# 7B.5 VERTICAL REFLECTIVITY PROFILE CLASSIFICATION AND CORRECTION IN RADAR COMPOSITES IN FINLAND

Jarmo Koistinen[1], Heikki Pohjola and Harri Hohti
Finnish Meteorological Institute, Helsinki, Finland

## 1. INTRODUCTION

It has not been fully realised until the 1990s that the main factor introducing bias to radar estimates of surface precipitation is the vertical measurement geometry of weather radars (Joss and Waldvogel 1990). Radar measurements are made at increasing height and with an increasing measurement volume with increasing range, making them decreasingly representative for surface conditions (Zawadzki 1984). A radar measurement ($Z_e$), and possibly even rainfall intensity $R$ or snowfall intensity $S$ from the applied $Z$-$R$/$Z_e$-$S$ relation can be accurate aloft, at the height of radar measurement, but it is not necessarily valid at the surface. This inaccuracy is not a measurement error but a sampling difference. The vertical profile of reflectivity (VPR) above each surface location can be denoted as $Z_e(h)$, here $h$ is height above the surface. The shape of the VPR determines the magnitude of the sampling difference. As we know the shape of the radar beam pattern $f^2$ and the height of the beam center $h$ at each range $r$, it is easy to calculate from a VPR what the radar would measure at each range, $Z_e(h,r)$:

$$Z_e(h,r) = \int f^2(y) Z_e(y) dy \quad (1)$$

where the integration is performed vertically ($y$) from the lower to the upper edge height of the beam (Koistinen 1991). The vertical sampling difference $c$ (in decibels) is then

$$c = 10 \log \frac{Z_e(0,r)}{Z_e(h,r)} \quad (2)$$

where $Z_e(0,r)$ is the reflectivity at the surface in the VPR. Hence, by adding the sampling difference ($c$) to the measured reflectivity aloft (dBZ) we get the reflectivity at the surface, dBZ(0,r):

$$dBZ(0,r) = dBZ + c. \quad (3)$$

One way to improve radar-based surface measurements of precipitation is to estimate the sampling bias $c$ (Eq. 2), i.e. to apply a correction based on the VPR. Despite the fact that several VPR correction schemes have been proposed and tested (Koistinen 1991; Joss and Lee 1995; Andrieu and Creutin 1995; Vignal et al. 2000; Marzano et al. 2002), operational solutions are not widely established (Collier 2001). The main difficulty is that the measurement geometry of a radar system, together with the shielding topography, prevents us from seeing the actual VPR at longer ranges above each geographical location at each moment in time. We must estimate the profiles from either the measured high resolution volumetric data at close ranges to the radar or apply climatological VPR. The magnitude of the correction factor at longer ranges is quite sensitive to variations in the vertical shape of the VPR in time and space. In order to avoid spurious transient corrections integration in time and in space is needed as well as quality weighting of the measured individual VPRs. This is most pronounced in cold climates, where precipitation is shallow and where a strong negative reflectivity gradient is dominant in the snowfall part of a precipitating system. A further problem appears when we try to apply VPR corrections in a radar network. Although straightforward with a single radar system, slightly different VPR corrections, applied independently at neighbouring radars, easily amplify reflectivity discrepancies where data from two neighbouring radars meet in a radar network composite product. In the following we describe one solution to these problems, i.e. the VPR correction scheme implemented with the Finnish radar network in November 2002. Although it is only one of several proposed schemes, the following describes problems and their solutions which are inherent to any VPR correction scheme. An additional deliverable from the scheme are the large statistics of the vertical structure of reflectivity in a cold climate. Such information is useful when both radar and satellite algorithms of remotely sensed precipitation, especially snowfall, are planned and tested.

## 2. MEASUREMENTS AND DIAGNOSTICS OF REPRESENTATIVE VERTICAL REFLECTIVITY PROFILES

The vertical profiles of reflectivity are derived from the 3D polar volume of each radar measurement in the Finnish network of 7 C-band Doppler radars. Each radar measures with ten elevation and 360 azimuth angles. In most cases the beamwidth is 0.95 degrees, the lowest elevation angle is 0,4 deg and the highest 45 deg. Polar volumes are measured every 15 minutes applying 0.5 km radial resolution of the measurement bins. Vertical profiles of reflectivity are derived inside the range of 2 to 40 km. VPR's vertical resolution is 200 meters. The reflectivity value for each 200 meters thick layer is the linear average of the radar reflectivity factor ($Z_e$) in those measurement bins where $Z_e$ exceeds the noise level and where beam center is located within the selected layer. Due to the settings of IRIS software no more than 5000

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[1] Jarmo Koistinen
FMI, P.O.BOX 503, 00101 HELSINKI, Finland.
e-mail: jarmo.koistinen@fmi.fi

bins are used for the calculation of the average reflectivity in each vertical layer. Prior to the application of a measured VPR, quality control is needed to guarantee that the vertical structure of the profile is physically reasonable. Each layer should contain enough measurement bins to be at least representative for it. An additional quality test requires that reflectivity gradients between layers should not bee too steep outside the bright band.

The most important information for the VPR classification, in addition to profile data itself, is the freezing level height. Freezing level height is interpolated to the radar sites linearly in time and space from radio sounding data at the Finnish stations performing soundings at 00 and 12 UTC (two stations) and at 06 and 18 UTC (one station). Despite efficient Doppler filtering of the reflectivity data, some very strong clutter targets close to radars may partly remain and introduce a pronounced maximum in the VPR close to the surface. The height of freezing level helps to separate real bright bands at the surface from spurious bright bands due to residual clutter. In the classification scheme, a local dBZ maximum is diagnosed as bright band when its height is within ±500 m from the estimated freezing level height. In the latter case a “clutter cutter” is applied i.e. the vertical reflectivity gradient close to ground level is limited to be less steep than -1 dBZ/200 m.

Automatic real time diagnostics classify the measured VPR to the following types: rain at ground, snow at ground, sleet (bright band) at ground, overhanging precipitation and clear air echo. All types may contain residual clutter, which is diagnosed; pure clutter is also possible. In case of rain or overhanging precipitation the possible occurrance of the bright band is diagnosed together with its height, amplitude (dB) and thickness. Classified example profiles for different precipitation cases are shown in Fig. 1. In Fig. 1 a) is a typical snow case from 32 to 4832 meters. The freezing level (FL) is spurious, -1713 meters under ground, as it is calculated from the 925 hPa level’s temperature with applying a moist adiabatic lapse rate of -6.5 deg C/km. The maximum dBZ (Max) is only -2.8 dBZ. Fig. 1 b) exhibites a typical rain case with strong bright band at 2161 meters (BB) identified with the interpolated freezing level at 1989 m. The minimum height of the bright band is 1761 m (Zdown) and the maximum height is 2561 m (Zup).

Examples of nonprecipitating VPR’s are shown in Fig. 2. In Fig. 2 a) the profile is easily classified to overhanging precipitation as the lowest layer of the profile is above the ground. Near the ground, there is only a thin ground clutter layer. In Fig. 2 b) is shown a clear air echo case. As the freezing level is located at 1700 m the profile can not be precipitation. That is based on the assumption that almost all precipitation in Finland is initiated in ice crystal process in temperatures of -6 deg C or less. This means that the top of the profile should be at least one kilometer above the freezing level to be diagnosed as precipitation. The assumption implicates that we are not able to diagnose drizzle from clear air echo or clutter based on the echo top height only. The profile in Fig. 2 b) is typical in the case of flying insects. Under the insect layer ground clutter may have intensified reflectivities in the layer near the surface.

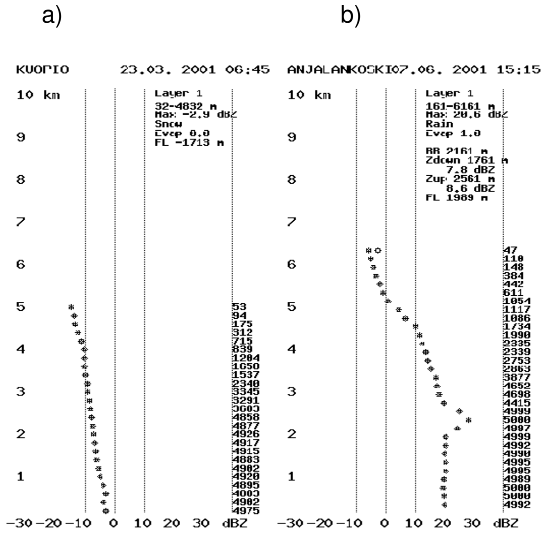

Figure 1: Example VPR’s for a) snow and b) rain. The number of averaged measurement bins exceeding noise level in each layer of the VPR is shown on the right. The profile diagnostics in the upper right corner are explained in text.

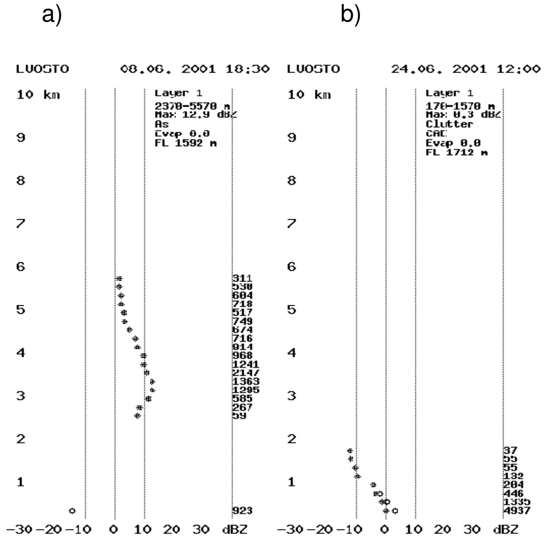

Figure 2: Nonprecipitating example VPR’s for a) overhanging precipitation and b) insects and clutter. Quality controlled VPR is shown with filled dots and original, non-corrected layer reflectivities with open dots.

Classification of 240 000 vertical profiles of reflectivity from a one year long period revealed that 40 % of all VPRs originated from clear air echoes reaching the ground (mostly insects and birds in summer, possibly drifting snow and solitary ice crystals in winter), 19 % from overhanging precipitation i.e. ice crystal clouds (typically Altostratus or Cirrostratus) or snowfall layers aloft, and 41 % involved precipitation reaching the ground level. Of all precipitation cases at ground level 56 % was snow, 5 % melting snow, 10 % rain with bright band (i.e. pronounced melting layer aloft) and 39 % rain without bright band. These figures prove that a correct classification is crucial for a working VPR correction scheme as only 41 % of all observed profiles represent precipitation reaching the ground level. They will be accepted as input to the VPR correction scheme and other types of profiles will be rejected.

## 3. VPR CORRECTION IN A RADAR NETWORK

In case the quality of a measured VPR is poor, or there is no precipitation within 40 km range, we should apply estimated profiles of reflectivity. We apply a so-called climatological VPR which has a fixed shape relative to the varying bright band height. The height of the freezing level is obtained from time-space extrapolated radiosonde data (a linear trend is assumed based on the latest two soundings). As has been shown (Koistinen 1991; Joss and Lee 1995), climatological or average VPRs remove the major part of the sampling bias.

Even when a high quality measured VPR exists, the instantaneous VPR correction factors ($c$) for a single polar volume as a function of range are always derived as the weighted mean of the corrections derived from both the quality weighted measured VPR (weight 0-1) and from the climatological VPR (weight 0.2). Further averaging is needed to make the corrections more representative in the whole single radar measurement area up to 250 km range. Assuming an average speed of 10 m/s for a precipitating system, it takes approximately six hours for a VPR to move across a single radar's coverage area. Therefore the corrections ($c$) based on climatological and measured instantaneous VPRs are further averaged in a 6 hour time window at each range.

The spatial representativity of a VPR correction in a network is obtained by spatial averaging of the time-averaged correction factors ($c$) obtained independently from each radar. In a network composite pixel, the reflectivity value dBZ(h,r) is typically taken from a single radar: the one which has the best visibility to the pixel. However, the time-averaged VPR correction from only the same radar is not necessarily representative enough, especially if the pixel is located almost as close to two or more radars. We apply spatially weighted time-averaged correction factors from all neighbouring radars closer than 300 km from the pixel to be corrected. The weight of each radar is inversely proportional to the distance to each radar squared. An important detail in the method is that the resulting spatial correction factor field will not introduce border effects or amplify possibly existing ones (e.g. due to calibration differences or due to elevation angle errors) along the borders which separate data from neighbouring radars in the given composite.

Fig. 3 exhibits the average sampling bias ($c$), i.e. the vertical reflectivity correction calculated from Eq. 2, applied to 96 000 measured precipitation profiles from the seven Finnish weather radars during a one year long period from March 2001 to February 2002. The lowest elevation angle is 0.4 deg and one-way half power beamwidth is 0.95 deg in six systems. In the seventh system, the lowest elevation angle is 0.1 deg and the beamwidth is 0.8 deg. The corrections are classified according to the precipitation type at ground level in each vertical profile of reflectivity. The curves should represent well the yearly average of the sampling differences brought about by the Finnish climate. It is strikingly evident that the sampling difference is by far much more important factor in the accuracy of operational radar-based precipitation measurements than the effect of an “optimal” relation between radar reflectivity factor and precipitation intensity.

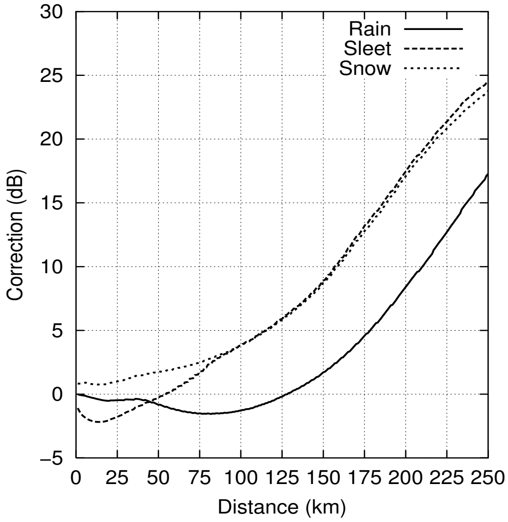

Figure 3: Annual average of the sampling difference (dBZ) between the ground level reflectivity factor and the reflectivity measured at the 500 m pseudo-CAPPI level as a function of range from a radar. The data were obtained from the 7 Finnish weather radars and they consist of 96 000 measured VPRs of precipitation which were classified according to the hydrometeor phase at ground level to snow (dotted), melting snow (dashed), and rain (solid).

Validation of the VPR correction scheme has been performed applying neighbouring radar pairs: Optimally, when the VPR correction has been performed for the lowest elevation data from radar A at range r, the corrected dBZ should be equal to the measured reflectivity at radar B, located at range r from radar A as data from B at very short ranges is obtained practically at ground level. Using data bins in the circular area between 5 - 25 km from radar Anjalankoski (B) and respective bins from radar Vantaa (A), located 140 km from Anjalankoski, and applying the VPR corrections for Vantaa from April 2002 to May 2003 we found that the average bias in radar A, dBZ(B) - dBZ(A), reduced from 2.6 dB to -0.05 dB. In winter the sampling bias is larger as precipitating VPRs are shallower. The reduction in bias in November 2002 - February 2003 was from 4.9 dB to -0.1 dB. These figures suggest that the VPR correction method works well at least in the ranges of 130-150 km. More validation data from other radar pairs with different mutual distances as well as gauge-radar comparisons are under construction. Composite images of accumulated precipitation from the whole network of 7 radars show clear improvement in longer ranges.

## 4. CONCLUSIONS

The work performed so far proves nicely that the sampling bias in radar-based surface estimates of precipitation due to VPR at longer ranges is much larger than any other error in a well calibrated system. As the magnitude of the VPR corrections in the Finnish climate are huge (5 - 30 dB) at longer operational measurement ranges, especially in snowfall, the impact of the correction is significant for any customer applying quantitative or even semi-quantitative radar based precipitation measurements (both dBZ and accumulated ones). It is to be expected that the fully operational implementation of the VPR correction scheme will result to much better performance of radar data at longer ranges and thus extend the quantitatively good radar coverage significantly. The method developed at FMI has the novel features that it classifies automatically in real time the type of the vertical reflectivity profiles, makes an objective quality weigting for them and integrates climatological and measured profiles to a continuous VPR correction field covering a network of radars. The climatological statistics of the properties of the measured VPR are useful for many purposes.

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