QUALITY-BASED RADAR DATA PROCESSING AND QPE AT THE SLOVAK HYDROMETEOROLOGICAL INSTITUTE

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1 Introduction

By the growing demand for meteorological radar data and products the question of its accuracy and quality rises more often and often. While the issue of radar measurement quality is resonating many years among the community of users of meteorological radars (e.g. projects like OPERA, BALTRAD, but also INCA-CE, H-SAF …), radar manufacturers are offering only limited capabilities in this field. One possible reason for such lack of capabilities in the radar data processing products may be the fact that they were developed primarily for processing single radar data and the compositing possibilities were added only as supplementary features. Improvement in the area of international radar data exchange and networking enables deeper analysis and a bit new approach, where data from different radars are mutually controllable, comparable and combinable. Integration of measurements form other sources (e.g. satellites, rain-gauges, numerical weather prediction outputs, lightning detection systems, cameras …) opens other opportunities to improve the quality of radar data and also other meteorological products. This approach could be potentially advantageous also in the field of X-band radars, where the quality issues could be especially challenging. As this approach requires such a broad spectrum of supporting meteorological data, it`s development is probably best fitted to national meteorological services, where these data are available. The meteorological services are than benefiting from the newly developed products with a very high additional value.

These considerations led to the development of the qRad radar data processing and the qPrec precipitation estimating software at the SHMÚ. The software uses a more network-centered view to the radar data processing, where the data form different radars are not processed independently, but together with other data sources are compared, controlled and combined by each other. The software is written in C++ in a modular way for easy portability and uses parallel processing techniques for fast run.

The qRad software estimates the actual quality of the radar volume data by various quality indexes and tries to correct some undesirable effect on the measurement (e.g. beam-blockage, ground-clutter, non-meteorological echoes …). The corrected volume data are then directly processed to composite radar product and quality maps. The resulting radar products are used by the forecasters and for QPE, and are used for validation of the EUMETSAT H-SAF precipitation products. The software was installed also at the Hungarian Meteorological Service to support the H-SAF validation efforts.

The qPrec package uses estimation theory and probabilistic approach to estimate the rainfall intensity as accurate as possible based on heterogeneous input data (rain-gauges, radars, satellites, lightning detection in the future…). The calibrated input data fields are combined according to their precision and actual quality. The resulting precipitation estimates are regularly validated by the climatological rainfall amounts and by hydrological model runs. The first results are showing dramatic improvement of the precipitation estimation against the methods used previously at the institute.

The development is in progress, so the near future plans are also mentioned.

2 Radar data quality estimation

The result of meteorological radar measurements is influenced by a variety of factors. Some of these factors derive from the radar hardware and from the measurement parameters settings (power, polarity, beam-width, noise, detection range, various filters on the hardware site …). Others are caused by the surrounding environment (beam height above the terrain, beam-blockage, sea-clutter, interference with other electronic devices …), or by the actual meteorological situation (beam propagation, partial beam-filling, bright-band, overshooting of the low clouds, second-trip echoes …). The majority of these factors can be directly calculated, estimated or at least estimate their probability. After the quantification of these quality factors, they are rescaled to a dimensionless number between 0.0 and 1.0 – the so called quality index (QI), where the value 0.0 stands for the lowest quality and 1.0 for the best quality. The qRad software estimates the quality of each measured bin in the volume data by different quality indexes. An example of the actually used quality indexes are shown on the Fig. 1. So far the next quality indexes were implemented:

2.1 Constant quality index

The quality factor in this case is the radar itself – it`s position, hardware, and settings. Measurements of the reliable and properly set radars are evaluated as good quality (QI=1.0), while the data of less reliable or less precise radar sites are labelled with lower QI values. This quality index is useful also when some other quality index was not computed (due to some missing data). Then the missing quality index can be replaced with a constant number.

2.2 Quality index according to the distance from the radar

Each radar bin is evaluated according to its distance from the radar. The radar beam is broadening and its volume is growing as it propagates in the atmosphere. The resulting measurement is then representing an average of a larger volume. In this case the next linear relationship is used:

$$qi = \begin{cases} 1.0; & r < r_{min} \\ 1.0 - \frac{r - r_{min}}{r_{max} - r_{min}}; & r_{min} \leq r \leq r_m \\ 0.0; & r > r_{max} \end{cases} \quad (2.1)$$

, where r is the distance from the radar and r_{min} and r_{max} are parameters of the computation (with default values of 0.0 and max. range of the radar).

2.3 Similarity with the surrounding bins

Two bins are considered as similar when their value differs less than a given threshold. The similarity QI is than the percentage of the similar bins in a defined window around the given bin. This QI is aimed to find some spikes or smaller holes and to evaluate the bins on the borders of the detected clouds. The software enables to replace the value of the bin with QI lower than a defined threshold with a QI-weighted average of the surrounding values.

2.4 Beam-blockage by the terrain

The percentage of the transmitted energy blocked by the terrain is computed according to the energy distribution along across the radar beam. The 10-meter resolution ASTER GDEM digital terrain model is used in the computation. The resulting QI is then

$$qi = \begin{cases} 1 - block; & block \leq block_{max} \\ 0; & block > block_{max} \end{cases} \quad (2.2)$$

, where $block_{max}$ is a user-defined threshold of blocking. The software offers the possibility to correct the blockage by dividing the measured energy by the blockage.

2.5 Beam height above the terrain

Some quality factors are influencing only certain type of radar products. The beam height above the terrain should be useful especially for rainfall estimating products - the estimated rainfall should be more precise, when the used bin is near the surface of the terrain. The QI is computed according to the next equation:

$$qi = \begin{cases} 1 - \frac{h_{above}}{h_{max}}; & 0 \leq h_{above} \leq h_{max} \\ 0; & h_{above} < 0 \text{ or } h_{above} > h_{max} \end{cases} \quad (2.3)$$

, where h_{above} is the bin height above the terrain and h_{max} is the user defined maximum height above the terrain.

2.6 Cloud type QI

The NWCSAF Cloud-Type product is used in this QI. Non-undetected bins are evaluated according to the cloud type in their position. The QI is associated according to the next table:

Table 1:QI according to cloud-type

Cloud-type	QI
Cloud-free (land, see, snow…)	0.01
Fractional	0.1
Height semi-transparent thin	0.1

Other clouds	1.0

The software enables to replace the low QI bins with an undetected value according to user settings.

2.7 Cloud top height QI

This test uses the NWCSAF Clout Top Temperature and Height product to assign low QI (0.01) to the non-undetected bins found above the cloud tops. The software enables to replace suspicious bins with an undetected value.

2.8 Time QI

The time of the measurement is evaluated in this QI. It is computed as a linear relationship of the difference between the time of the measurement and a given product validity time:

$$qi = \begin{cases} 1 - \dfrac{\Delta T}{\Delta T_{max}};\ \Delta T \leq \Delta T_{max} \\ 0;\ \ \Delta T > \Delta T_{max} \end{cases} \qquad (2.4)$$

, where ΔT_{max} is a user-defined maximal allowed time-difference.

2.9 Average QI

This QI is computed as an average of user-selected QIs from a couple of last measurements. This could be useful to detect some ground-clutters or other permanent error sources. In our application the combination of Cloud-type and Cloud-top-height QIs is used in this test.

3 QI-based radar product generation

The resulting QI of each radar bin is computed by multiplying the used partial QIs for the given product:

$$qi_{R_i} = \prod_{j=1}^{n} qi_{R_i}^{j} \qquad (3.1)$$

, where qi_{R_i} is the QI of then bin from the *i*-th radar and $qi_{R_i}^{j}$ is the *j-th* QI from the actually used QIs. The value of the product is then computed as a QI-weighted average from all available radars in the given point:

$$z = \frac{\sum_{i=1}^{N} qi_{R_i} z_{R_i}}{\sum_{i=1}^{N} qi_{R_i}} \qquad (3.2)$$

, where *z* is the value of the resulting product, and z_{R_i} is the value from the *i-th* radar. The resulting QI of the product in the given point is computed with a probabilistic approach, where qi_{R_i} is treated as the probability of good measurement.. The resulting QI than a 1.0 minus the probability of bad measurement in the given point:

$$\begin{aligned} qi &= 1{,}0 - P' = \\ &= 1{,}0 - \prod_{i=1}^{N} P'_i = \\ &= 1{,}0 - \prod_{i=1}^{N} (1{,}0 - qi_{R_i}) \end{aligned} \qquad (3.3)$$

, where P' and P'_i is the probability of bad measurement for the resulting product and for the *i-th* radar. In this way the fact that the point covered with more radars will have a higher QI. An example visualization of the CMAX composite and the resulting QI composite is shown on the Fig. 2. The software is capable at this time to compute the PPI, CMAX, 3D-CAPPI and the PP products. The PP product stands for Precipitation Potential. It is a product developed at the SHMÚ, and it computes the average reflectivity in the layer above the terrain. The thickness of the layer is user-defined (2km used as default). The input bins are weighted according to their height above the terrain (the beam-height QI used for this purpose).

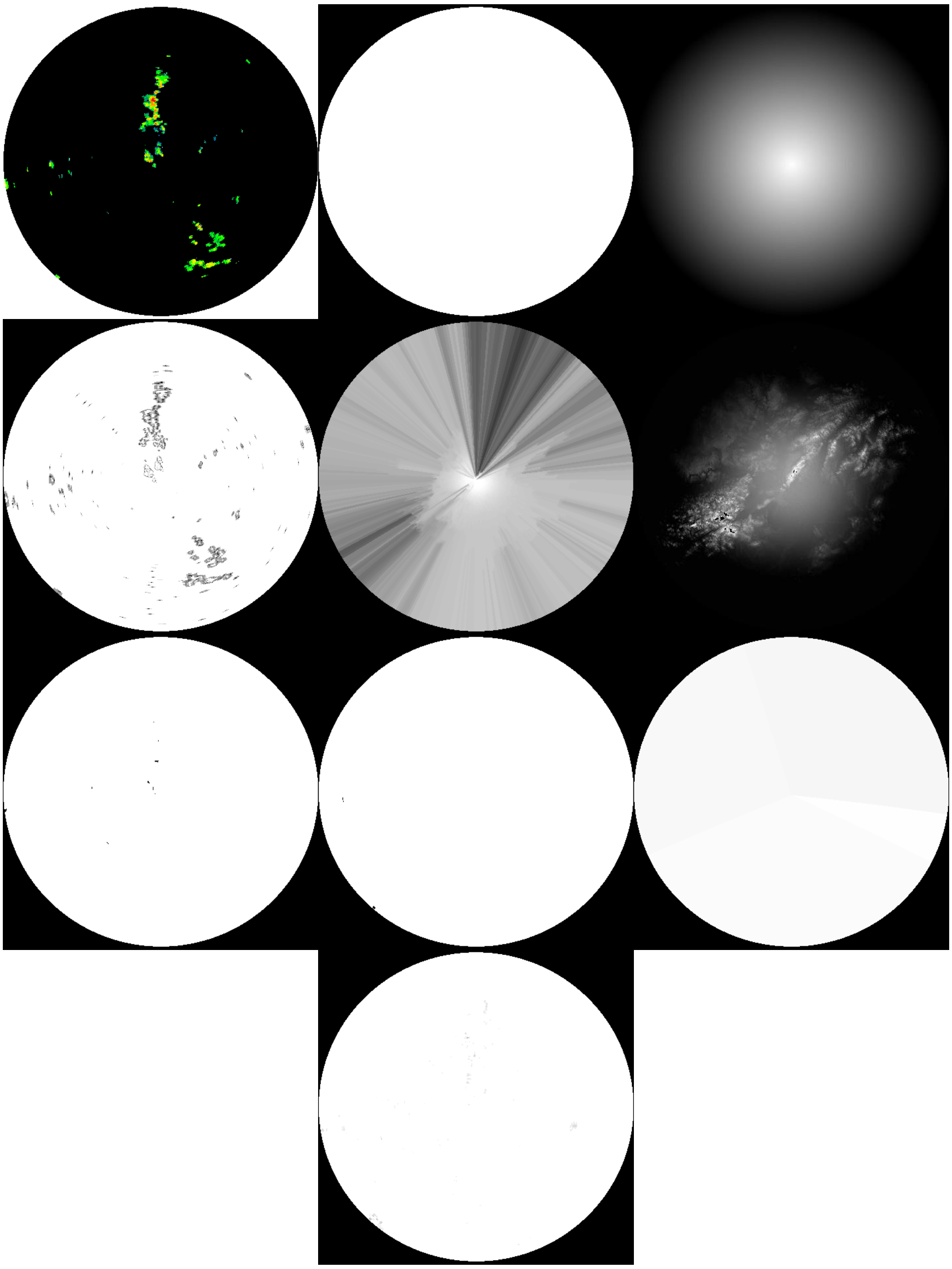

Figure 1:Example visualization of the so far implemented quality indexes. From the top-left corner: PPI of the DBZH, Constant QI, Distance QI, Similarity QI, Beam-blockage QI, Beam-height QI, Cloud-type QI, Cloud-top-height QI, Time QI, Average QI

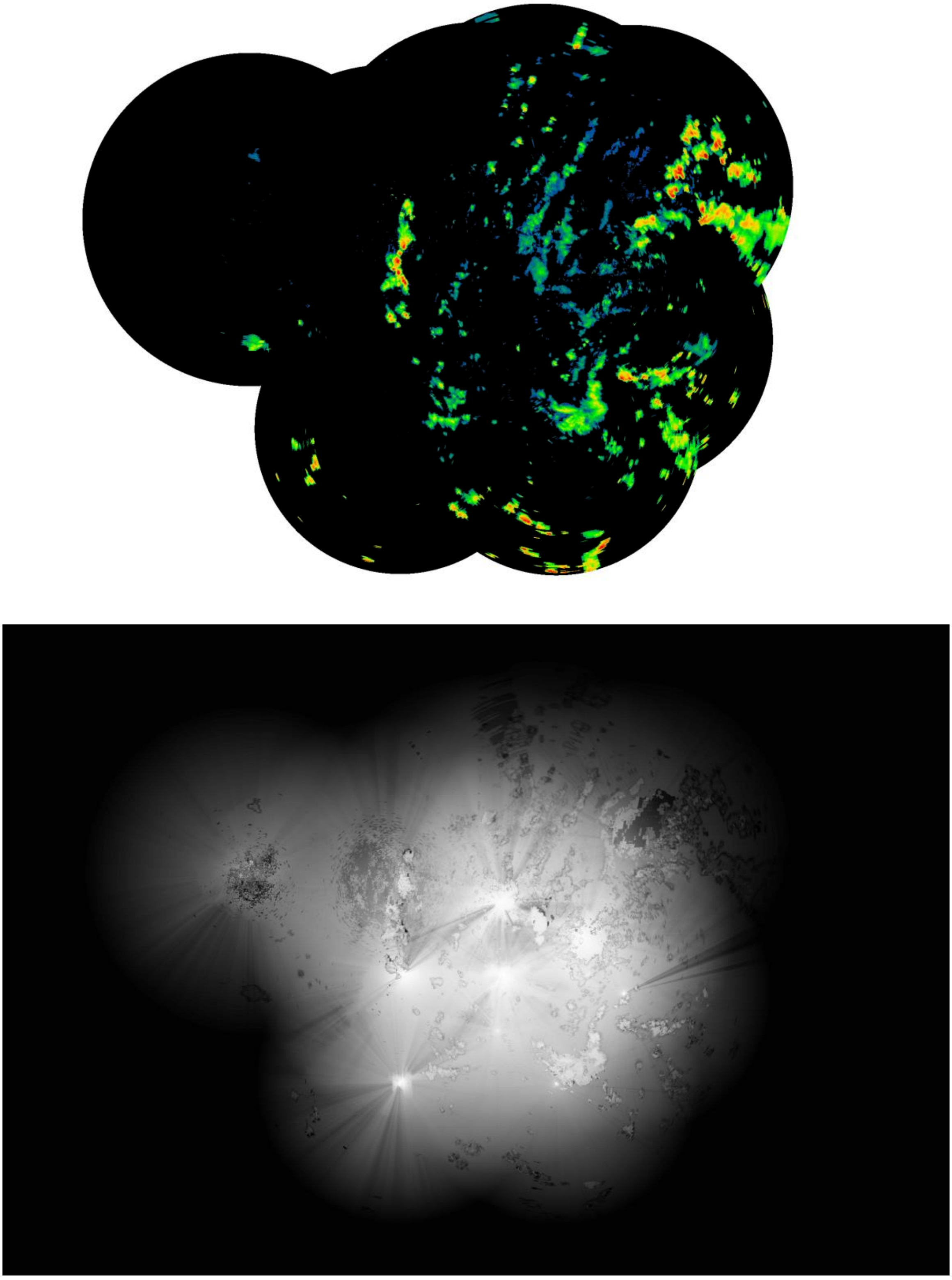

Figure 2: Example visualization of the CMAX composite product and the associated QI field from a network of 13 radars.

4 QI-based QPE

The design and development of the qPrec precipitation estimation software was started from the basics. The distribution of rainfall values measured by the automatic rain-gauges for different radar products was examined and a combination of probabilistic and variational approach was chosen. The processing chain is sketched on the Fig. 3.

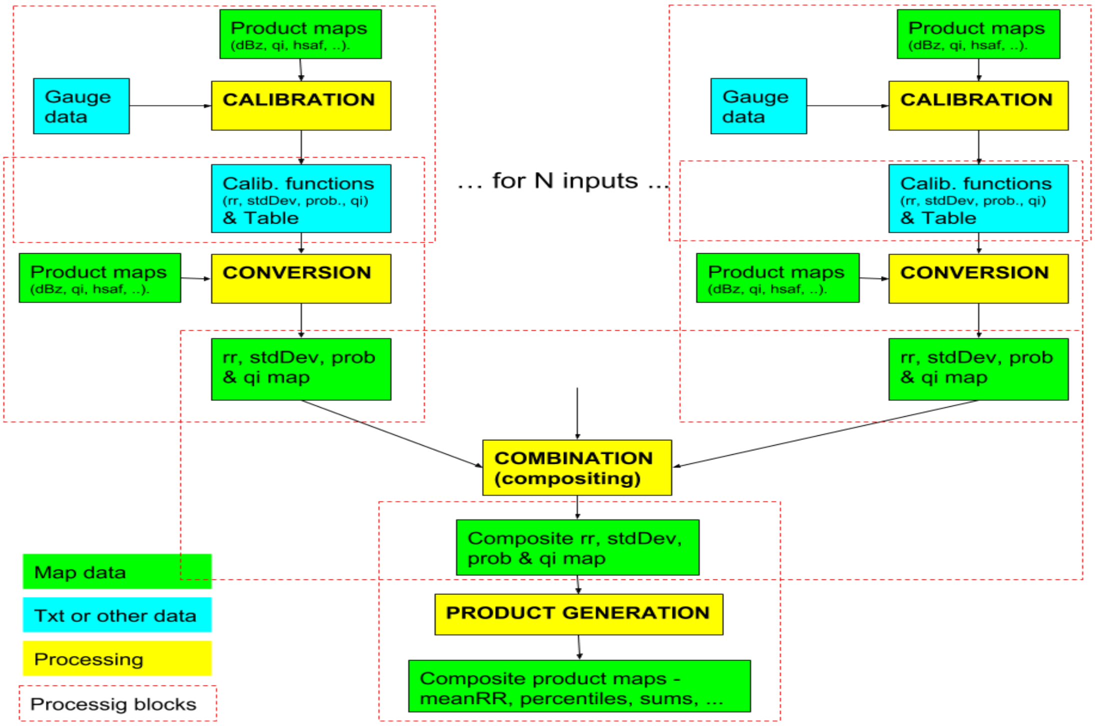

Figure 3: Processing chain in the qPrec software.

The processing chain consists of four processing blocks. The first block is the calibration step. Here the input fields, which may be related to the precipitation, are calibrated by the rain-gauge data to obtain an unbiased estimate of the rainfall-rate from the given product. The outputs of this step are four functions to describe the actual relationship between the input field and the probability of precipitation, the mean rainfall rate, the standard deviation of the rainfall-rate and the average QI of the inputs (Fig. 4).

The second processing block is the conversion. In this step the input maps are converted by the calibration functions to maps of mean rainfall-rate, standard deviation of the rainfall-rate, probability of precipitation, and quality index.

The third block is the combination, where converted input maps from different sources (different radars, other precipipataion products …) are combined to a common map of mean rainfall-rate, standard deviation of the rainfall-rate, probability of precipitation, and quality index. The second and third step can be described by the equations below:

$$P_a = \frac{\sum QI_i \times f_P(y_i)}{\sum QI_i} \qquad (4.1)$$

$$RR_a = \frac{\sum f_{mean}(y_i)/\sigma_i^2}{\sum 1/\sigma_i^2} \qquad (4.2)$$

$$\sigma_a^2 = \frac{1}{\sum 1/\sigma_i^2} \qquad (4.3)$$

$$\sigma_i = \frac{\overline{QI}}{QI_i} \times f_\sigma(y_i) \qquad (4.4)$$

, where P_a, RR_a and σ_a^2 are the resulting combined probability of precipitation, mean rainfall-rate and standard deviation of the rainfall rate. The combined quality index is computed by the equation 3.3. y_i is the *i-th* input value (e.g. reflectivity) in the given point and QI_i is the quality of the *i-th* input value in the given point. f_P, f_{mean} and f_σ are the calibration functions for the probability of precipitation, mean rainfall-rate and standard deviation of the rainfall rate and $\overline{QI}$ is the mean quality index of the inputs used in the calibration step (lower right in the Fig. 4). As seen in the equation 4.4, the actual QI is used to scale the standard deviation of the actual input value, which is then used as the weighting factor in the equation 4.2.

The last processing block is the product generation. Given the probability of zero precipitation (1- P_a) and the parameters of the non-zero rainfall-rate distribution (RR_a, σ_a^2), the probability density function of the rainfall rate is known in the given point and several products can be generated – actual rainfall-rate ($P_a * RR_a$), probability of some rainfall-rate levels, percentiles, sums …

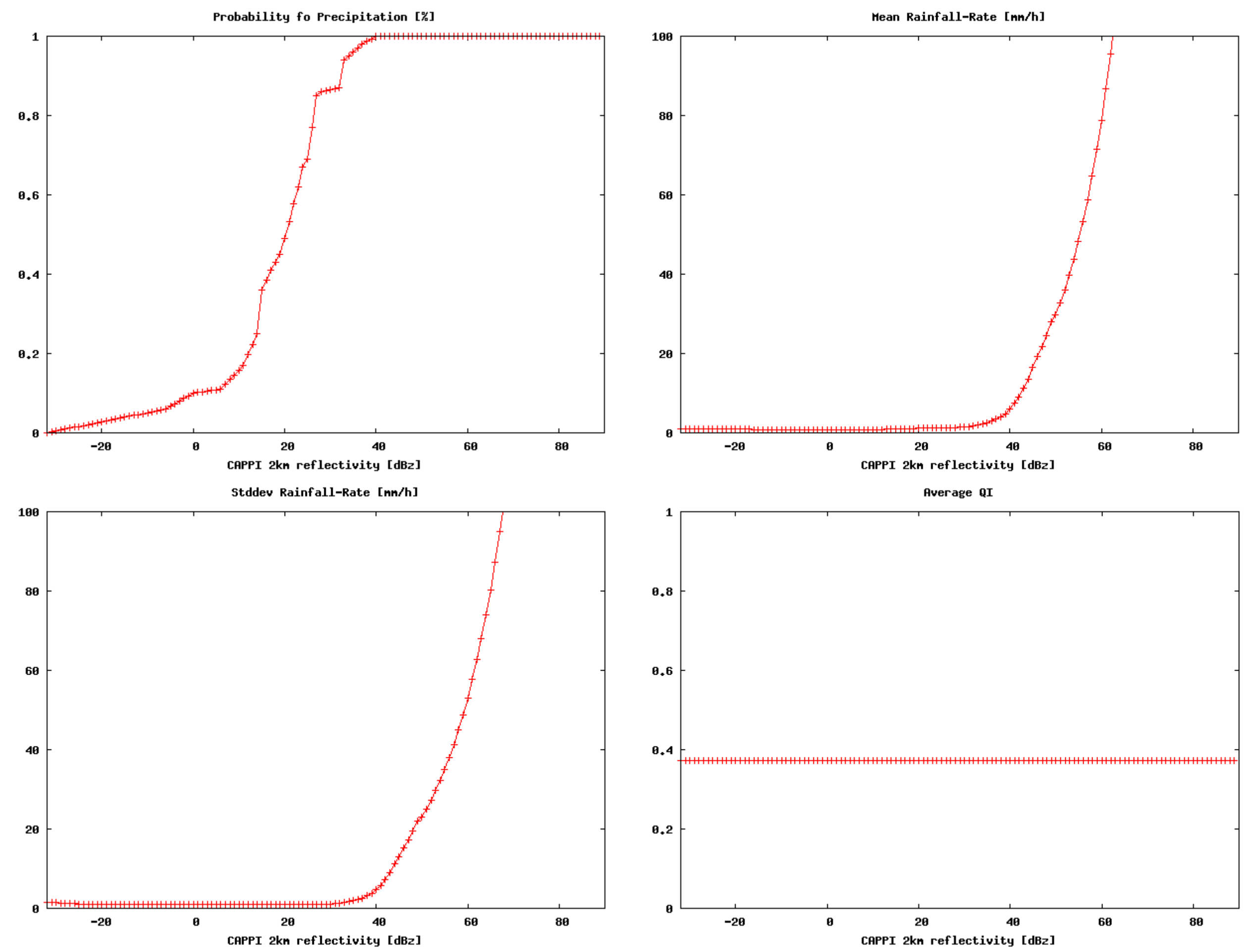

Figure 4: Example of calibration functions of the CAPPI-2km product from a given radar.

5 Usability and validation of QIs and QI-based products

As the definition of individual QIs, its scaling or its combination technique is rather subjective and not standardized, there isn`t a common objective way to validate the QIs itself. Their usefulness depends on the user's application and on the method their usage (weighting, thresholding, max. QI …). Probably the different QI algorithms should be validated by their benefits in the different use-cases. For example when the radar data are used for QPE, the benefit of the QI algorithm should be evaluated as the improvement of the QPE precision using the given QI algorithm. Similarly when the radar data are used in NWP, the QI should be evaluated by his influence on the NWP results.

5.1 Subjective visual improvement

Our forecasters and other internal users of the radar products are using these QI-based products in our visualization tool and are very satisfied by their quality. Almost all of our contributors on the Facebook page of our institute (mostly our forecasters) are choosing the qRad outputs against the products from the software of our radar manufacturer, when some interesting radar data needs to be presented.

5.2 Improvement in the H-SAF precipitation validation project

The Slovak Hydrometeorological Institute is an active contributor to the EUMETSAT H-SAF project especially in the precipitation validation working group. Since the beginning of the work the CAPPI-2km product from our radar manufacturer software - scaled by the Marshal-Palmer equation – was used in the validation of the satellite products. After using the CAPPI-2km product generated by the qRad software (and scaled by the Marshal-Palmer equation in the same manner as the old product), the magnitude of the detected deviations went lower and the distribution of the deviations became more symmetric than in the case of the old CAPPI-2km product (Fig. 5). Using qRad validation data we experienced more reliable H05 H-SAF product quality in terms of statistical scores than it used to be in the past when we used radar data from simple mosaic software that basically maximized rainfall values at every point, where data from more than one radar were available. The qRad software was installed also in the Hungarian Meteorological Service to support the H-SAF validation tasks in this institute.

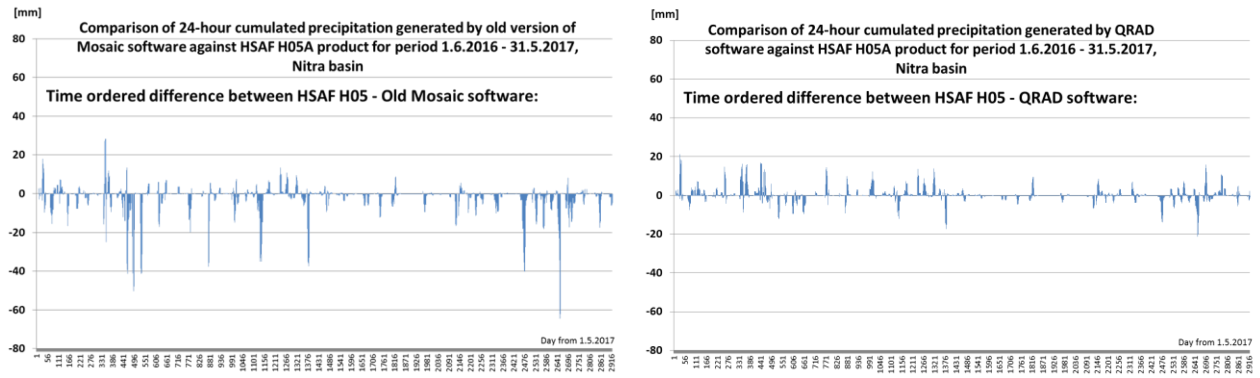

Figure 5: Difference in the usage of the old radar manufacturer generated CAPPI and the qRad generated CAPPI in the H-SAF validation project.

5.3 Improvement in our iterative QPE development project

The qPrec software is developed in an iterative approach. Each new version or change of the software (usage of a new QI, new input field, new algorithm …) is validated against the 24-hour climatological precipitation sum from our 600 climatological precipitation stations. Gradual addition of QIs to the processing had the consequence of improving the precision of the 24-hour precipitation estimation of the qPrec software (Fig. 6).

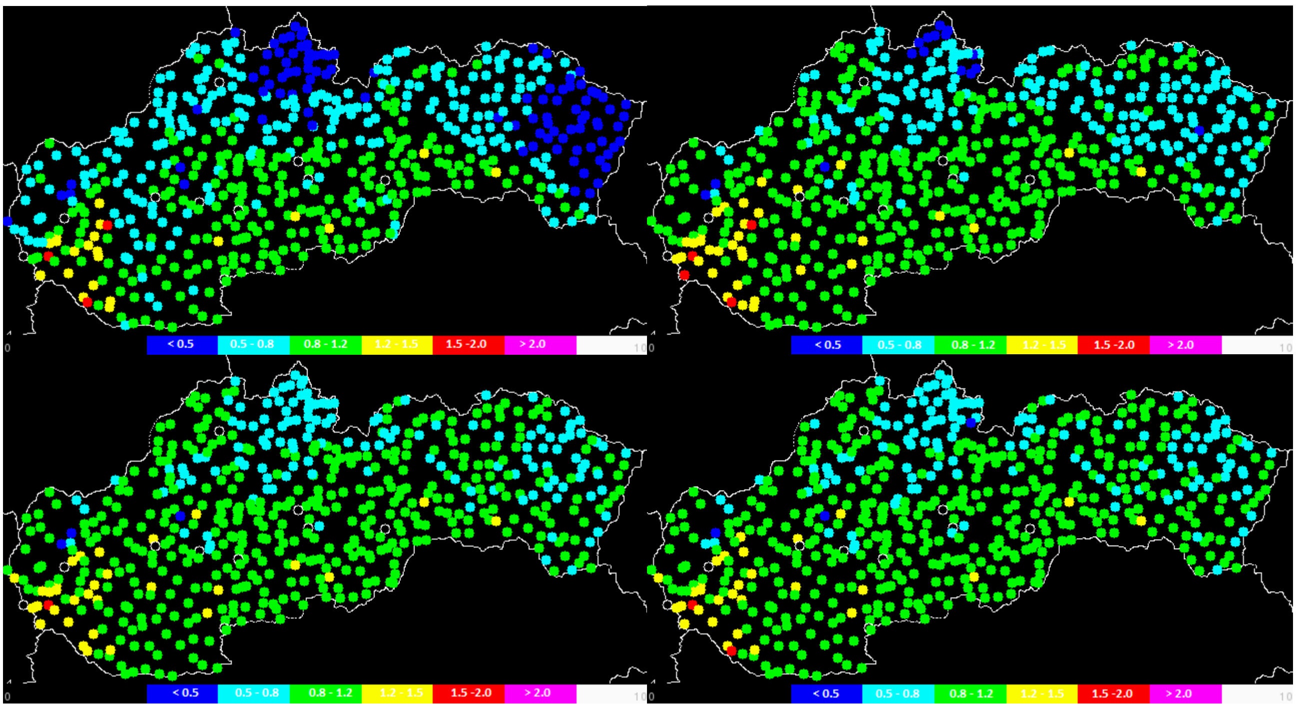

Figure 6: Average ratio of 24-hour precipitation sums from the qPrec software and from the climatological stations - qPrec / clim – for the period of 1.5.2017 – 30.9.2017. Upper left – without QI, upper right – distance QI added, lower left – beam-blockage QI added, lower right – similarity QI added. The number of points with ratio between 0.8 and 1.2 (green) is increasing by adding the QIs. Some residual underestimation in the north and east and some overestimation in south-west needs to be treated by additional changes in the future.

5.4 Improvement in the hydrological applications

An improvement in the hydrological modelling outputs was also reported by our hydrological forecasting department when the outputs of the qPrec software were used instead of the previously used INCA precipitation analyses (Fig. 7). The hydrological validation is also a part of the iterative development process of the qPrec software.

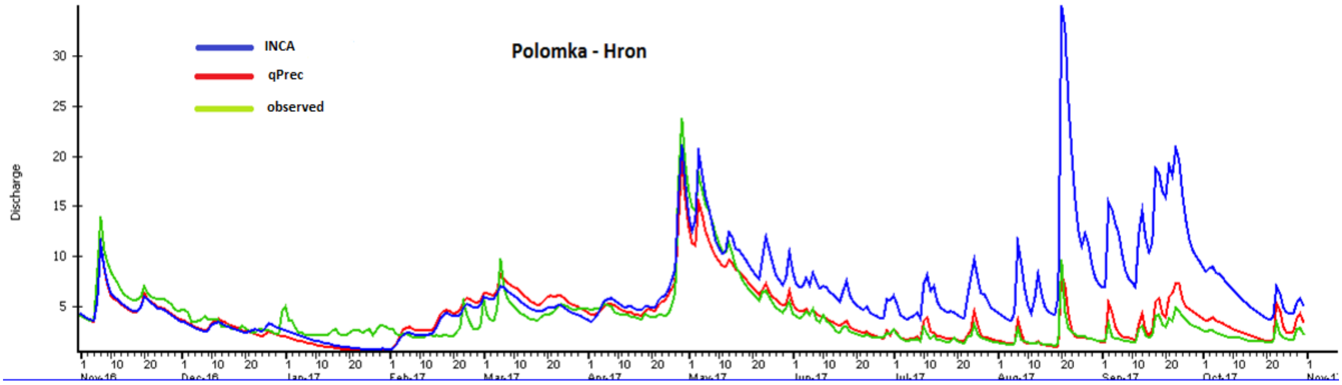

Figure 7: Hydrological model outputs for the Hron river in the central part of Slovakia from 1.10.2016 to 1.10.2017. Model using the qPrec product was producing more precise estimation of the observed outflow than with the INCA precipitation analyses.

6 Summary

The qRad quality-based radar data processing software and the qPrec quality-based precipitation estimation software is under development in the Slovak Hydrometeorological Institute. This quality-based approach combined with the iterative development process seems to give promising results (improved visual and statistical parameters of the radar products, improved precision of the precipitation estimates). The development is ongoing: new QIs and product are planned to the qRad software, while usage of the new QIs and testing of some new input fields are planned for the qPrec software.