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Radar Data Quality-Ensuring Procedures at European Weather Radar Stations

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1. Introduction

Weather radars have become an invaluable tool for real time measurements of precipitation and winds with superb spatial and temporal resolution. To make full use of inherent radar capabilities, it is necessary to know the main sources of radar errors and various procedures to avoid, minimise, or correct them. The purpose of this document is to overview the main quality-ensuring procedures used or planned for operational generation of single-site radar products in the European weather radar network.

Contemporary weather radars can be classified into four types: conventional, coherent, multiparameter, and electronic scanning radars. This document is restricted to pulsed conventional and pulsed coherent-on-receive radars with axially symmetric antenna patterns and with analogue logarithmic and linear receivers; they constitute the overwhelming majority of contemporary radars used operationally by European national meteorological services.

The quality of radar data depends on radar transmitting and receiving characteristics, on accurate calibration of the radar system, on appropriate data acquisition and product generation techniques, and on effective quality control procedures during the complete life cycle of the product generation. Quality control consists of assessing the quality of data items and of (optional) correcting the bad quality data. All these quality-ensuring constituents are treated in subsequent sections.

2. Weather radar

To identify and discuss the main radar data quality-ensuring procedures, a preliminary overview of the data generation process itself is needed. This section describes the radar data acquisition and product generation process, together with the inherent limitations of the radar system.

2.1 Data generation

Radar measurements are made by transmitting electromagnetic microwave pulses in a specific direction and receiving and analysing the echoes they produce. After each pulse is transmitted, the conventional radar receiver will output a time-dependent power signal $S(t)$, which is proportional to the logarithm of the power of each echo, $P(r)$, along the radar distance r. A coherent receiver outputs two signals, $I(t)$ and $Q(t)$: the inphase signal I is proportional to the echo amplitude and the sine of its phase (relative to the transmitted wave), whereas the quadrature signal Q is proportional to the cosine. The sum $I^2 + Q^2$ is proportional to the echo power, and $\arctan(I/Q)$ is proportional to the echo phase. Analogue outputs S, I, and Q of the radar receiver, conventional or coherent, complemented by the synchronisation, calibration, time, antenna position, and status information, will henceforth be referred to as raw radar data.

Raw data originating from subsequent radar pulses which are transmitted in nearly the same direction is fed into the radar signal processor. For each range bin along the beam axis a time series of digitised data is produced. Power signals from each range bin are averaged in time, and time-averaged signals from several adjacent bins—a range cell—are averaged in space. Similarly, the inphase and quadrature signals from each range cell are processed to yield the echo spectrum's power, mean pulse-to-pulse phase change rate—Doppler frequency, and spectrum width. The estimated echo power from a specific range cell is under appropriate conditions proportional to the target reflectivity Z, Doppler frequency to the target mean radial velocity V, and spectrum width to the target velocity dispersion W. The digitised output of the radar signal processor for each range cell in every direction is stored in the computer memory as three-dimensional fields in polar co-ordinates (r, ϕ, θ) relative to the radar site. Conventional radars produce fields of radar reflectivity, whereas coherent radars produce additional fields of radial velocity and velocity dispersion. Polar fields Z, V, and W will henceforth be referred to as base radar data.

Base data serve as a starting point for calculations of various derived quantities, represented as three-, two-, or one-dimensional fields in cartesian co-ordinates (x,y,z) over various projection planes, and referred to as radar site products. These products can be classified into three groups: reflectivity, precipitation, and wind products. The most important reflectivity products in operational applications are the constant altitude reflectivity, ground projected maximum reflectivity, echo top, and vertical reflectivity profile. They are all calculated from the base reflectivity in a straight-forward way. The main precipitation products include the surface rainfall rate and surface rainfall accumulations for various time intervals. Rainfall rates are derived from a functional relationship between rain rate and reflectivity. The only wind product in operational use is the vertical profile of the horizontal wind over the radar site. It is calculated from radial velocities and their spatial gradients.

2.2 Instrumental accuracy

Every radar system exhibits inherent limits in the spatial resolution and echo power detection. These limits define the instrumental accuracy of the system.

The angular and range resolutions of a radar depend on the beam width and pulse length. For contiguous targets, they amount to about half of its beamwidth and half of its pulse length, respectively. As the beam diameter increases linearly with range, the tangential resolution deteriorates proportionally. Thus, at long ranges, fine-scale precipitation field details become undetectable.

The lower and upper limits of the correctly detectable echo power depend on the transmitted power, on the antenna power gain, and on the receiver noise and dynamic range. The radar receiver can detect an echo only if its power exceeds the system noise. Since the microwave energy flux density in the radar beam decreases with the square of the range, the targets at long ranges are poorly illuminated and their echoes might be too faint to be detected. Thus, at long ranges, light precipitation becomes undetectable.

For accurate estimates of the average echo power with a conventional receiver, a sufficiently large number of pulses must be transmitted, with the pulse repetition frequency usually low enough for the echoes to be mutually uncorrelated. The relative error of the mean estimate is inversely proportional to the square root of the number of uncorrelated echoes. With a coherent receiver, accurate measurements require a large number of pulses as well, but with the pulse repetition frequency high enough for the echoes to be correlated.

3. Radar calibration

The first step for ensuring the quality of radar data is a sufficiently accurate calibration of the radar system. A well calibrated radar should produce, under optimal measuring conditions, accurate base data, i.e. correct estimates of location, reflectivity, radial velocity and velocity dispersion of suitable test targets. The calibration is applied to the radar antenna positioning system and to the radar transmitting and receiving chain.

3.1 Antenna alignment

Calibration of the antenna alignment consists of comparing the antenna azimuth and elevation angle readouts with the actual azimuth and elevation angle of the antenna beam axis, and of minimising the differences. Antenna alignment can be calibrated visually, by passive targets, or by active targets. Where appropriate, the difference between physical and electrical pointing must be taken into account.

- *Spirit level and compass.* Vertical tilt of the antenna pedestal is checked by a built-in spirit level, and azimuthal orientation with a compass.
- *Bore sighting.* Antenna is equipped with a bore sight in line with the antenna beam axis. A suitable ground target of a known azimuth and elevation is sighted by looking through the bore sight and turning the antenna. This method is possible only in the absence of radome.
- *Passive ground target.* A suitable ground target of a known azimuth and range, e.g. a radio tower, is irradiated and, by moving the antenna, the maximum echo is sought. Ground targets are usually not suitable for elevation calibrations.
- *Passive elevated target.* A suitable elevated target of a known azimuth, elevation, and range, e.g. a balloon with a reflector, is irradiated and the maximum echo is sought by moving the antenna.
- *Active ground target.* A microwave source is placed at a convenient place of a known azimuth and elevation, e.g. on a tower or hill, and the maximum echo is searched for with the radar transmitter turned off.
- *Sun tracking.* Instead of a human-made microwave source, one can utilise solar microwave radiation. This method requires exact knowledge of the position of the Sun in the sky at the moment of measurement.

3.2 Transmitting chain

Calibration of the transmitting chain consists of measuring and adjusting various parameters used in the radar equation (pulse repetition time, pulse duration, wavelength, average power, peak power, waveguide loss, radome loss, beam width, antenna power gain), and in calculating the radar constant.

- *Pulse repetition time.* Pulse trigger signals are fed into the oscilloscope and time intervals between them are recorded. Alternatively, the number of trigger pulses per time interval can be counted using an electronic counter.
- *Pulse length.* Transmitted power is fed into the oscilloscope and pulse durations are recorded. Pulse length is calculated from the pulse duration.
- *Wavelength.* Transmitting power is fed through the resonant cavity frequency-meter to the powermeter. The cavity volume—calibrated in frequency units of the corresponding cavity waves—is adjusted to minimise the powermeter readout. Wavelength is calculated from the recorded frequency. Alternatively, the frequency purity and bandwidth can be measured with a spectrum analyzer.
- *Average power.* Transmitting power in the waveguide at the transmitter output is measured by a powermeter.
- *Peak power.* Peak power is calculated from the average power, pulse duration, and pulse repetition time.
- *Waveguide loss.* Transmitting power in the waveguide at two points—transmitter output and antenna input—is measured. Difference between the two measurements equals to a one-way power loss in the waveguide.
- *Radome loss.* A piece of radome is inserted between a lab microwave source and sensor. Difference in the sensor power readout equals to a one-way power loss in the radome. However, the radome attenuation is strongly influenced by water deposition which is difficult to assess.
- *Beam width.* A microwave source is placed at a convenient location in the antenna far field. With radar transmitter turned off, the maximum power signal from the source is searched for. The antenna is then gradually turned away from the source and relative power signals are recorded, yielding the directional gain and half-beam width.
- *Antenna power gain.* A microwave sensor with a known intercept area is placed at a known distance in the antenna far field. The radar transmitter is turned on and the antenna is moved until the sensor records the maximum radiation intensity. Simultaneously the transmitting power at a convenient point in the waveguide between the transmitter and antenna is measured by a powermeter. The antenna power gain is calculated from the sensor-recorded maximum intensity and the powermeter-recorded transmitting power. It includes all losses between the transmitting power measuring point and the microwave sensor.

3.3 Receiving chain

Calibration of the logarithmic receiving channel consists of the measuring and adjusting of the logarithmic receiver and digitizer parameters (bandwidth, noise, dynamic range, power gain, response function), and in setting up the complete radar equation.

- *Receiver noise, response function, and dynamic range.* Using a signal generator, continuous microwaves of known power are injected in the waveguide just before the transmitter/receiver switch, and the analog-to-digital converter output is recorded. Measurement is performed with gradually changing input power, yielding the combined receiver and converter response function. The recorded function must be corrected by taking into account the power losses due to the receiver finite bandwidth (typically 2.3 dB) and the logarithmic averaging (typically 2.5 dB). Receiver noise and dynamic range are derived from the response function in a straight-forward way.
- *Receiver power gain.* Receiver response to a known input power from a calibrated signal generator is recorded directly at the receiver output and not after the analog-to-digital conversion, yielding the receiver power gain.
- *Receiver bandwidth.* Varying the frequency of the injected continuous microwaves, the receiver output is recorded, yielding the receiver bandwidth.

Calibration of the power output of the linear channel is similar. However, no logarithmic averaging correction is needed. The mean Doppler frequency output is calibrated via injected continuous microwaves of a known linearly varying frequency.

3.4 Transceiving chain

Calibration of the conventional transmitting and receiving chain consists of illuminating a target of a known backscattering cross-section or reflectivity, of comparing the radar estimates with actual values, and of minimising the differences. For operational purposes, a reflectivity calibration accuracy within 1 dB is both reasonable and sufficient.

- *Elevated sphere.* A metal sphere of a known backscattering cross-section is raised in the atmosphere using a suitable balloon, and its equivalent radar reflectivity is measured.
- *Ground distrometers.* Raindrop size spectrum is measured by a ground-based distrometer, the corresponding radar reflectivity is calculated and compared with the simultaneous radar estimate.

Calibration of the reflectivity output of the coherent transmitting and receiving chain is similar. The radial velocity output can be calibrated, in principle, via suitable targets of known velocity. For obvious reasons this is difficult to achieve in praxis.

4. Operational monitoring

The goal of an operational radar measurement of the atmosphere is to scan as widely, fast, and accurate as permissible by the inherent radar accuracy and by various sources of errors. During scanning, however, some of the radar operating parameters can deviate from calibrated values due to various causes. To avoid the corresponding data quality deterioration, a regular monitoring of the radar transceiving and scanning parameters is needed, complemented with appropriate actions to either restore their values or to account for the changes.

4.1 Transceiver status

From all transmitting and receiving radar parameters, the transmitting power and noise power are most prone to variations. By using a suitable built-in test equipment, they can be measured during or after each volume scan, and quality checked against the calibration values.

4.2 Antenna position

All operational radars scan the atmosphere with antennas rotating around the vertical axis at sequential elevation angles specified in system configuration files. Signal processor output data are complemented with the elevation and azimuth angle information provided by the antenna controller. Elevation information is quality checked against the configuration values, and azimuth information is quality checked for continuity.

5. Base data correction

During the operational radar measurement, large errors can be produced and appropriate methods to avoid or minimise them are necessary. This section describes data correction methods related to occultation, attenuation, range and velocity aliasing, and clutter problems.

5.1 Occultation

At low elevations, radar beams can be blocked, partially or totally, by orography or human-made obstacles. The blocking, if not accounted for, introduces errors in the radar reflectivity estimates. A half beam blocking results in an underestimation of 3 dBZ. Occultation can be avoided by using sufficiently high elevation angles, or corrected via a pre-defined polar map of occultation factors. The map can be constructed using visual measurements of the horizon, numerically simulated beam propagation, or statistical analysis of radar data.

- *Theodolite measurement.* The visual horizon is recorded with a standard theodolite placed at the radar site. The atmospheric refractive index is nearly the same for light and microwaves, and the visual horizon is a good approximation of the radar horizon.

- *Propagation simulation.* A suitable numerical model simulates the radar beam propagation in a standard atmosphere over a digitised terrain.
- *Statistical visibility analysis.* A large set of radar polar volumes recorded during widespread precipitation events is analysed. Range cells with lower-than-average records are occluded.

5.2 Attenuation

Radar microwaves are attenuated (absorbed and scattered) by atmospheric gases and hydrometeors. Attenuation decreases with increasing wavelength. If not corrected for, it introduces errors in radar estimates of reflectivity. The gaseous one-way attenuation is of the order of 1 dB per 100 km whereas the attenuation of the C-band microwaves in heavy precipitation can reach 10 dB per 100 km. The corresponding reflectivity errors amount to 2 dBZ and 20 dBZ, respectively.

Attenuation can be avoided by utilising sufficiently long wavelengths. However, long microwaves are substantially less reflectable from hydrometeors (in inverse proportion to the forth power of the wavelength), and are more contaminated by ground clutter. In addition, they require larger antennas for focusing in narrow beams, the beamwidth being proportional to the wavelength and inversely proportional to the antenna diameter.

The gaseous attenuation correction consists of adding an estimate of the attenuated power to the actually recorded echo power. Power increments per range cell are either constant or they vary with the elevation and range. The precipitation attenuation correction is similar. However, the power increment for a specific range cell depends on the corrected echo power from all previous cells, making the correction at long ranges very sensitive and potentially unstable.

5.3 Range aliasing

The maximum unambiguous range r_{max} is the range to which a transmitted pulse can travel and return before the next pulse is transmitted. Preceding pulse echoes from targets beyond that range are received simultaneously with the last pulse echoes from closer targets. If no special precautions are met, the targets at $r_{max} + \delta r$ will be erroneously positioned at δr, although they are substantially weakened.

Range aliases, i.e. multitrip echoes, can be avoided by using sufficiently low pulse repetition rates. This is acceptable for conventional systems which require noncorrelated echo sampling. Coherent systems require correlated sampling and impose an upper limit to pulse repetition times. In addition, the maximum unambiguous range is inversely proportional to the maximum unambiguous velocity, and avoiding range aliasing increases velocity aliasing.

Multitrip echoes can by recognised by analysing the reflectivity field structure or the echo signal coherency, and then quality-tagged for subsequent processing.

- *Vertical reflectivity profile test.* Multitrip echoes extend vertically only for the lowest 1–2 elevation angles. They can be detected by analysing the low-level vertical reflectivity profiles.

- *Velocity dispersion test.* Multitrip echoes exhibit random phase shifts (relative to the current referent wave), producing extremely large estimates of the velocity dispersion.
- *Signal coherency test.* From the high-pass filtered time series of linear channel signals, the actual coherency of the signal, defined by the signal quality index, can be computed. Multitrip echoes exhibit low index values.

5.4 Velocity aliasing

The maximum unambiguous velocity v_{max} is the velocity which produces the pulse-to-pulse echo phase change of π. Phase changes $\pi + \phi$ are indistinguishable from the changes $\pi - \phi$. If no special precautions are met, velocities $v_{max} + \delta v$ will be therefore erroneously interpreted as $-v_{max} + \delta v$, i.e. velocity aliases. Velocity aliasing can be avoided by using sufficiently high pulse repetition rates. This approach, however, results in shortening the maximum unambiguous range, and is usually feasible for high elevation angles only. Maximum unambiguous velocity can be increased to some extent, without shortening the maximum unambiguous range, by using two staggered pulse repetition frequencies.

Velocity aliases exhibit abrupt changes in the velocity value and direction towards or away from the radar. They can be located by analysing the radial velocity gradient, and quality-tagged for subsequent processing.

5.5 Ground clutter

Radar echoes can originate not only from hydrometeors but from other sources as well, especially from ground targets, insects, and birds. Without appropriate precautions, these non-hydrometeor echoes will be erroneously attributed to precipitation. Ground clutter contamination can be either detected and quality-tagged for subsequent processing, or filtered-out from the echo signal. Clutter detection is based on clutter maps, echo fluctuation and radial velocity tests, whereas clutter-filtering of echo signals is implemented in the time or frequency domain.

- *Clutter map test.* During fine weather, a reflectivity map of the atmosphere is recorded and stored. Range bins with reflectivities exceeding a given threshold are declared to be clutter bins. Subsequent reflectivity measurements are compared with the map, and corresponding clutter bins are tagged. In the subsequent processing, the information from the tagged bins is not used. Using a clutter map has two main disadvantages: large parts of the atmosphere become blind zones, and a substantial amount of clutter might pass through due to its spatial fluctuation.
- *Echo fluctuation test.* Echo power signals from hydrometeors exhibit larger pulse-to-pulse fluctuations than signals from ground clutter. Range cells with low fluctuations are declared to contain clutter.
- *Radial velocity test.* Ground targets are more or less stationary whereas weather targets usually move. Range cells with non-zero reflectivity and with near-zero velocity are declared to contain clutter. One minor disadvantage of

the method is the wrong quality-tagging of weather echoes having near-zero velocities.

- *High-pass filter on logarithmic signals.* A suitable high-pass time filter on logarithmic signals can eliminate a fairly large part of clutter contamination. However, the differentiation between the clutter and a weather echo on the basis of their intensity fluctuations is not a sharp one and a substantial amount of weather echo can be removed together with the clutter echo.
- *High-pass filter on linear signals.* In signal processors utilising PPP, high-pass filtering is applied on I and Q time series to filter out low frequencies attributed to clutter. Difference between the total and filtered echo power, both estimated from the linear channel data, is used to correct the logarithmic channel reflectivity. One minor disadvantage of the method is the elimination of weather echoes having near-zero velocities.
- *Zero-velocity channel blocking.* In signal processors utilising FFT, echo power from the zero-velocity channel is blocked and interpolated from adjacent channels. Clutter contamination is thus effectively removed without weakening the weather echo.

6. Product enhancement

The quality of single-site radar products can be enhanced in several ways. Data cells with bad quality tags can be assigned interpolated values from adjacent good-quality data, domain regions without radar measurement can be filled out by extrapolation, data fields can be smoothed to eliminate various artefacts, and data values can be adjusted using radar-independent measurements.

6.1 Vertical extrapolation

Due to the Earth curvature and orography it is not always possible to measure precipitation close to the ground, especially at long ranges. The surface rainfall can only be estimated from measurements aloft. If precipitation is assumed to be constant with height, significant under- or over-estimations can be produced, depending mainly on the radar beam diameter and its relative position to the precipitation melting layer. These errors can easily reach a factor of 10.

Low-level precipitation can be extrapolated from the upper-level measurement by taking into account the vertical reflectivity profile. Real-time measured profiles close to the radar, climatological profiles, or simplified synthetic profiles can be used. The use of reflectivity profiles is so far the best method to improve the quality of surface rainfall estimates under non-optimal conditions, and quite capable of ensuring the accuracy to a factor of 2 in hourly point accumulations up to the range of 150 km.

6.2 Spatial interpolation

Some data cells in a radar polar data field or in a cartesian product can be tagged as containing data of a bad or susceptible quality. These quality tags, produced by preceding quality control procedures, reflect problems related to operational malfunctioning, occultation, attenuation, aliasing, and clutter. The tagged data cells can be assigned new values interpolated from the adjacent good-quality cells. The interpolation in polar data fields is performed radially or tangentially, and in cartesian products horizontally or vertically.

6.3 Smoothing

After the spatial interpolation, radar data fields can still exhibit various artefacts: non-recognised clutter speckles, radial sectors of heavy attenuation behind strong convective cells, radial irradiations from other radars, circular rings in echo top or precipitation accumulation products due to discrete scanning angles, etc. These artefacts introduce sharp gradients in otherwise smooth weather fields and can be eliminated, to some extent, by a suitable texture smoothing. However, the smoothing process effects weather data as well, resulting in a loss of fine-scale details.

6.4 Adjustment

Many of the radar-measured atmospheric quantities can be measured by other equipment as well. Surface rainfall, for example, can be measured by a network of ground raingauges. In general, radar and non-radar measurements of the same quantity will differ. The idea of radar data adjustment is to compare the radar and non-radar data and to modify radar data to minimise the observed differences. The only sensors for operational radar data adjustment in Europe are ground-based raingauges, and the adjustment is performed via gauge-tuned ZR relations, radar-to-gauge factors, and radar-to-gauge regressions.

- *Gauge-tuned ZR relations.* Simultaneous radar-measured reflectivities aloft and gauge-measured rainfall at the ground are connected via the ZR equation, and the equation parameters are adjusted to minimise the difference. Tuning is done in real time or previously-tuned and classified parameter values are used. The classification can include season, orography, precipitation type, and other variables.
- *Radar-to-gauge factors.* Simultaneous radar and gauge estimates of rainfall are compared, radar-to-gauge ratios are formed, and radar data are multiplied with their inverse values—adjustment factors. The generation of adjustment factors is performed in real time or previously-established and classified values are used.
- *Radar-to-gauge regressions.* The connection between the radar and gauge estimates of rainfall is formulated via a suitable regression equation, for example via the linear regression of radar rainfall on the gauge rainfall and the radar-gauge range. Regression parameters are adjusted in real time or previously calculated values are used.

7. Conclusions

In this document the main radar data quality-ensuring procedures, implemented or planned to be used in the next few years at operational weather radar sites in Europe, have been identified and summarised, using generally available information. These procedures are both numerous and versatile. However, they are all devised to deal with the same quality-detoriating factors: system miscalibration and malfunctioning, occultation, attenuation, range and velocity aliasing, clutter contamination, and vertical variability of precipitation fields. A well-chosen set of quality-ensuring procedures is a necessary prerequisite for accurate radar measurements of the atmosphere under operational measuring conditions.