constitute consecutive stages in radar data processing in order to get the best final radar products. These corrections include algorithms related to specific needs of the given product. The particular quality factors employed for calculating quality indices for 3-D data which also influence quality of 2-D data are not described here.

Many algorithms for surface precipitation field estimation from weather radar measurements applied in operational practice (e.g. Michelson et al., 2005) are described in this Section. For precipitation accumulation a different group of quality factors is applied. More common quality control algorithms employed in the practice are listed in Table 2.

Task	**Correction algorithm**	**Quality factor**	**QC**	**QI**
Z–R relationship estimation	Changeable *Z–R* relationship used	–	x	
Bright band (melting layer) effect correction	VPR-based correction	Presence of melting layer	x	x
Data extrapolation onto the Earth surface	VPR-based correction	Height of the lowest radar beam	x	x
Orographic enhancement	Physical model	Magnitude of the enhancement	x	x
Adjustment with rain gauge data	Correction using rain gauge data	Radar precipitation – rain gauge differences	x	x
For accumulation: number of rate data	–	Temporal continuity of data (number of the products)		x
For accumulation: averaged *QI* for rate data	–	Quality of included data (averaged *QI*)		x

Table 2. Quality control algorithms (correction and characterization) for 2-D surface precipitation data (in order of implementation into the chain).

5.1 Estimation of *Z–R* relationship

The *Z–R* relationship ($Z = aR^b$) variability is one of the most significant error sources in precipitation estimation. Each hydrometeor contributes to the precipitation intensity roughly to 3.7th power of its diameter, thus assumption on the drop size distribution is needed as the integral intensity is measured. Nowadays, for a single polarization radar it is a common practice to apply a single (usually Marshall and Palmer formula $Z = 200 \cdot R^{1.6}$) or seasonally-dependent *Z–R* relationship. However, use of a fixed *Z–R* relation can lead to significant errors in the precipitation estimation, as it depends on precipitation type (stratiform or convective), its kind (rain, snow, hail), etc. There are approaches that use tuned *Z–R* relationships for different meteorological situations. It requires the different types of precipitation to be identified on the basis of dedicated algorithms, which is easier if disdrometer measurements are available (Tenório et al., 2010).

Improvement in precipitation rate R estimation is noticeable using dual-polarization parameters, especially for heavy rainfall. In addition to the horizontal reflectivity Z_H available for single polarization radar, the specific differential phase K_{DP} and the differential reflectivity Z_{DR} can be applied (Bringi & Chandrasekhar, 2001). Typical forms of relationships for precipitation estimation are as follows: $R = f(K_{DP})$, $R = f(Z_H, Z_{DR})$, $R = f(K_{DP}, Z_{DR})$, and $R = f(Z_H, K_{DP}, Z_{DR})$. These approaches for precipitation rate estimation are potentially unaffected by radar calibration errors and attenuation, unbiased by presence of hail, etc.

5.2 Bright band phenomenon

Vertical profile of reflectivity (VPR) provides very useful information for radar data quality control. An averaged VPR is suggested to be taken from radar pixels lying at distance between about from 30 to 80 km from radar site to obtain the profile valid for the whole range of heights (Franco et al., 2002; Germann & Joss, 2004; Einfalt & Michealides, 2008). The bright band is a phenomenon connected with the presence of the melting layer. It is assumed that the melting layer is placed in range from the 0°C isotherm down to 400 m below (Friedrich et al., 2006). The melting of ice precipitation into water drops and related overestimation of precipitation rate results in errors of ground precipitation estimation. The phenomenon is clearly visible in vertically pointing radar observations. For dual-polarization radar a vertical profile of correlation coefficient (ρ_{HV}) is investigated instead of reflectivity profile analysis (Tabary et al., 2006).

It is proposed that the relevant quality index equals 0 inside the melting layer due to bright band, and equals 0.5 for measurement gates above the layer (Friedrich et al., 2006). In the case when the melting layer does not exist (in winter season or within convective phenomena) the quality index equals 1.

5.3 Data extrapolation onto the Earth surface

Information available from VPR can be used for another quality correction algorithm, which is extrapolation of precipitation data from the lowest beam to the Earth surface, especially at longer distances over 80 km. The averaged VPR is estimated for distance to radar site in range from 30 to 80 km and then employed to extrapolate radar data from the lowest beam to the Earth surface (Šálek et al., 2004). A quality factor which describes the relevant quality index is the height of the lowest radar calculated from radar scan strategy, digital terrain map (DTM), and the radar coordinates. It strongly depends on terrain complexity and related radar beam blocking and is defined as a minimum height for which radar measurement over a given pixel is feasible.

5.4 Orographic enhancement (seeder-feeder effect)

Orographic enhancement is a result of so called seeder–feeder mechanism which is observed when ascent of air is forced by hills or mountains. The low-level clouds formed in this way (feeder clouds) provide a moisture source that is collected by drops falling from higher clouds (seeder clouds). Radar is not able to capture the enhancement, which occurs close to the ground, as the measurement is performed at certain height over the hill. This effect can be estimated by 3-D physical model taking account of information from numerical weather prediction model: wind speed, wind direction, relative humidity, temperature, as well as the topography of the region (Alpert & Shafir, 1989). Magnitude of such correction can be taken to determine related quality index.

5.5 Adjustment with rain gauge data

Weather radar-based precipitation may differ from "ground truth", which can be locally estimated from rain gauge measurements, especially in close vicinity of the gauge. It is assumed that rain gauge measures precipitation exactly as its correction can be calculated (Førland et al., 1996), whereas radar provides information about space distribution. The idea is to use rain gauge information to improve radar data, as so called adjustment. The following solutions are proposed (Gjertsen et al., 2004):

- Mean field correction is a simple method to make the radar measurements unbiased. The correction factor is calculated from comparison of the averaged radar observations over the whole considered area, and the analogical averaged rain gauge measurements. The mean field bias can be calculated from historical data set or dynamic time-window. The last method allows to take into consideration variability in precipitation characteristics with time, but the time-period of the dynamic window cannot be too short due to requirement of data representativeness.
- Other methods of radar precipitation correction employ the distance to radar site L as the predictor apart from rain gauge information. Correction factor C can be expressed as e.g. polynomial relationship in form proposed by Michelson et al. (2000):

$$C = aL^2 + bL + c \tag{10}$$

  where a, b, and c are the empirically estimated parameters of the equation.
- More advanced methods based on multiple regression involve more predictors which play significant role in precipitation estimation. Especially in mountainous terrain the distance to radar site turned out not sufficient because of strong influence of beam blockage and shielding. Additional predictors can be height of the lowest radar beam, height above sea level, etc.

Quality index related to the adjustment with rain gauge data can be determined from magnitude of the correction.

5.6 Quality factors for precipitation accumulation

The following quality factors for precipitation accumulation can be considered:

- *Number of precipitation rate products.* Accumulated precipitation field is composed from a certain number of discrete radar measurements. The number of precipitation rate products included into the given precipitation accumulation can be used to calculate a related quality index. Lack of one or more products during the accumulation period results in a significant decrease of quality. Moreover lack of the products one after the other results in much lower quality.
- *Averaged quality index from precipitation rate products* is computed as a mean from all values of quality indices for precipitation rates (e.g. maximally seven for 10-minute time resolution and 1-hour period of accumulation) that are aggregated into the accumulation.

5.7 Combination: weather radar precipitation – rain gauges

The combination of radar precipitation and rain gauge data is treated as the next stage in precipitation field estimation: the adjustment is considered as the radar data correction, whereas the result of combination is not corrected radar data, but precipitation estimated from larger number of data sources.

The measurement techniques such as rain gauges, weather radar, and satellite are considered as independent ones, which provide rainfall information with different error characteristics. Rain gauges are assumed to measure precipitation directly with good point accuracy. However in the case of rather sparse network density, the number of rain gauges might not be sufficient to successfully reproduce spatial variability of precipitation. On the other hand weather radar is capable of reflecting the spatial pattern of rainfall with high resolution in time and space over a large area almost in the real-time. Nevertheless radar data are burdened with non-negligible errors: both non-meteorological and meteorological. Therefore, merging these two sources of information could lead to improvement in precipitation estimation. As a consequence, several methods have been developed to estimate rainfall field from radar- and raingauge-driven data.

One of them is a geostatistical approach, where spatially interpolated rain gauge data and radar field are combined employing the Cokriging technique (Krajewski, 1987). However the need for estimation of required empirical parameters might be crucial and may lead to significant errors. Velasco-Forero et al. (2004) tested different Kriging estimators (ordinary Kriging, Kriging with External Drift, Cokriging and Collocated Cokriging) to produce merged field from raingauge observations and radar data. Kriging with External Drift technique turned out to give the best final field.

In another approach (Todini, 2001) Kalman filtering is applied to optimally combine data from the two sensors (rain gauge network and weather radar) in a Bayesian sense. Radar field taken as the *a priori* estimate and the block Kriging of the raingauge observations treated as the measurement vector enable to find the *a posteriori* estimate of precipitation.

As it was pointed out, radar data is considered to be better than rain gauge network in reproduction of spatial distribution, whereas rain gauges measure precipitation accurately in their locations. This observation is a starting point in a technique proposed by Sinclair & Pegram (2005) in which the radar information is used to obtain the correct spatial structure of the precipitation field, while the field values are fitted to the raingauge observations.

5.8 Example of *QI* data

An example of the *QI* scheme application implemented in Institute of Meteorology and Water Management (IMGW) is presented below. Polish weather radar network POLRAD consists of eight C-Band Doppler radars of Gematronik with Rainbow software for basic processing of data. In Figure 3 an example of precipitation composite for selected event is presented together with quality index *QI* obtained from the aforementioned quality factors (Table 2) using additive scheme (Equation 2b).

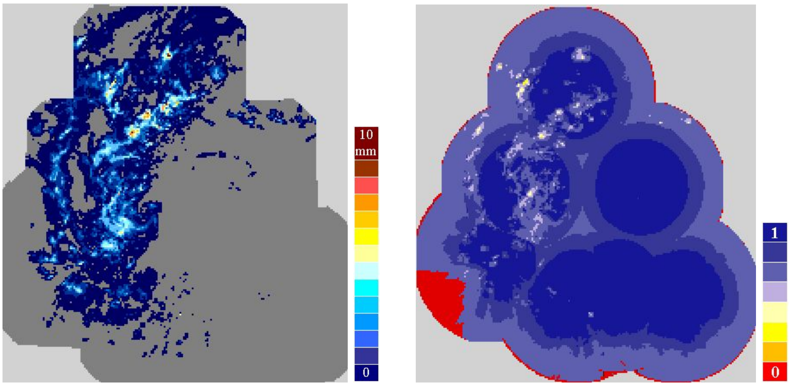

Fig. 3. Example of corrected field of precipitation rate (on the left) (composite from 5 August 2006, 03 UTC, when 7 from 8 weather radars were running) and resulting averaged quality index *QI* (on the right) (Szturc et. al., 2011).

The final quality index *QI* field depends on all quality factors included in the scheme. The most significant ones are height of the lowest radar beam, especially for places at longer distances to the nearest radar site and in mountainous areas (the zero-quality area south-west of the right map), and precipitation field variability (calculated analogically to the related 3-D algorithm) that follows the pattern of the precipitation field to some degree. It is noticeable that some quality factors are related to the precipitation field, whereas other fields are static if the set of running radars is constant, as they depend on radar locations only.

6. Conclusions

Weather radar data before being applied by the end-users must be quality controlled at all data processing stages. The main stages are generation of 3-D data (volumes) and then specialized 2-D data (products) dedicated to certain groups of the end-users. At first, the 3-D data should be corrected as they constitute the information source for generation of radar products. The corrections that are related to specific products should be made at the next stage – 2-D data processing. Due to numerous radar errors various correction techniques must be employed, moreover radar hardware limitations determine application of particular corrections. First of all dual-polarization radars, which will be a standard in the near future, open up new possibilities.

In quality control of radar data apart from the data correction, information about the data uncertainty plays also a key role. The high importance of radar data quality characterization is appreciated not only by radar people (meteorologists, hydrologists, etc.) but by end-user communities as well. Dealing with such quality information is a difficult task, however it is crucial for risk management and decision-making support.

For these reasons the quality control of radar data is becoming an essential task in weather radar data generation and processing. It has been a main subject of many international programmes, especially: the COST Action 731 (“Propagation of uncertainty in advanced meteo-hydrological forecast systems”, 2005-2010), the EUMETNET OPERA (“Operational Programme for the Exchange of Weather Radar Information”, from 1999), the BALTRAD

("An advanced weather radar network for the Baltic Sea Region: BALTRAD", Baltic Sea Region Programme, 2009-2014), the WMO programme RQQI ("Radar Quality Control and Quantitative Precipitation Intercomparisons", from 2011), etc. In the frame of the projects some recommendations are being developed, that will ensure harmonisation of practices in particular national meteorological services.

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