P11.5

QUALITY INDEX SCHEME FOR 3D RADAR DATA VOLUMES
(Study before real-time implementation)

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1. OVERALL DESCRIPTION

The paper presents a preliminary attempt at developing a technique for quality (uncertainty) estimation of raw radar reflectivity data recorded in 3D volumes. Such technique should be universal and not connected with any specific application. Because there is no benchmark available for 3D data (such as rain gauge data for ground precipitation), another way of the quality evaluation is needed.

The volumes are generated as sets of PPI scans from different elevations. In Fig. 1 example of volume data is presented for each of 10 elevations separately. From the 3D data various 2D products can be obtained, like MAX product which consists of maximum reflectivity values from the whole column of atmosphere over a given pixel. Example of MAX product generated by Rainbow from the volume depicted in Fig. 1 is presented in Fig. 2.

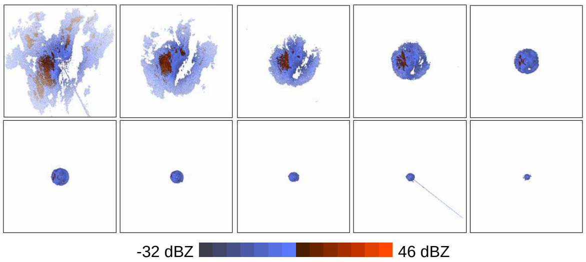

Fig. 1. 3D radar reflectivity data in form of particular PPI scans for each elevation (see Table 1) (Legionowo radar, 3 March 2009, 0730 UTC). Range of data gets smaller with higher elevation. At 9th elevation a spike from an external microwave antenna is visible.

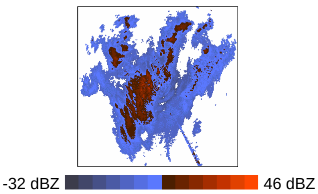

Fig. 2. 2D radar product generated by Rainbow software from the volume data (Fig. 1) as maximum of reflectivity product (Legionowo radar, 3 March 2009, 0730 UTC).

For evaluation of the 3D data quality an idea of quality index (*QI*) scheme is proposed in this paper.

The *QI* is a unitless quantity with values ranging from 0 (bad quality) to 1 (excellent quality). The algorithm consists of the following steps:

- selection of set of the most significant error sources – quality parameters QP_i (where i is the number of the parameter),
- estimation of particular radar data errors as functions of the parameters,
- calculation of particular quality indices QI_i,
- averaging the QI_i into total quality index *QI*.

A scan strategy currently used in POLRAD weather radar network is defined by parameters presented in Table 1.

Parameter	Value
Radar beam	1°
Number of azimuths	360
Maximum range from radar	250 km
Distance between sampling along radar beam	1 km
Number of elevations	10
Elevation angles	0.5, 1.4, 2.4, 3.4, 5.3, 7.7, 10.6, 14.1, 18.5, 23.8°

Table 1. Scan parameters currently used in POLRAD weather radar network.

The following factors were preliminarily selected as important sources of uncertainty: horizontal and vertical extensions of radar beam, main beam blocking by ground targets, attenuation in meteorological targets, and presence of a melting layer (Table 2).

The two first parameters (described in Section 2 and 3) are static and result from scan strategy, whereas the next quality parameters (described in Sections 4 and 5) are dynamic and depend on current meteorological conditions.

2. HORIZONTAL AND VERTICAL EXTENSION OF A RADAR BEAM

2.1 Algorithm

The two parameters: horizontal and vertical extension of radar beam (Fig. 3) are related to area of its cross sections. These cross sections define area from which measurements are averaged.

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Error source	Quantitative parameter	Quality index
Horizontal extension of a radar beam	Area of horizontal cut of a radar beam A_H (km^2)	$QI_{AH} = \begin{cases} 1 & A_H < 1.9\ \text{km}^2 \\ \frac{9.1 - A_H}{9.1 - 1.9} & 1.9 \le A_H \le 9.1\ \text{km}^2 \\ 0 & A_H > 9.1\ \text{km}^2 \end{cases}$
Vertical extension of a radar beam	Area of vertical cut of a radar beam A_V (km^2)	Analogous formula (with A_V instead of A_H)
Radar main beam blocking by ground targets	Percentage of radar beam shielding *BL* (%)	$QI_{BL} = \begin{cases} 1 & \text{not blocked} \\ 0 & \text{blocked} \end{cases}$
Attenuation of radar beam in meteorological targets	Attenuation A_{ATT} (dB km^{-1})	$QI_{ATT} = \begin{cases} 1 & R_{cor}/R < 1.1 \\ R_{cor}/R & 1.1 \le R_{cor}/R \le 2 \\ 0 & R_{cor}/R > 2 \end{cases}$
Melting layer related to isotherm 0℃ (height of the isotherm is H_{T0})	Flag related to height of melting layer (ML). Three levels are considered (Friedrich et al., 2006): (i) above ML; (ii) inside ML; (iii) below ML	$QI_{ML} = \begin{cases} 1 & (h < H_{T_0} - 400\ \text{m})\ \text{or (no ML)} \\ 0.5 & h > H_{T_0} \\ 0 & H_{T_0} - 400\ m \le h \le H_{T_0} \end{cases}$

Table 2. Selected quality parameters.

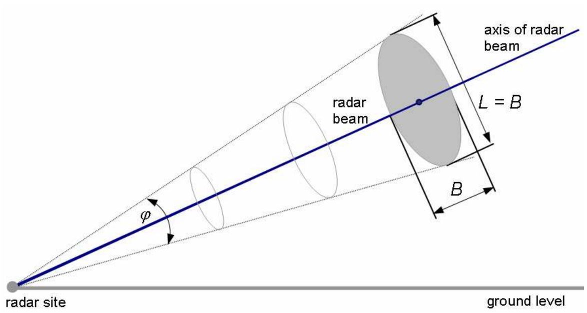


Fig. 3. Cross section of radar beam along the beam depicted in perspective (φ is the radar beam angle width, *B* and *L* are sizes of the cut that depend on angle φ and distance to radar site).

In Fig. 4a a scheme of horizontal extension of radar beam is depicted, where: ***ε*** – the elevation angle; ***α*** – the azimuth angle; ***φ*** – the angle of radar beam; ***l*** – the radial distance to radar site.

The following values should be computed:

B_H – horizontal width of radar beam perpendicularly to the beam:

$$B_H = 2l \cdot \tan(\varphi/2) \tag{1}$$

L_H – horizontal width of radar beam along the beam:

$$L_H = B_H \cdot \sin(\varepsilon) \tag{2}$$

A_H – area of horizontal cross section of radar beam:

$$A_H = \pi \frac{B_H}{2} \frac{L_H}{2} = \pi \cdot l^2 \cdot \tan^2(\varphi/2) \cdot \sin(\varepsilon) \tag{3}$$

In Fig. 4b a scheme of vertical extension of radar beam is presented. A relevant algorithm is analogous to one for the horizontal extension and the following

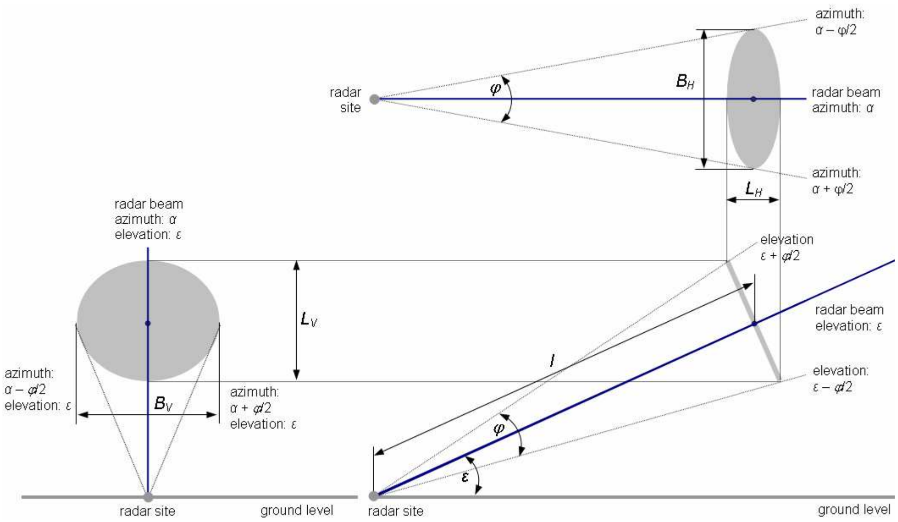


Fig. 4. Horizontal (a) and vertical (b) cross sections of radar beam in data volume.

a)

values should be computed:

B_V – vertical width of radar beam perpendicularly to the beam:

$$B_V = 2l \cdot \tan(\varphi/2) \qquad (4)$$

and $B_V = B_H$;

L_V – vertical width of radar beam along the beam:

$$L_V = B_V \cdot \cos(\varepsilon) \qquad (5)$$

A_V – area of vertical cross section of radar beam:

$$A_V = \pi \frac{B_V}{2}\frac{L_V}{2} = \pi \cdot l^2 \cdot \tan^2(\varphi/2) \cdot \cos(\varepsilon) \qquad (6)$$

2.2 Maps of horizontal and vertical radar beam extensions for POLRAD radars

Having employed the algorithm a map of horizontal quality parameter field expressed as area of horizontal cross section of a radar beam A_H can be generated for scan strategy used in the POLRAD radars. In Fig. 5 the quality parameter fields for all 10 elevations are displayed in polar co-ordinates.

It can be noticed that the extension becomes bigger with distance to radar site. Moreover the higher radar beam elevation is, the bigger area of horizontal cross section is. The area of horizontal cross section is related to spatial averaging of measurement.

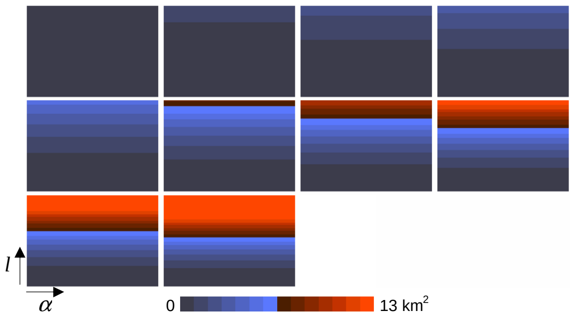


Fig. 5. Area of horizontal cross section of radar beam A_H for scan strategy used in POLRAD network for each elevation.

By analogy, a map of vertical quality parameter as area of vertical cross section of a radar beam A_V can be produced. The quality parameter fields are presented for a few selected elevations (Fig. 6). It can be observed that differences between the maps are not significant.

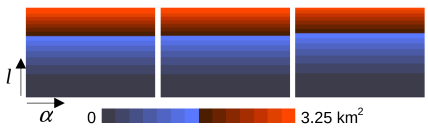
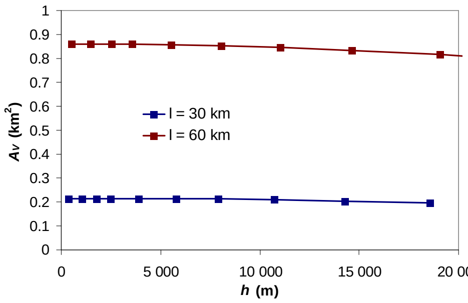
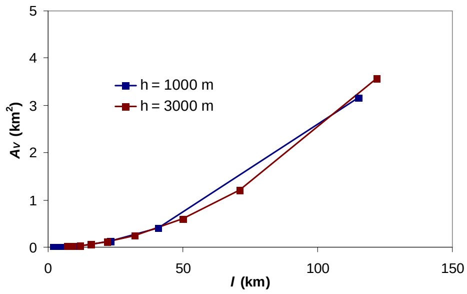


Fig. 6. Area of vertical cross sections of radar beam A_V for scan strategy used in POLRAD network for three example elevations (from the left: 0.5, 7.7, and 23.8°).

In Fig. 7 examples of relationships between the A_V values and both height above the radar site altitude (Fig. 7a) and distance from radar site (Fig. 7b) are illustrated.



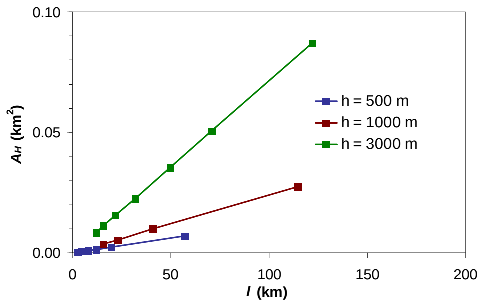
a)



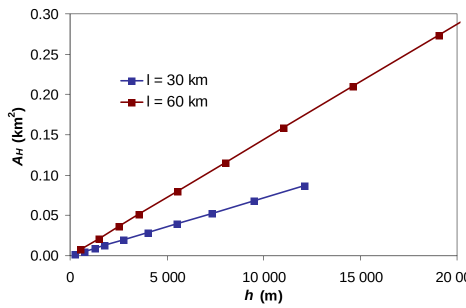
b)

Fig. 7. Relationships between the A_V values and: (a) height above the ground h (two distances from radar site: l = 30 and 60 km); (b) distance from radar site l (two heights above the ground: h = 1000 and 3000 m).

In Fig. 8 examples of increasing the A_H values with distance from radar site (Fig. 8a) and height above (Fig. 8b) the ground are presented.



a)



b)

Fig. 8. Increase of the A_H values with: (a) distance from radar site (three heights above the ground: h = 500, 1000, and 3000 m); (b) height above the ground (two distances from radar site: l = 30 and 60 km).

Finally, a static 3D map of the parameters may be generated, which depends on radar scan strategy only: A_V, $A_H = f(\varepsilon, \alpha, l)$ (variables: elevation angle, azimuth angle, radial distance to radar site).

2.3 Computation of quality indices *QI* from radar beam extensions A_H and A_V

Starting point to the investigation of relationships between the quality parameters and related quality indices is experience with estimation of precipitation data quality at the ground level (Szturc et al., 2009). On this basis it is possible to try to estimate data quality due to distance to the radar site. It was concluded that radar data is not burdened when the distance is not longer than 89 km, whereas is quite wrong when the distance is over 195 km. Considering the precipitation at the ground level, it can be hypothetically assumed the elevation angle equals zero. Consequently distance to the radar site equals the radial distance *l*. Following this observation boundary values can be taken as (Szturc et al., 2009):

$$QI_l = \begin{cases} 1 & l < 89\ \text{km} \\ (0,1) & 89 \le l \le 195\ \text{km} \\ 0 & l > 195\ \text{km} \end{cases} \tag{7}$$

Since the above formula was obtained considering overall quality of the measurement that is connected with distance to radar site, the total area of radar beam cross section *A* should be calculated as:

$$A = \pi \cdot (B/2)^2 \tag{8}$$

where: $B = 2l \cdot \tan(\varphi/2)$.

Employing the formula the boundary values for *A* can be obtained. Assuming that the same shape of formula can be applied to the both quality parameters A_H and A_V their boundary values can be estimated as:

$$QI_{AH} = \begin{cases} 1 & A_H < 1.9\ \text{km}^2 \\ \dfrac{9.1 - A_H}{9.1 - 1.9} & 1.9 \le A_H \le 9.1\ \text{km}^2 \\ 0 & A_H > 9.1\ \text{km}^2 \end{cases} \tag{9}$$

with analogous formula for QI_{AV}.

3. RADAR BEAM BLOCKING BY GROUND TARGETS

3.1 Algorithm

Radar beam with 1°-width can be blocked by ground targets, i.e. places where the beam hits terrain. A quality of measurement burdened by ground clutters dramatically decreases. Orography of terrain recorded in digital terrain map (DTM) is a starting point for analysis of the ground clutters.

Quality QI_{BL} of data for areas where radar beam is blocked is very low, that it can be assumed that the quality equals zero:

$$QI_{BL} = \begin{cases} 1 & \text{not blocked} \\ 0 & \text{blocked} \end{cases} \tag{10}$$

3.2 Example

In Figs. 9 example for Ramża radar is presented. The radar is located near to Beskidy and Sudety Mountains in south of the radar site. DTM for Ramża radar is depicted in polar co-ordinates in Fig. 9a along with connected ground clutters with blocked areas for the lowest elevation 0.5° (Fig. 9b-c). At higher elevations no ground clutters are observed for this radar site.

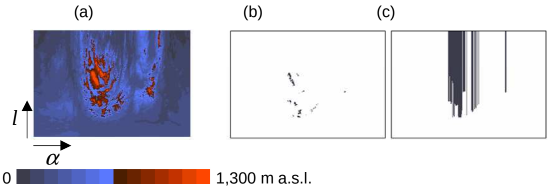


Fig. 9. (a) DTM map for Ramża radar (elevation 0.5°); (b) related ground clutter map for the radar (in black); (c) blocked areas map for the radar (in black).

4. ATTENUATION OF RADAR BEAM IN METEOROLOGICAL TARGETS

4.1 Algorithm

Attenuation is defined as decrease in radar signal power after passing a meteorological target, that results in underestimation of the measured precipitation *R*:

$$K = 10 \cdot \log_{10} \frac{R_{cor}}{R} \tag{11}$$

where *K* is the attenuation coefficient; R_{cor} is the non-attenuated precipitation.

The aim of the proposed algorithm is to calculate the non-attenuated precipitation R_{cor} to compare it to the measured one. Empirical formulas for reflectivity attenuation can be found in literature. Using 5.7-cm radar wavelength (C-Band radar) for precipitation rate the two-way attenuation *K* (in dB km^{-1}) in 18°C can be estimated from (Collier, 1989):

$$K = 0.0044 \cdot R^{0.17} \tag{12}$$

In POLRAD radars the Marshall-Palmer formula is used for calculation of precipitation rate *R* (in mm h^{-1}) from the measured reflectivity values *Z* (in dBZ):

$$Z = 10 \cdot \log_{10}\left(200 \cdot R^{1.6}\right) \quad \rightarrow \quad R = \left(\frac{10^{Z/10}}{200}\right)^{\frac{1}{1.6}} \tag{13}$$

On a distance between two neighbouring measurement points (from x_{i-1} to x_i in Fig. 10) underestimation of precipitation rate $R_{(i)}$ due to attenuation is calculated from formula:

$$R_{(i-1,i)} = 10^{\left(\frac{K}{10} + \log_{10} R_{(i)}\right)} - R_{(i)} \tag{14}$$

Radar precipitation rate $R_{(i)cor}$ at the measurement point x_i corrected due to attenuation may be computed by integration of attenuation along the whole radar beam path from radar site to the measurement point x_i and back:

$$R_{(i)cor} = R_{(i)} + \sum_{j=1}^{i} R_{(j-1,\,j)} \tag{15}$$

The computation should be performed iteratively, for each measurement point, as attenuation in a given point depends on corrected (i.e. non-attenuated) precipitation in all previous points. For scheme shown in Fig. 10 for a measurement point x_i firstly corrected precipitation rates for points from x_1 to $x_{i\text{-}1}$ are calculated one by one, to get values from $R_{(0,1)}$ to $R_{(i\text{-}1,\,i)}$.

Finally, the total $R_{(i)cor}$ value can be calculated from the precipitation rates corrected due to attenuation along the whole radar beam path L_x.

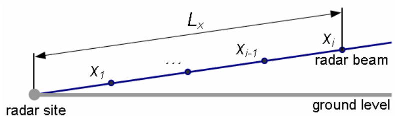


Fig. 10. Scheme of estimation of a radar beam attenuation along the beam.

Since correction in precipitation rate is a measure of radar beam attenuation, so a value $R_{(i)cor}/R_{(i)}$ calculated by means of the formula (15) is used as one of quality parameters for measurement point x_i. Two boundary values are employed in the proposed scheme: quite good measurement is considered if the attenuation is smaller than 10%, i.e. $R_{(i)cor}/R_{(i)} < 1.1$, and totally wrong if $R_{(i)cor}/R_{(i)} > 2$. Therefore the quality parameter QI_{ATT} is calculated from the formula:

$$QI_{ATT} = \begin{cases} 1 & R_{cor}/R < 1.1 \\ \dfrac{2.0 - R_{cor}/R}{2.0 - 1.1} & 1.1 \le R_{cor}/R \le 2.0 \\ 0 & R_{cor}/R > 2.0 \end{cases} \tag{16}$$

4.2 Example

In Fig. 11 example of attenuation fields for all elevations is presented for the data shown in Fig. 1.

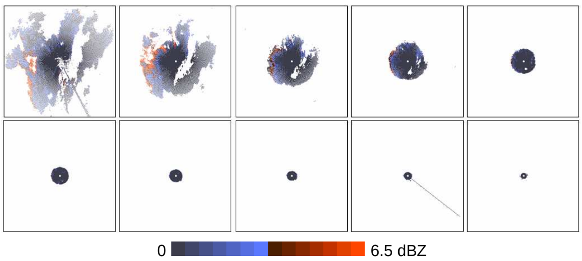


Fig. 11. 3D fields of radar data attenuation for each elevation (in Cartesian co-ordinates) expressed in dBZ (Legionowo radar, 3 March 2009, 0730 UTC).

5. MELTING LAYER

Melting layer (ML) as phenomenon related to a vertical profile of reflectivity (VPR) strongly impacts on quality of radar measurements. The errors are connected with altitude of 0℃ isotherm H_{T0}. It is assumed that melting layer is placed in range from the 0℃ isotherm down to 400 m below it (Friedrich et a l., 2006). It is assumed that the quality index equals 0 inside the melting layer due to bright band and other perturbing phenomena, and equals 0.5 for measurement points above the layer (Friedrich et al., 2006):

$$QI_{ML} = \begin{cases} 1 & (h < H_{T_0} - 400\text{ m}) \text{ or (no ML)} \\ 0.5 & h > H_{T_0} \\ 0 & H_{T_0} - 400\,m \le h \le H_{T_0} \end{cases} \tag{17}$$

where h is the altitude of the measurement. In the cases when the melting layer does not exist the relevant quality index equals one.

In Fig. 12 example of QI_{ML} for 0℃ isotherm observed at 5-km altitude is presented for selected beam elevations.

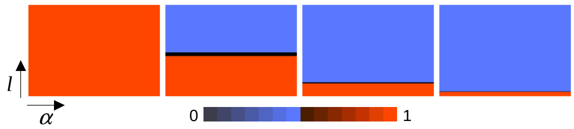


Fig. 12. Quality index due to melting layer QI_{ML} at altitude 5 km for scan strategy used in POLRAD network for four example elevations (from the left: 0.5, 2.4, 7.7, and 23.8°).

6. TOTAL QUALITY INDEX

After calculation of the five individual quality indices QI_i (see Table 2):

- QI_{AH} – due to area of horizontal cross section of a radar beam,
- QI_{AV} – due to area of vertical cross section of a radar beam,
- QI_{BL} – due to radar beam blocking by ground targets,
- QI_{ATT} – due to attenuation of radar beam in meteorological targets,
- QI_{ML} – due to melting layer.

the final step is to compute the total quality index.

The multiplying scheme of total quality index QI calculation is employed:

$$QI = \prod_{i=1}^{n} QI_i \tag{18}$$

where n is the number of quality parameters (individual quality indexes), that in this paper equals five. Using the formula total quality index QI equals zero if at least one of the individual quality indices QI_i equals zero.

In Fig. 13 example of total quality index QI for the lowest elevation (0.5°) is presented in the case wh en no precipitation (i.e. no attenuation) is observed and melting layer exists at altitude 2 km. In this map especially impact of ground clutters is evident.

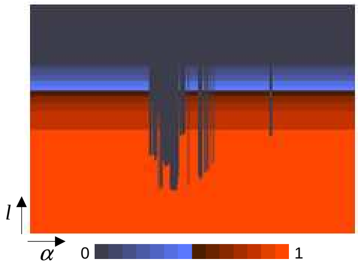


Fig. 13. Example of averaged quality index *QI* for the lowest elevation (0.5°) in the case when no precipitation is observed and melting layer exists at altitude 2 km (Ramża radar).

Acknowledgment

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