A quality index for radar-based rainfall estimation and the impact of its introduction on the validation of H-SAF satellite precipitation products.

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Abstract
In the framework of the Hydrological-SAF Precipitation Product Validation Service, a common validation methodology has been defined to perform the validation of the satellite rainfall estimations using radar data as ground reference. The radar networks of Belgium, Germany, Hungary, Italy, Turkey, and Slovakia are used in the H-SAF Precipitation Product Validation Group (PPVG). A network of C-band and Ka-band radars throughout Europe ensures a wide area coverage with different orographies and climatological regimes, but the definition of a Quality Control Protocol for obtaining consistent ground precipitation fields across several countries is required.
It is well known that radar-based rainfall estimation is affected by several sources of uncertainty, such as ground clutter, beam blocking, range distance, vertical variability, attenuation. Thus, among the hydro-meteorological community, the evaluation of the data quality is a quite consolidated practice, even though a unique definition of a common evaluation methodology between different countries and institutions has not been stated yet.
The quality information is helpful in stating the reliability of data used for satellite precipitation products validation. Moreover, the algorithms for the calculation of rainfall estimation from radar raw data can keep into account the quality in the choice between radar maps at different elevations.

Introduction
Quantitative precipitation estimation from ground-based weather radars is a cumbersome task considering it is conditioned by several error sources. In spite some of them can be faced to a reasonably extent, any quantitative use of radar rainfall products should take into account the quality of input radar data and related precipitation estimates. This is especially recommendable either for radar data assimilation or for the validation of satellite-based precipitation products.
A theoretical treatment over the radar quality index is here presented, and the procedure derived from it has been applied on data from a C-band radar belonging to DPC, located at mount Il Monte (Abruzzo region, Central Italy) at 700 m above the sea level, with significant orographical obstruction in W-SW direction.
Then, the impact of the introduction of this quality information on the validation of satellite-based rainfall estimation from H-SAF has been evaluated, for different quality thresholds.
1. Quality concept

Starting from the paradigm that the quality is a subjective quantity, there is not a unique way to determine it as well as there is not a unique way to deal with the radar error sources. However, it can be possible to reasonably provide a theoretical definition for data quality that might require specific set up for every radar system.

The quality is a random variable ranging between 0 and 1 that depends on the considered quality indicators \( f_i \) (i.e., random variables related to the error sources). For each quality indicator a relative quality index can be defined \( q_i \), the overall quality \( Q \) can then be computed as combination of the relative quality indices.

Assuming, the radar systems are well maintained we will focus on the following quality indicators: clutter, beam blocking, distance from the radar, height of measurement and attenuation.

1.1: Ground Clutter

The ground clutter can be evaluated using several methods, those employing only the Doppler information (ground clutter is expected to be basically stationary) might produce a suppression of precipitation echoes having the radial component of velocity close to zero. Consequently, any efficient clutter identification algorithm should also consider other information.

A potential approach to discriminate the radar echoes generated by non-meteorological targets from weather returns relies on the combination of the following quality indicators: static clutter map (CMAP), radial velocity \( V \), texture of differential reflectivity \( Z_{dr} \) (TxZdr), texture of co-polar correlation coefficient \( \rho_{hv} \) (TxRho) and texture of differential phase shift \( \Phi_{dp} \) (TxPhi). CMAP is a volumetric map obtained by averaging a wide set of reflectivity data (expressed in linear units, i.e. mm^-6 m^-3) observed in clear-air conditions. It is worth noting that CMAP is dependent on the propagation conditions so that it would be recommended to build CMAP on a seasonal basis.

For each quality indicator \( X_j \) (i.e., \( X_1 = \) CMAP, \( X_2 = V \), \( X_3 = \) TxZdr, \( X_4 = \) TxRho, \( X_5 = \) TxPhi) the degree of membership to the non-meteorological target class \( d_j \) is defined through a trapezoidal transformation function

\[
d_j = \begin{cases} 
0 & \text{if } X_j < X_{i_1} \text{ or } X_j > X_{i_4} \\
(X_j - X_{i_1})(X_{i_2} - X_{i_1}) & \text{if } X_{i_1} < X_j < X_{i_2} \\
(X_{i_3} - X_j)(X_{i_4} - X_{i_3}) & \text{if } X_{i_2} < X_j < X_{i_3} \\
1 & \text{if } X_{i_3} < X_j < X_{i_4} 
\end{cases} \quad (2)
\]

where \( X_{i_j} \) is the \( i \)-th vertex of the trapezoid relatively to the \( j \)-th quality indicator. Table 1 shows the parameterization used for defining \( d_j \).

| \( X_j \) | \( w \) | \( X_{i_1} \) | \( X_{i_2} \) | \( X_{i_3} \) | \( X_{i_4} \) |
|---|---|---|---|---|
| CMAP | 0.5 | 10 | 30 | \( \infty \) | \( \infty \) |
| \( V \) | 0.3 | -0.2 | -0.1 | 0.1 | 0.2 |
| TxZdr | 0.4 | 0.7 | 1.0 | \( \infty \) | \( \infty \) |
| TxRho | 0.4 | 0.1 | 0.15 | \( \infty \) | \( \infty \) |
| TxPhi | 0.4 | 15 | 20 | \( \infty \) | \( \infty \) |

\( Table 1. \) Parameters of the applied system for evaluating \( q_{\text{clutter}} \).

The relative quality index \( q_i \) associated to \( X_j \) is then defined as the complementary of \( d_j \) (i.e., \( q_i = 1 - d_j \) )
\[ q_{\text{clutter}} = \frac{\sum w_j q_j}{\sum w_j} \]  

Radar returns with associated low quality (i.e., \( q_{\text{clutter}} < 0.6 \)) can be finally rejected. No correction is applied. Fig. 2 shows an example of radar image, the corresponding \( q_{\text{clutter}} \) map and the clutter-filtered image.

\[ R = \text{reflectivity measured by DPC radar "Il Monte", on June 1, 2009, at 14.00 UTC, elevation 0.4 (left); clutter quality map associated to the image (centre); reflectivity image with clutter quality field applied (} q_{\text{clutter}} < 0.6) \) (right).

### 1.2. Beam blocking

In order to properly take into account the beam shielding effects an Electromagnetic Propagation Model (EPM) can be used to identify the obstructed radial directions. The Partial Beam Blockage (\( PBB \)) map, representing the occultation degree at a specific antenna elevation, can be retrieved by resorting to the simplified obstruction function proposed by Bech et al. (2003)

\[ PBB = \frac{y \sqrt{a^2 - y^2} + a^2 \arcsin \frac{y}{a} + \frac{\pi a^2}{2}}{\pi a^2} \]  

where \( y \) is the difference between the height of the terrain and the height of the center of the radar beam (\( h \)), \( a \) is the radius of the beam cross section. The height of the center of the radar beam \( h \) at a distance \( r \) can be written as (Doviak and Zrnic, 1993)

\[ h = \sqrt{r^2 + (k_e R)^2 + 2rk_e R \sin \theta - k_e R + H_0} \]  

where \( R \) is the earth radius, \( \theta \) is the antenna elevation, \( H_0 \) the radar antenna height and \( k_e = 4/3 \) (assuming the wave propagation in the standard atmosphere).

The quality associated to the beam blocking can then be computed as the complementary of the \( PBB \)

\[ q_{PBB} = 1 - PBB \]  

The estimated PBB might be compensated up to 0.7 as in Tabary (2007), consequently the resulting quality would be (Fig.2):

\[ q_{PBB} = \begin{cases} 1 & \text{for } PBB < 0.7 \\ 1 - PBB & \text{for } PBB > 0.7 \end{cases} \]  

### 1.3. Range distance

The quality of radar data decreases at increasing distance from the radar either for the beam broadening related to the spherical divergence of the electromagnetic waves or for the increasing
height with respect to terrain (due to the earth curvature and vertical variability of the refractive index of the atmosphere). Following the approach proposed by Friedrich et al. (2006), but introducing a square root to make it smoother, it can be evaluated as follows:

$$q_{\text{range}} = \begin{cases} 
0 & \text{for } r \geq r_{\text{max}} \\
\frac{\min(r)}{r_{\text{max}} - r_{\text{min}}} & \text{for } r \leq r_{\text{min}} \\
\frac{r_{\text{max}} - r}{r_{\text{max}} - r_{\text{min}}} & \text{for } r_{\text{min}} < r < r_{\text{max}}
\end{cases}$$  \hspace{1cm} (8)

where $r_{\text{max}}$ can be set to 150 km and $r_{\text{min}} = \Delta r / 2$ ($\Delta r$ is the radar range resolution) (Fig.2).

![Visibility quality map](image)

**Fig. 2:** Visibility quality map associated to radar ”Il Monte”, on June 1, 2009, at 14.00 UTC, elevation 0.4 (left), and the corresponding reflectivity (see fig.1) corrected for clutter, filtered with a two-dimensional median filter and corrected for partial beam blocking (PBB < 0.7) (center) (right); range distance quality map associated to radar ”Il Monte”, on June 1, 2009, at 14.00 UTC, elevation 0.4 (right).

### 1.4. Vertical variability

As result of storms vertical variability the radar observations made at relatively high altitudes are not representative for estimating precipitation at ground level. In order to deal with such issue the reflectivity field can be ground-projected by estimating the so-called Vertical Profile of Reflectivity (VPR). In case radar data are not compensated for such effect, the VPR quality index can be estimated as in Friedrich et al. (2006):

$$q_{\text{VPR}} = \begin{cases} 
\frac{h_{3dB} - h_{FL,200}}{2(h_{3dB} - h_{3dB})} & \text{for } h_{3dB} < h_{FL,200} \text{ and } h_{3dB} > h_{FL,200} \text{ and } h_{3dB} > h_{FL,500} \\
0.5 & \text{for } h_{3dB} \leq h_{FL,200} \\
1 & \text{for } h_{3dB} > h_{FL,200} \text{ and } h_{3dB} < h_{FL,500} \\
\frac{h_{3dB} - h_{FL,500}}{2(h_{3dB} - h_{3dB})} & \text{for } h_{3dB} < h_{FL,500} \text{ and } h_{3dB} > h_{FL,500}
\end{cases}$$  \hspace{1cm} (9)

Where: $h_{FL}$ is the freezing layer height,

$$h_{3dB} = h_{\text{beam}} + h_{\Delta \Phi}$$

$\delta_{\text{up}} = r \sin(\phi_0) / \sin(\gamma + \phi_0)$,

$\delta_{\text{dn}} = r \sin(\phi_0) / \sin(\gamma - \phi_0)$,

$\varphi = 0.5 \Phi_{3dB}$ and $\gamma = \arctan((R+H_0)^* \cos(0))/(R+(R+H_0)^* \sin(0))$, with $\Phi_{3dB}$ being the 3dB beam width and $\theta$ the antenna elevation. $h_{\text{beam}}$ is the beam height defined in (5).

### 1.5. Attenuation

Rain path attenuation is one of the main impairments when estimating rainfall frequencies higher than S-band. While for dual-polarization systems there are a variety of possible solutions all based on the use of differential phase shift (Vulpiani et al., 2008), for conventional single-polarized radar the solutions are potentially unstable. For this reason it only recommended to evaluate it qualitatively. The quality index associated to rainpath attenuation can be defined as...
where \( PIA_{\text{min}} = 1 \, \text{dB} \), \( PIA_{\text{max}} = 5 \, \text{dB} \) and \( PIA \) is the path integrated attenuation that can be computed from radar reflectivity \( Z \) (expressed in \( \text{mm}^6 \, \text{m}^{-3} \)) as follows:

\[
PIA(r) = \int_0^r \alpha(s) \, ds
\]

(11)

where specific attenuation \( \alpha \) in rain (below FL-500) can be estimated as in Le Bouar et al. (2001):

\[
\alpha = a \times \left( n_0^{-b} \right) Z^b
\]

with: \( a = 1.08 \times 10^{-6} \), \( n_0 = 0.8 \times 10^7 \), \( b = 0.798 \)

(12)

Before evaluating the attenuation quality, it is recommended to remove unrealistic “spikes” in the field by applying a 2-dimensional median filter. Fig.3 shows the path-integrated attenuation for the sample radar image.

1.6. Overall Quality
The final radar data quality can be retrieved by combining all the considered quality indicator. It is proposed a multiplicative combination rule

\[
Q = \prod_k q_k
\]

(13)

where \( q_k \) are defined in (3) and (5)-(9). The quality associated to rain rate products at time \( t \) \( (Q_{R,t}) \) is the same as for radar data (we are not considering errors associated to the inversion process), while the quality associated to the cumulated rainfall can be estimated as the time average of \( Q_{R,t} \), i.e.

\[
Q_{CR} = \frac{1}{N_t} \sum_t Q_{R,t}
\]

(14)

with \( N_t \) being the number of integrated rain rate fields. Fig. 3 shows the overall quality for the sample radar image.

Fig. 3: Attenuation quality map associated to radar “Il Monte”, on June 1, 2009, at 14.00 UTC, elevation 0.4 (left); reflectivity measured by radar “Il Monte”, on June 1, 2009, at 14.00 UTC, elevation 0.4 (centre), and overall quality map associated to it (right). The dominant component in quality is the range distance.

2. Surface rainfall intensity calculation
In order to use the radar measurement for rainfall estimation, the SRI (Surface Rainfall Intensity) has to be calculated, starting from raw data and applying a \( Z(\text{reflectivity})-R(\text{rainfall intensity}) \) relationship.

It is worth to remind that any possible choice of Z-R relationship is strongly sensitive to the drop size distribution variability. However, in the present work the \( Z-R \) relationship proposed by Marshall and Palmer (1948) has been adopted:

\[
Z = 200 \times R^{1.6}
\]

(15)

because it is the most widespread the operational radar community in Europe, even though it is more suitable for the estimation of stratiform precipitation. For the specific geographical area considered in the present study, Vulpiani et al., (2012) found that the use of radar reflectivity for estimating
precipitation is frequently subject to underestimation, mainly due to orographical obstruction of radar beam, precipitation overshooting and attenuation. This is more pronounced when LBM (Lowest Beam Map) is the reflectivity product used for rainfall estimation. In order to reduce this effect, here it was chosen to derivate the SRI from the VMI (Vertical Maximum Intensity), ground-projected by means of the retrieved vertical profile of reflectivity. In the present work, the uncertainty related to the applied inversion algorithm has not been taken into account, so the overall quality associated to rainfall intensity is just the one related to $Z$, calculated as in (13).

3. Radar validation of satellite-based rainfall estimations in H-SAF:
The H-SAF Precipitation Product Validation group (PPVG) is composed of experts from the National Meteorological and Hydrological Institutes of Belgium, Bulgaria, Germany, Hungary, Italy, Poland, Slovakia, and Turkey. Hydrologists, meteorologists, and precipitation ground data experts, coming from these countries are involved in the H-SAF precipitation products (satellite-based estimation of rainfall) validation activities. A network of 4100 Rain Gauges and 41 meteorological radars provides ground data for reference. Since the beginning of the project, the importance to define a common validation procedure in order to make the results obtained by several institutes comparable, and to better understand their meanings, was clear. The main steps of this methodology have been identified inside the validation group, in collaboration with the product developers. The common validation methodology is based on ground data (radar and rain gauge) comparisons to produce large statistic (multi-categorical and continuous), and case study analysis. The products differ in data retrieval technique, space and time resolution, so every product needs a specific validation procedure tuned on its features. Precipitation products are based on data derived from different microwave and infrared sensors, such as SSMI, SSMI-S, AMSU and SEVIRI radiometers. In particular, the PR-OBS-3 product, which has been used as test product for the present work, is a SEVIRI-based rainfall intensity estimation. Infrared data from SEVIRI are blended with microwave images from SSMI, SSMI-S and AMSU. The spatial resolution of PR-OBS-3, at the latitude and longitude of the sample region, is around 3 Km, and the time resolution is 15 minutes. The common validation methodology established for precipitation products implies the up-scaling of radar data at the native grid of the satellite. While in some cases (microwave-based products) the aggregation of radar data has been weighted over a two-dimensional antenna pattern function, in this case (PR-OBS-3), due to the satellite product higher resolution, the up-scaling is performed through a simple arithmetical average (fig.4).

Fig.4: Surface Rainfall Intensity measured by DPC radar “Il Monte”, on June 1, 2009, at 14.00 UTC on basis of VMI (left), same image up-scaled on the grid of PR-OBS-3 (centre); section of PR-OBS-3 image (corresponding to the radar-covered area) at 13.57 UTC (right).

The quality index calculated with the methodology illustrated above was used as a filter in the radar validation of the PR-OBS-3 product for a preliminary work consisting in one single case study (June 1, 2009), using radar data from DPC radar “Il Monte”: the radar pixels considered in the up-scaling phase are all the ones for which the associated quality index (from the quality map obtained as described in 1.6) exceeds the considered threshold.
The ones with quality index lower than the threshold are discarded.

4. Evaluation of the impact on the validation for the quality threshold:
In order to evaluate how the introduction of a quality threshold in the up-scaling impacts on the validation results, the same validation has been performed for different quality thresholds: 0.0 (no threshold – as if no quality information is available), 0.2, 0.4, 0.6, 0.8. Two approaches have been selected (fig.5):
   a. considering for validation all radar pixels having quality index above the chosen threshold. Every satellite pixel is compared with the arithmetical average of corresponding radar pixels, regardless their number;
   b. validating just the satellite pixels which remain completely covered by valid (i.e. with quality above the chosen threshold) radar pixels after the application of the quality threshold. Approach b avoids the introduction of an additional error source, i.e. the up-scaling error due to incomplete (valid) radar coverage. But its affect on statistics is very strong, drastically reducing the validation sample (fig.5)

![Fig.5: Up-scaled radar images (upper row) under the different quality thresholds (from left to right, 0.0, 0.2, 0.4, 0.6, 0.8) considering all satellite pixels with at least one radar pixel available for validation (approach a) compared with the corresponding ones (lower row) obtained ng just the satellite pixels remaining completely covered with valid radar pixels (approach b).](image)

5. Results and discussion
The statistical scores typically calculated in H-SAF precipitation product validation (continuous scores, such as mean error, standard deviation, mean absolute error, multiplicative bias, correlation coefficient, root mean square error, percent root mean square error, and dichotomous scores, such as probability of detection, false alarm ratio, critical success index) have been evaluated for the different values of the quality index threshold. The results obtained are still very preliminary, due to the limited sample considered (one single case study in the warm season over Central Italy). Nevertheless, some noticeable results have been obtained, in particular regarding the percent root mean square error, which is the reference score to assess the achievement of the user requirements defined inside the project. As it can be observed in fig. 6, for both the approaches considered the percent RMSE is considerably decreasing as the quality threshold increases.

If this is not due to a special feature of the limited sample we chose, it might be the signature of a strong impact of the radar data quality on the validation of satellite-based rainfall estimation using radar data as reference. If confirmed, these results might indicate that the use of low-quality radar data in validating a precipitation product could lead to underrate the product, wrongly stating that it does not reach the user requirements (which are correctly reached if the validation is performed with high quality radar data). Further investigations are in progress to confirm the obtained results.

6. Conclusions and future plans
A quality index for non-polarimetric radar-derived rainfall measurement has been defined and applied to a test radar site in Central Italy. A preliminary investigation has been performed in order to state
Fig. 6: Plot of Percent RMSE depending on the quality threshold, following approach a (left) and b (right) how the introduction of a threshold in the quality index of the radar data used as reference impacts over the validation results of H-SAF satellite-derived precipitation products. The results here presented indicate a noticeable impact, with validation results showing better figures at higher radar quality thresholds.
In order to obtain more robust results about the impact on satellite-based rainfall products validation, quality, and to extend the concept of radar-derived rainfall data quality to polarimetric radars, the following steps are in progress:
- extension of the present investigation to a larger sample comprising rainfall events of all seasons and different geographical areas;
- evaluation of the impact of the quality index introduction in validation of other satellite products (e.g. microwave-based products);
- definition of a quality index also for polarimetric radar measurements, and evaluation of its impact on satellite product validation.

7. References
- Rinollo A. et al., 2012: A common protocol for the validation of satellite rainfall estimations using radar data over the European territory, submitted to NHESS