CARPE DIEM

Critical **A**ssessment of available **R**adar **P**recipitation **E**stimation techniques and **D**evelopment of **I**nnovative approaches for **E**nvironmental **M**anagement

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Improvement of radar derived surface precipitation using integrated VPR correction from a radar network and from a NWP model

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1. *Introduction*

The surface estimate of precipitation pattern based on radar reflectivity algorithms suffers from variations in both hydrometeors water phase (i.e. the dielectric factor) and their vertical distributions. This is valid especially in cold climates where rain, snow and sleet are always present in the 3D volumetric radar data. This WP concentrates on the reduction of sampling differences between the real surface precipitation and that estimated from the radar sample aloft. Combined correction algorithms which take into account radar data, surface observations and NWP model fields were created and implemented to the operational radar product generation at FMI. These products are applied, among others, by the End Users of FMI, i.e. Kemijoki Oy (for hydrological purposes) and the Finnish Road Authority (for optimizing prevention actions against slippery conditions due to snowfall).

2. *Applied methodologies*

The Work has been organised following this logical steps:

- The impact of attenuation correction considering the actual 3D water phase distribution**.**
- Diagnosis and elimination of long range precipitation errors due to overhanging precipitation not reaching the ground.
- The impact of variations in the vertical profile of reflectivity (VPR).

3. *Scientific achievements*

Reflectivity data from 7 C-band Doppler radars (>500 000 VPRs), temperature data from 3 sounding stations and data from the high resolution NWP model HIRLAM were used. Figures 1 and 2 exhibit example VPRs. The following methods were created.

Automatic real time diagnosis of the type and quality of each measured VPR. Applies the shape of VPR measured close to the radars (2 - 40 km) and time-space interpolated freezing level height at radar sites from 3 sounding stations and from the NWP model HIRLAM. Main methods are to pass ground reaching precipitation profiles to the VPR correction scheme and give a quality weight, denoted as w_q in Figures 1-2, for each measured precipitation profile (quality ~ height scaled precipitation volume).

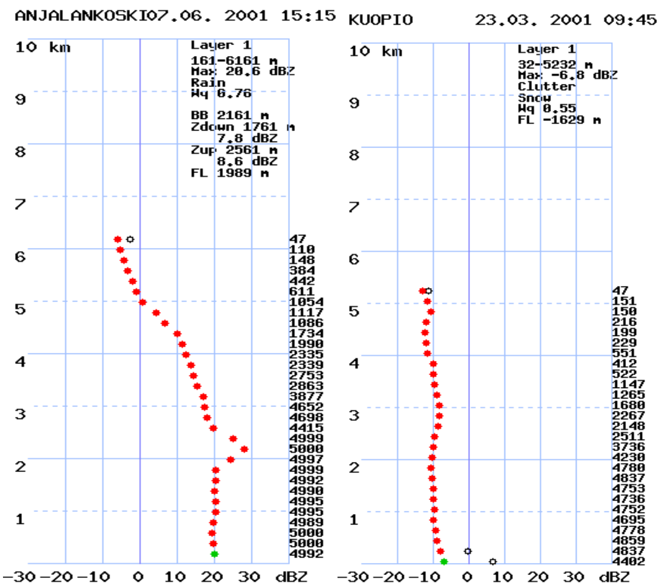

Fig. 1 – Typical rain profile with bright band and snow profile with clutter.

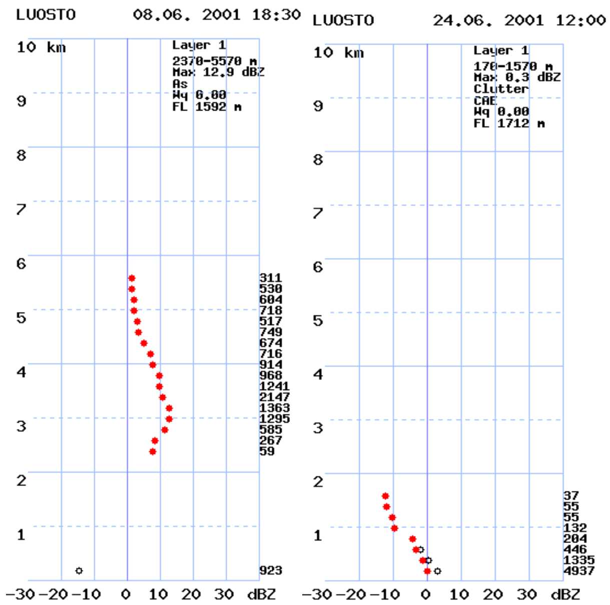

Fig. 2 – Typical VPRs of overhanging precipitation and clear air echo.

In two and a half year long period of radar data (556 471 VPRs) 49 % of all VPRs represented clear air echo, 11 % overhanging precipitation (OP) and no precipitation at ground, 4 % precipitation at ground and a second layer of OP, 19 % snowfall at ground, 14 % rain and 3 % sleet. A classification scheme is crucial for a working VPR correction scheme as only 40 % of all observed profiles represent precipitation reaching the ground level. Therefore we set the following methods: 1- To derive climatologically representative VPRs from a very large radar sample. 2- To create objective quality controlled mixing algorithm of climatological and measured VPRs. The relative weight of each climatological VPR is constant (0,2). (more details in Koistinen and Pohjola 2003), Fig. 3.

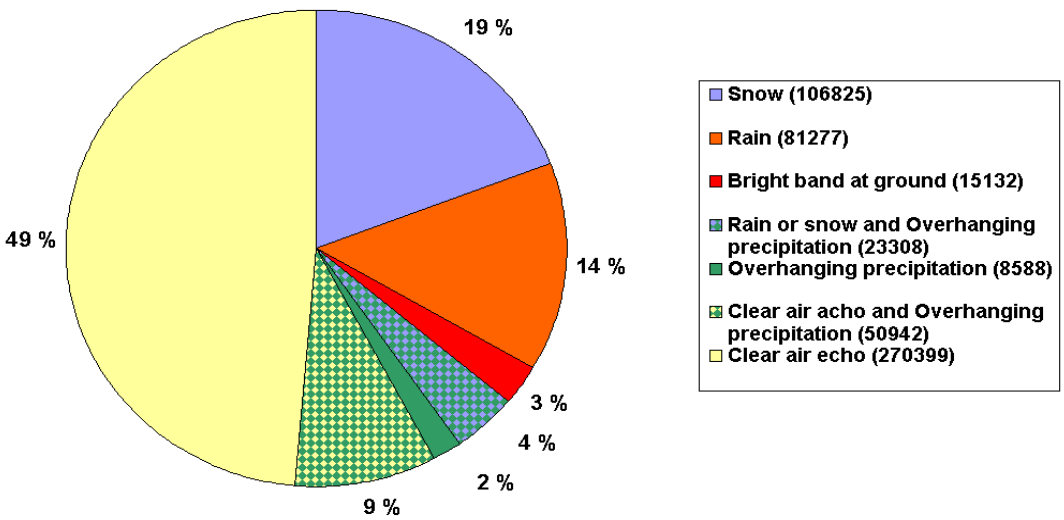

Fig. 3 – Frequency distribution of all VPR classes in the measured data.

Climatological profiles for snow and rain based on precipitation profiles from March 2001 to August 2003 are shown in Figure 4. The height of the bright band varies with the actual freezing level altitude.

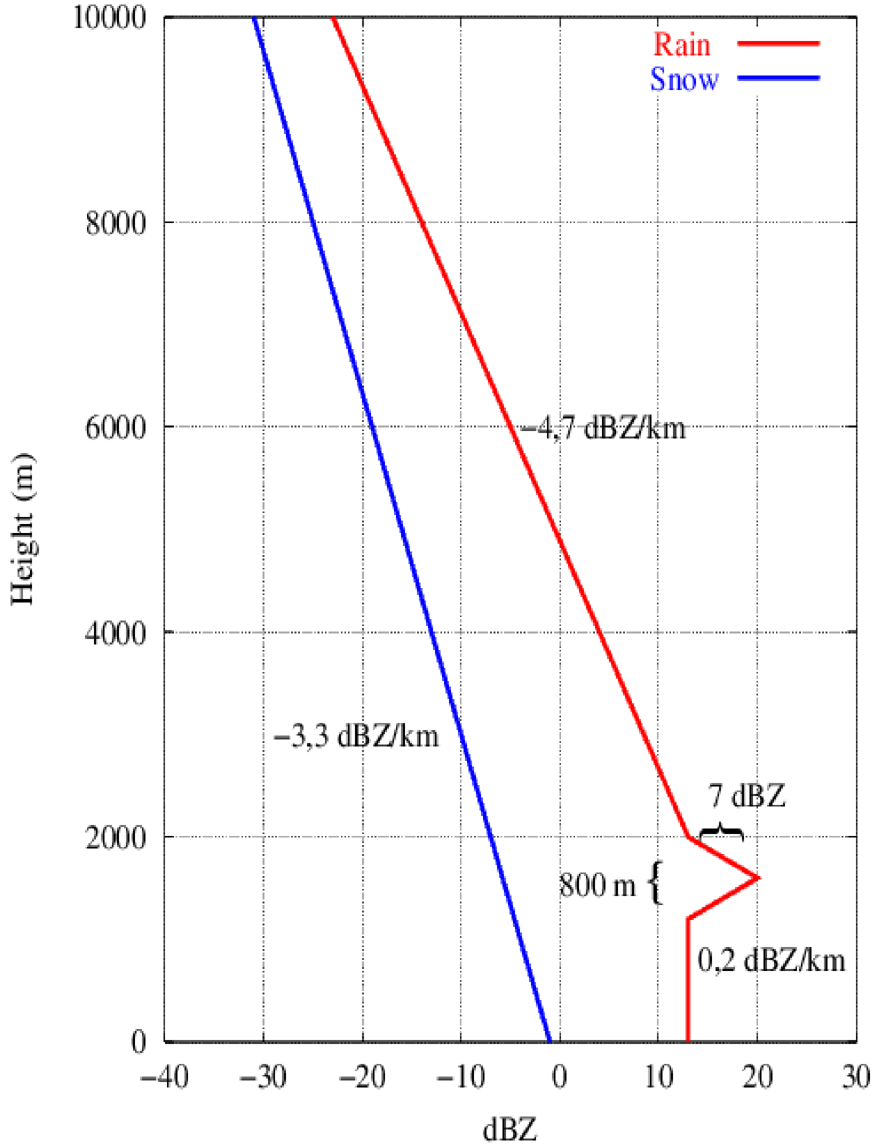

Fig. 4 – Climatological profiles for snow and rain based on precipitation profiles from March 2001 to August 2003. Note that only shape, not the actual dBZ values do effect on the magnitude of the VPR correction.

A VPR correction scheme in a radar network, based on radar and NWP data. This scheme was implemented to a operational test production in the network of the 7 FMI radars in November 2004. Figure 5 shows the data flow structure of the method and Figure 6 the scientific basis of it.

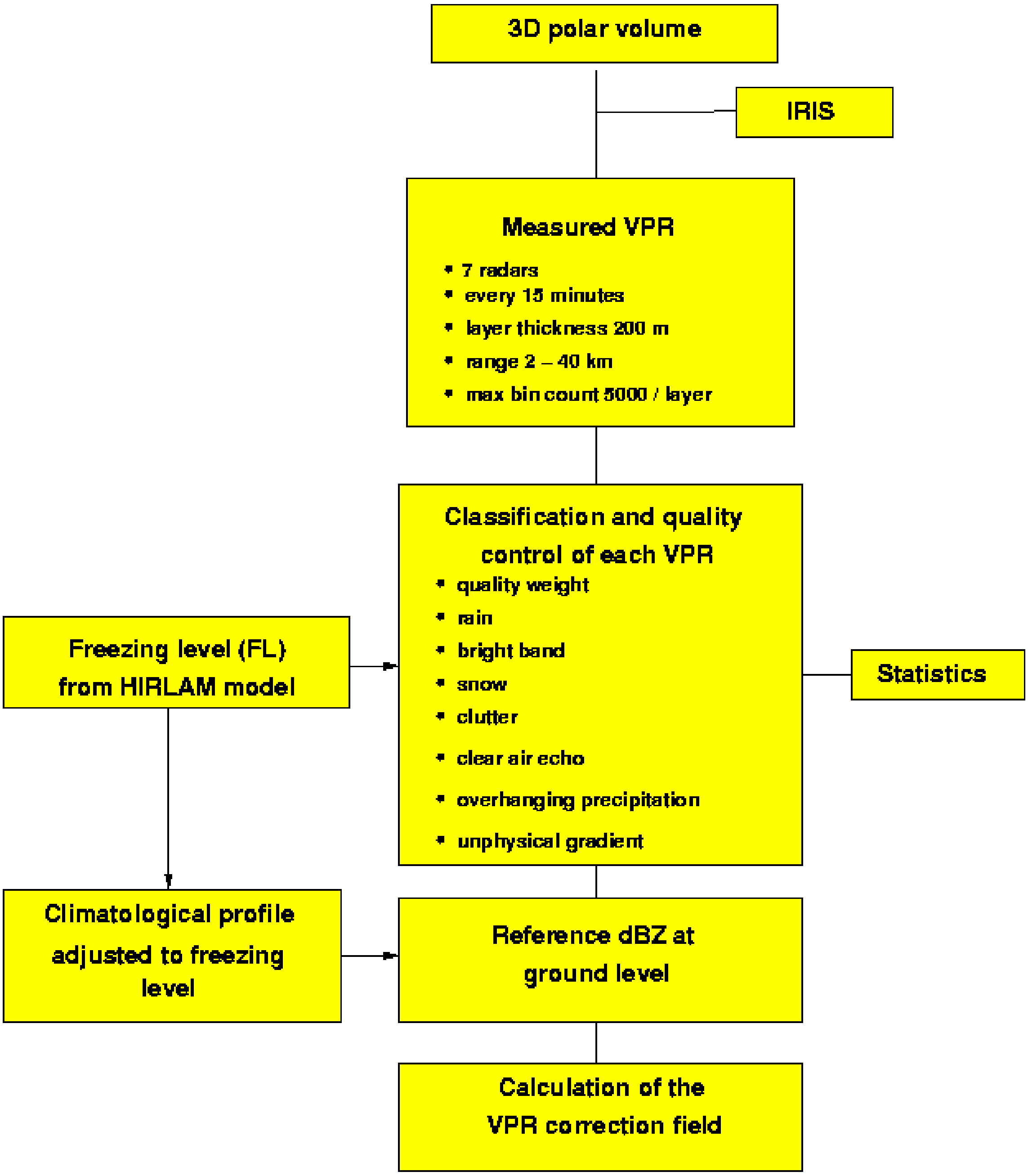

Fig. 5 – VPR correction steps in the radar network of Finnish Meteorological Institute.

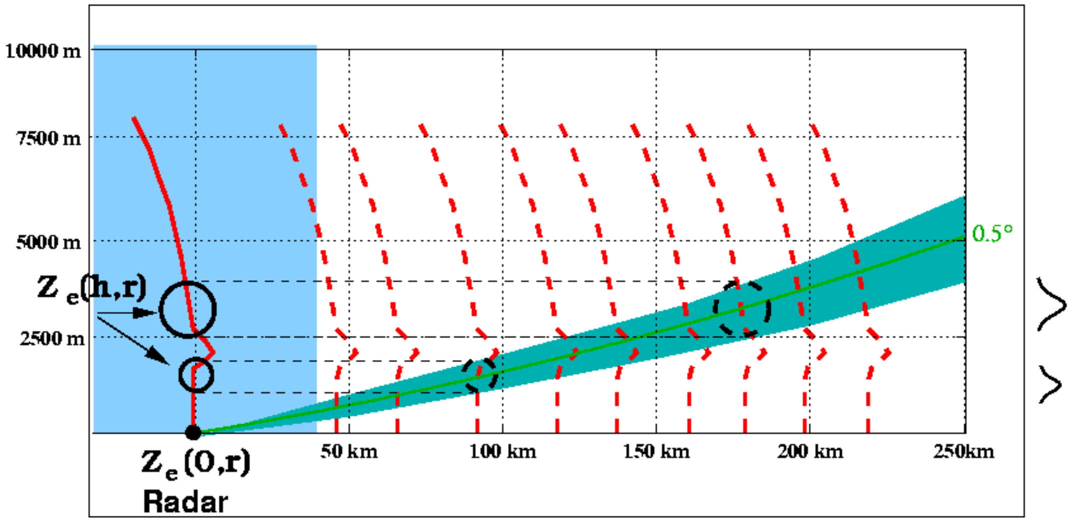

Fig. 6 – The VPR correction method principle in a single radar case. The correction factor S(dB) is the ratio of the reflectivity at ground level Z_e (0,r), obtained from the VPR measured in the light blue subvolume, to the measured beam-smoothed lowest elevation reflectivity Z_e (h,r) also obtained from the measured VPR in the subvolume but moved to distance r. The red curve represents schematically locations of the moved VPR. Two examples of Z_e (h,r) correspond measured reflectivities at ranges 90 km and at 160 km from the radar, respectively.

The single radar correction factor S (dB) is the ratio between the reflectivity at ground level Ze (0,r) and the beam smoothed lowest elevation reflectivity Z_e (h,r) according to equation 1.

$$S = 10 \log \frac{Z_e(0,r)}{Z_e(h,r)} \tag{1}$$

Then we developed probably the first real time VPR correction factor field scheme in a radar network. It does not enhance existing reflectivity level steps (due to possible calibration errors or elevation angle differences) at the composite "seams" separating data from neighbouring radars. The method takes into account the following issues, when the correction factor S for each composite pixel of dBZ is generated:

At each radar any instantaneous VPR correction S(r,t) in dB-units, where r is range from the radar and t is the starting time moment of a 3D radar scan, is a weighted average of the correction based on the quality weighted, measured VPR and on the climatological VPR. Climatological profile is adjusted to the height of the actual freezing level. Correction is based only on the climatological VPR in cases when no qualified reflectivity profile is measurable at ranges 2 - 40 km from a radar.

As measurements extend to the range of 250 km from the radars, the instantaneous VPR corrections S(r,t) are transformed more representative in the whole single radar coverage area by averaging 25 latest corrections S(r,t) from the last 6 hours applying linear weight: the older is the correction the less is the weight. Six hours comes from the fact that with an average velocity 10 m/s if takes roughly 6 hours of a VPR to move across a single radar coverage area.

At each composite pixel the reflectivity is taken from the nearest radar dBZ(r,t). The correction factor at that point is the spatially weighted average of the instantaneous correction factors from all radars within 300 km from the pixel, <S(h,t)>, where h is the height where the lowest beam from each radar hits the height from where the data dBZ(r,t) is taken. The spatial weight is proportional to 1 - (R**2/300**2), where R is distance to each radar (in case of the nearest radar R=r).

The corrected reflectivity, dBZ(r,t) + <S(h,t)>, is not allowed to exceed preselected dBZ-thresholds, which depend on the actual precipitation water phase at ground level obtained from an operational analysis based on zero level height temperature and relative humidity.

The climatological average magnitude of the VPR correction has been calculated applying 96 000 precipitation VPRs from a one year long period in Finland, Fig. 7. In rainfall the correction is < 3 dB up to range 160 km and exceeds 10 db at 210 km. In sleet and in snowfall the correction is larger than 3 dB beyond the range 90 km, exceeds 10 dB at 160 km and 20 dB at 220 km. It can be seen that the climatological rain profile is representative but the snow profile shape should be modified.

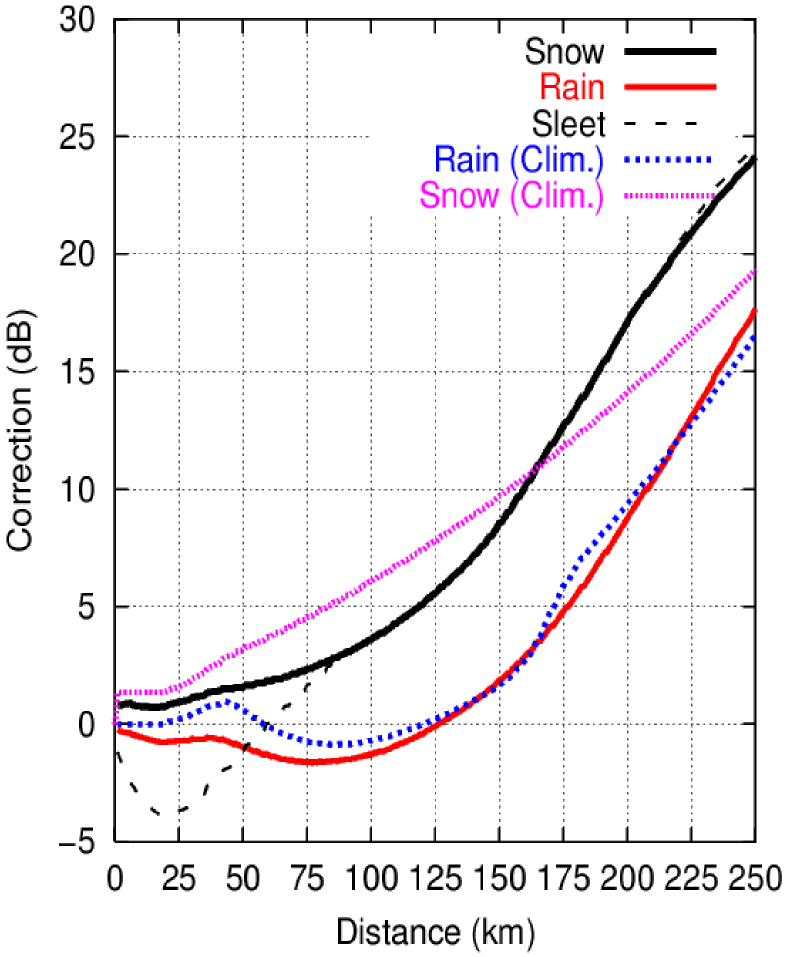

Fig. 7. – Yearly average VPR correction based on all measured profiles (Snow, Rain, Sleet) and on the climatological profiles (Clim.)

Figure 8 shows how nicely climatological profile based on freezing level height from NWP model HIRLAM fits with observed profile measured at the same time. Also the bright band of the climatological profile looks very much like the observed one. In this situation freezing level height is descending during a couple of hours. Freezing level height is updated applying one hour steps at zero hours from the NWP model HIRLAM.

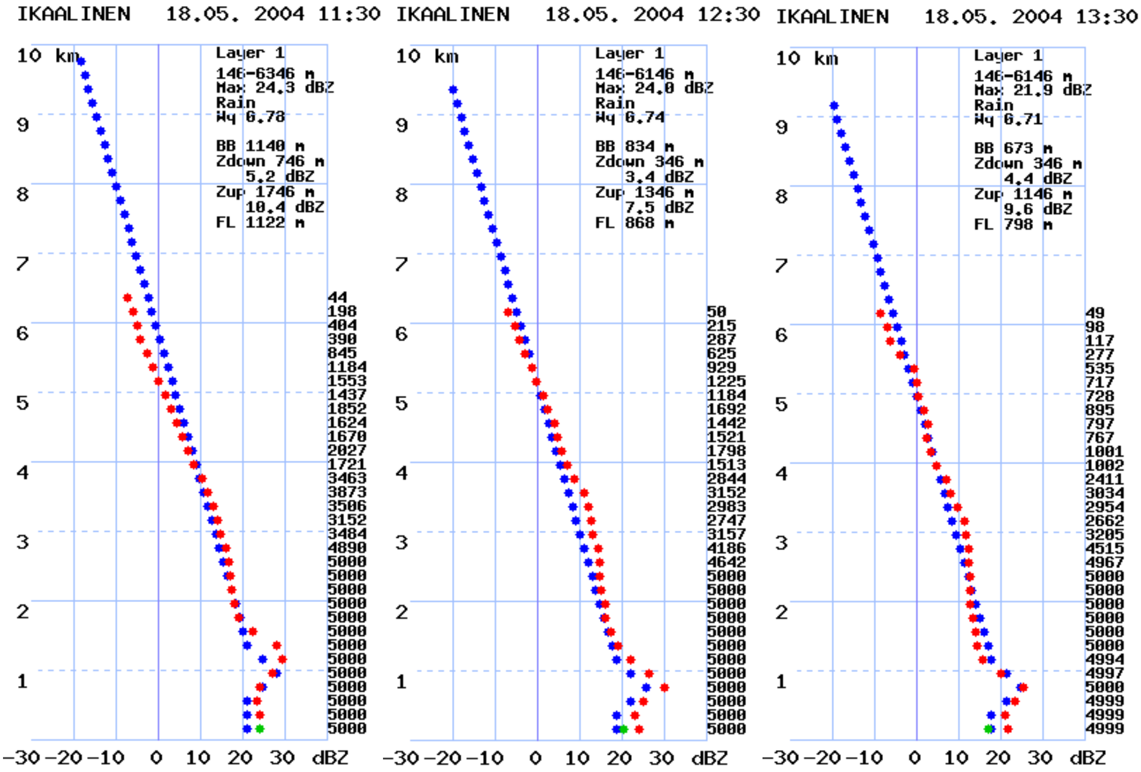

Fig. 8 – Measured VPR (red) and climatological VPR (blue) based on freezing level height from NWP model HIRLAM measured at Ikaalinen radar.

Method for actual precipitation water phase at ground level is based on 3D temperature and relative humidity from the HIRLAM model. It is very important for VPR correction algorithm to know correct water phase especially near the ground to separate similar looking bright band and ground clutter cases of each other. VPR correction may be dramatically different in bright band or ground clutter cases. The software obtaining the 3D distribution of temperature and relative humidity has been implemented for the diagnosis of the 3D hydrometeor water phase, Figs. 9 and 10.

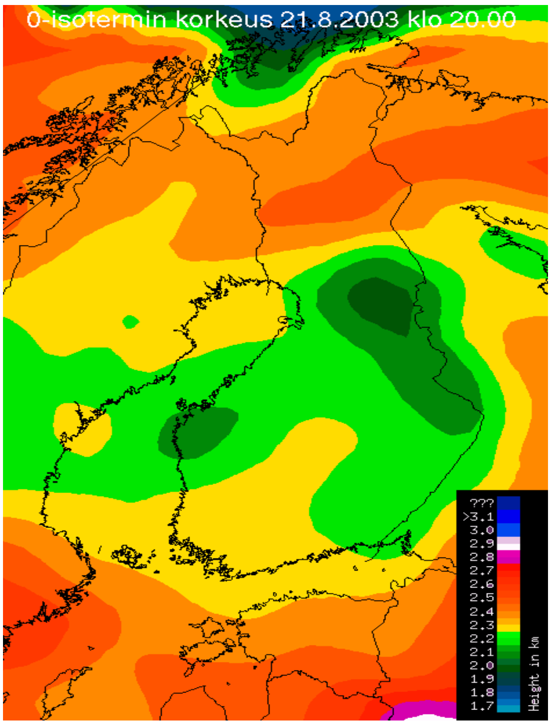

Fig. 9 – An example of the freezing level height field from the NWP model HIRLAM.

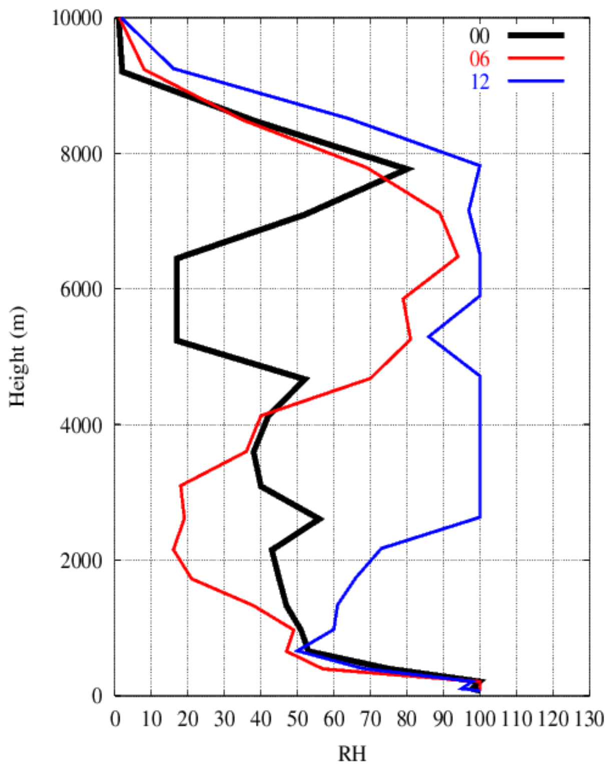

Fig. 10 – An example of the vertical distribution of relative humidity obtained from the NWP model HIRLAM at the radar site Utajärvi during a period of OP.

Validation of the surface precipitation product, obtained applying the VPR correction scheme has been done with overlapping radar pairs. Optimally, when the VPR correction has been performed for the lowest elevation data from radar 1 (Rad 1) at range r, the corrected dBZ should be equal to the measured reflectivity at radar 2 (Rad 2), located at range r from radar 1. Data from radar 2 at very short ranges is obtained practically at ground level. This method is shown in Fig. 11. Using data bins in the circular area between 5 - 15 km from radar 2 and respective bins from radar 1 we can calculate the average bias C (eq. 2) in radar 1:

$$C(dB) = dBZ(Rad1) - dBZ(Rad2) \qquad (2)$$

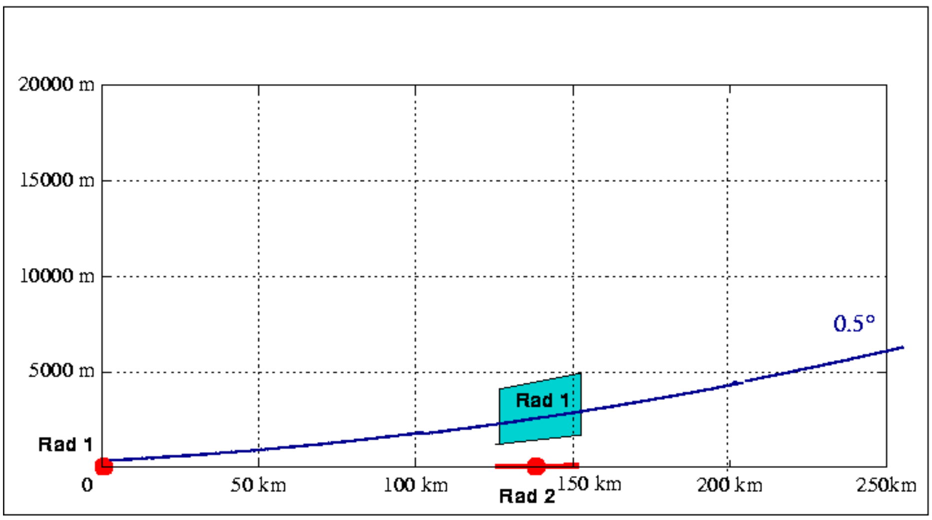

Fig. 11 – The validation method of the VPR correction based on radar pairs in the radar network of FMI.

Validation of the VPR correction scheme has been performed applying all possible radar pairs in the radar network of FMI. Average bias C before and after the VPR correction from February 2003 to November 2003 is shown in Table 1. Removal of the large bias shows that VPR correction works very well. At short distances the bias in dBZ is about -3 dB which means that correction factor for precipitation intensity aloft versus that at surface is 1,8. When bias is about -12 dB at longer distances the correction factor is 5-6. Standard deviation is about 5 dB for all distances before and after correction. This proves that the method does not enhance random errors. The radar pair validation method seems to be sensitive to calibration and antenna's angle problems between radars. This is for example the reason for the lower bias in the case of radar pair KUO-ANJ compared to the mirror pair ANJ-KUO in Table 1.

Table 1 – Average bias before and after VPR correction from February 2003 to May 2003.

Radar pair	Distance (km)	Avg bias C (dB)	Avg bias C after correction (dB)	Std. Dev. (dB)	Std. Dev. after correction (dB)
ANJ-VAN	141	-5,74	-0,02	5,45	4,41
VAN-ANJ	141	-3,77	1,33	4,16	4,73
KOR-VAN	180	-6,72	2,15	5,65	4,67
VAN-KOR	180	-8,40	0,57	4,65	4,67
IKA-VAN	193	-8,32	1,05	5,07	4,77
VAN-IKA	193	-10,07	-0,27	4,94	5,65
IKA-KOR	198	-6,63	1,35	5,88	4,61
KOR-IKA	198	-9,65	1,78	5,11	5,43
KUO-UTA	219	-12,13	1,42	4,48	5,45
UTA-KUO	219	-12,92	0,19	4,76	5,50
ANJ-KUO	219	-12,86	1,41	4,81	5,16
KUO-ANJ	219	-7,21	3,27	4,97	4,89

Validation with rain gauges has been performed applying 375 WMO weather stations in Finland from 1st of April to 3rd of June 2004 and from 12th of June to 20th of October 2004. The measured 24 hour accumulated precipitation was compared to accumulation calculated from radar data. Validation contains all gauge observations in which accumulated precipitation was more than 1 mm/24 hour. Total number of the data was 18903 observations that were shared according to the range from radar as is shown in Table 2. Up to 150 km VPR correction factor seems to be small but for ranges 150-250 km from the radar correction factor is remarkable. Validation with rain gauges confirms the radar pair validation shown in Table 1: VPR correction works very well removing the large bias between radar and gauge accumulations.

Validation of the VPR correction scheme with rain gauges has been performed applying 375 WMO weather stations in Finland from the 1st of April to the 3rd of June 2004 and from the12th of June to the 20th of October 2004. The measured 24 hour accumulated precipitation was compared to accumulation calculated from radar data. Validation contains all gauge observations in which accumulated precipitation was more than 1 mm/24 hour. We can calculate average bias P from equation 3

$$P(dB) = R_p(dB) - R_g(dB) \qquad (3)$$

, where R_g is the accumulated precipitation in dB measured by rain gauges and R_p is the accumulated precipitation in dB measured by radars.

Total number of the data was 18903 observations that were stratified according to the range from radar as it is shown in Table 2. Up to 150 km VPR correction factor seems to be small but for ranges 150-250 km from the radar correction factor is remarkable. Standard deviation is larger at longer distances, which is to be expected as the magnitude of hydrometeor growth, size sorting and horizontal drifting due to shear vary more when the distance between the radar bin and the reference gauge is longest. Validation with rain gauges confirms the radar pair validation shown in the previous yearly report: VPR correction works very well removing the large bias between radar and gauge accumulations. As a conclusion it can be said that method is a major improvement to the quantitative accuracy of weather radars at longer distances.

Table. 2 – Validation of the VPR correction scheme applying rain gauges. Average radar/gauge bias and standard deviation before and after VPR correction from the 1st of April to the 3rd of June 2004 and from the 12th of June to the 20th of October 2004.

Range (km)	Number of observations	Avg bias P (dB)	Avg bias P after correction (dB)	Std. Dev. (dB)	Std. Dev. after correction (dB)
0-50	2609	-0,50	1,14	7,21	7,44
51-100	8281	-0,06	0,97	7,04	7,60
101-150	5725	-2,02	0,03	8,11	8,38
151-200	2045	-7,49	-0.82	9,64	8,46
201-250	243	-14,52	-2,09	10,10	9,67

4. *Main deliverables*

As the magnitude of the VPR corrections in any cold climate or in the winter time cold climates are huge (5 - 30 dB) at longer operational measurement ranges, 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). The operational implementation of the VPR correction scheme results to much better performance of radar data at longer ranges and thus extends the quantitatively good radar coverage significantly. Such improvement can directly affect on the reliability and accuracy of End User operations. Less dense C-band radar networks can also save investment costs.

The work performed proves nicely that the 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. Especially in a cold climate a VPR correction at longer ranges is necessary in all QPE. Any hydrological application aimed e.g. for flood prevention should always ensure that at longer ranges the VPR correction should be performed. Otherwise a significant underestimation of the river flow can follow. The existing version of the VPR classification and correction scheme developed in CARPE DIEM is already an outstanding deliverable, both scientifically and for any operational radar system, which was also supported by the End Users of FMI at the National End User Meeting in February 2003.

Acronyms and abbreviations

Acronym	Explanation
CWC	Cloud Water Content
FMI	Finnish Meteorological Institute
HIRLAM	HIgh Resolution Limited Area Model
MSC	Mesoscale Convective complex
NWP	Numerical Weather Prediction
OP	Overhanging Precipitation
PPI	Plan Position Indicator
QPE	Quantitative Precipitation Estimation
RH	Relative Humidity
VPR	Vertical Reflectivity Profile
WMO	World Meteorological Organization