5B.7 QUANTITATIVE ASPECTS OF CLUTTER HIGHPASS FILTERING AS USED BY DWD

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1 INTRODUCTION

Clutter removal in weather radar images using digital highpass filters in the time or spectral signal spaces has become a standard tool in routine networks as operated in Germany by DWD, the German Meteorological Service. However, clutter mitigation techniques have mainly been focussed on qualitative clutter suppression. This paper is to highlight the quantitative improvement by clutter correction in radar precipitation amount and in radial wind using calculations based on model and operational radar data.

2 QUANTITATIVE CLUTTER CORRECTION

2.1 LOG IIR-, Doppler IIR- And Fourier Filters

With raw signal clutter filtering, highpass filters are applied in order to estimate the relative clutter power CCOR. While this may be used to suppress cluttered pixels, 'active' correction is additionally implemented in the DWD processors to recover some of them (Sigmet, 1996): corr. Z [dBZ] = uncorr. Z [dBZ] - CCOR [dB].

Either IIR time series filters of fourth order (stop band depth 40 dB, width 3 to 14 % of the Nyquist interval V_N, for table see fig. 6), or Fourier filters removing one to 13 spectral points around zero velocity and adaptively interpolating the gap, are being used on Doppler Radars, third order IIR filters on non-Doppler amplitude series.

2.2 Dependence On Antenna Azimuth Rate

While theoretically determined by filter and target characteristics, system coherency and LinAmp dynamic range, not all of them known, the dependence of available clutter reduction on scan parameters such as PRF and antenna azimuth rate is of equal practical interest. Viz., clutter suppression approaching the theoretical filter depth can only be achieved with a slowly rotating antenna. The dependence of CCOR on scan rate is shown by way of example in fig. 1.

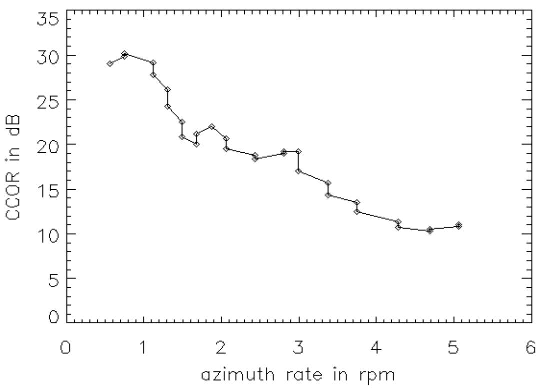

Fig. 1. *Efficiency of clutter filtering depends on scan rate. When azimuth rate was increased from 0.6 to 5.1 rpm, clutter correction on a pure clutter target (Zugspitze mountain) decreased from 30 dB to 10 dB, approximately, for IIR-filter #2.*

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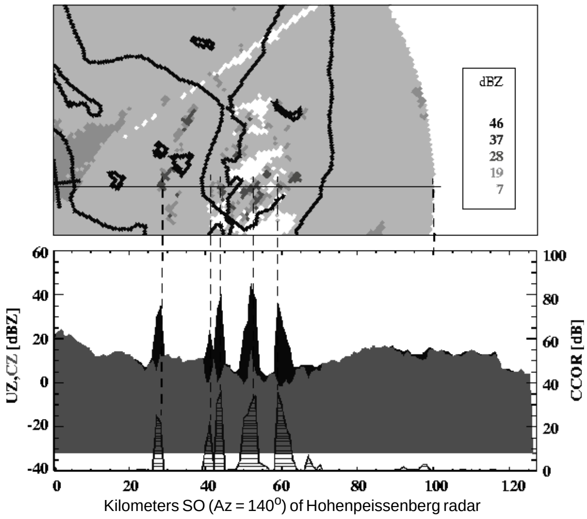

Fig. 2. *Quantitative IIR Doppler filtering with rotating antenna (1.9 rpm, 600 Hz). In the upper part, clutter embedded in a precipitation field can be seen in a cut-out from the uncorrected dBZ product. The thin black line marks the radar's line of sight over the Karwendel mountains. Below, a section along this line is presented with the corrected dBZ value (gray, IIR filter #2), underlaid by its uncorrected counterpart (black), together with their difference (hatched, right scale). The mountain clutter is suppressed, restoring the precipitation field without producing "holes", and no or very low correction occurs in precipitation.*

2.3 IIR Filter Reflectivity Losses

Even though the filters' clutter suppression capabilities have been proven before (Seltmann & Riedl, 1999), the question arises to what extent precipitation is damped, too.

Fig. 2 is to demonstrate the effective removal of the clutter fraction under operational conditions (scan rate 1.9 rpm, IIR-filter), while precipitation is preserved. In general, with both kinds of Doppler filters, an overwhelming majority of pixels is left unchanged, followed in

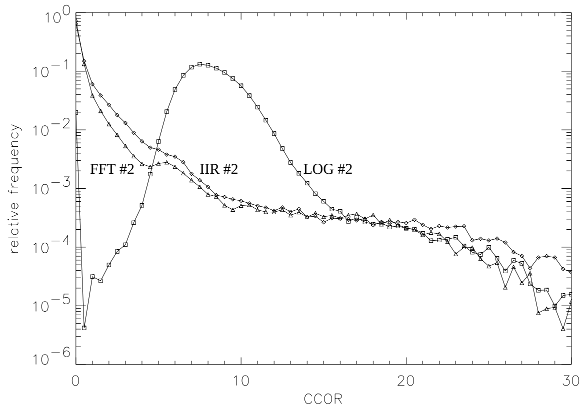

Fig. 3. *Frequency of relative clutter corrections in a rain event of March 09, 2001; PRF = 600 Hz, six PPIs accumulated. While for Doppler filters (IIR and FFT), most pixels are not corrected and the frequency of higher corrections drops sharply, the LOG filter's frequency maximum at 7.5 dB is higher than its value at 0 dB by a facor of 10, causing intolerable losses in precipitation.*

number by those corrected by 0.5 to 1 dB, see fig. 3. For uncoherent LOG filtering (#2), there is a pronounced frequency maximum at CCOR = 7.5 dB. In the case considered there, areal rain totals using DWD standard Z/R relation were 48% for IIR-filter, 43% for FFT filter, and 12% for LOG-filter, if the respective uncorrected totals (including clutter) were set to100%. Therefore, LOG amplitude filters at a PRF of 600 Hz are considered too aggressive towards precipitation to be applied for quantitative correction but may be used to threshold uncorrected data.

2.4 Reflectivity Losses Vs Velocity

Even if clutter is not present, IIR-filters will nevertheless cut out their portion of signal power whenever the precipitation spectrum and IIR-filter notch overlap, e.g. with the radar beam tangential to the drop motion, or when velocity folding occurs, giving rise to a loss of measured precipitation power (see also 3.2 and 3.4). The frequency distribution of a given amount of clutter correction over estimated velocity v' is given in fig. 4.

If this plot is differentiated between South (alps) and North (low clutter if any), the zero correction curve is shifted further upward in the North (and downward in the South), and high corrections (> 5dB) are concentrated around zero velocity in the North, but more spread in the South due to precipitation velocities retrieved under clutter conditions.

If Fourier interpolation filters are applied, the general picture is much the same, but zero correction around zero velocity occurs more often (the 0 dB curve is shallower), and medium corrections (1.5 ... 5 dB) are much rarer than low ones (frequency of 0.5 plus 1 dB correction surpasses that of 1.5 +...+ 5 dB correction).

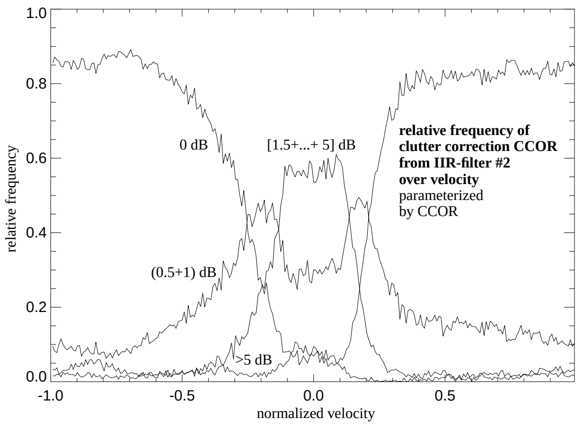

Fig. 4. *Clutter correction CCOR as a function of (filtered) velocity, valid for Doppler filter #2. The figure shows the total (including both clutter and precipitation) frequency distribution from a real case (March 9, 2001, widespread rain, 600 Hz, 1.9 rpm), normalized to a pixel number of one for each velocity. At high velocities, 85% of the data are not corrected at all, but 60% are 'corrected' by more than 1 dB around zero velocity.*

3 CLUTTER AND RADAR WIND

3.1 Clutter Influence On Radial Wind

Not only does a clutter peak corrupt reflectivity, but it also biases the first moment v of the Doppler spectrum in proportion to its weight. For any given mean velocity V of the precipitation spectrum, this bias tends to 0 with low CSR, is 50% at CSR = 0 dB, and increases to 100% with increasing clutter/signal-ratio. As a function of V, bias is maximum for $V = \pm V_N$. Fig. 5 shows the curve family with V as a parameter from simulator calculations (Seltmann, 2000).

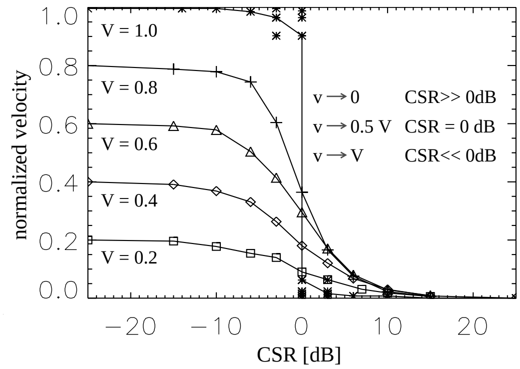

Fig. 5. *Clutter impact on retrieved velocity as a function of clutter/signal- ratio CSR from simulator calculations, parameterized by the "true" velocity V which is corrrectly retrieved at low CSR. At high CSR, clutter forces v = 0. Equal strength of clutter and precipitation signals is marked by CSR = 0 dB and thus by v = 0.5 V. A span of [-25 dB, +25 dB] is typical of real situations.*

Velocity bias, too, may be counteracted by Doppler highpass filters in the time or spectral domains, thus recovering velocity data thresholded due to bad signal quality (3.2), de-bias radial wind speed, and in turn cancel zero velocity clutter. Of course, unlike Doppler corrected reflectivity, corrected velocity is computed directly from the filtered time series via pulse pair processing (PPP).

Doppler-filtering reduces CSR so that the whole curve family of fig. 5 is shifted to the right by about the filter depth, in theory. This has been verified by model calculations of velocity retrievals from filtered time series with different filters and velocities. Even IIR filter #1 (width 3 %) is capable of recovering the correct velocity for as high a CSR as 25 dB. Practically, the achievable clutter improvement is reduced by imperfect system coherency and by antenna azimuth rate (see 2.2) in dependence of clutter and signal spectral characteristics. As is well known, 25 dB or even 30 dB of clutter suppression are realistic with magnetron radars.

The shift of CSR for adaptive FFT filtering is similar. Up to high CSR, the model input velocity is retrieved correctly by whatever filter width may be chosen except for filter #1 which cannot perform sufficient clutter reduction removing but one spectral point.

Generally speaking, the retrieved velocity v' is less susceptible towards filter tuning over the major part of the Nyquist interval than is reflectivity correction, as only the spectral mass center, not a calibrated integral is calculated.

3.2 Signal Quality Index And Clutter Filter

The bimodal Doppler spectrum produced by clutter plus precipitation spectra violates the gaussian assumption underlying the concept of a mean velocity. This is expressed in a reduced signal quality index SQI (= power normalized modulus of the autocorrelation at lag one). With CSR = 0 dB, SQI even tends towards zero as V approaches unity, the retrieved velocity v becomes pure noise because both complex components (clutter and precipitation signal) of the vector sum v are directed opposite (+1 and -1), and any value may be measured between the folding boundaries $\pm v_N$. SQI is used to threshold against such uncoherent (SQI = 0) signals. Thus, bimodal spectra may be lost through thresholding for SQI; if filtered, the remaining monomodal spectrum of precipitation will pass the SQI test. In turn, having a high SQI, clutter without or largely surpassing rain is also considered valid data but filtered clutter may not, because filtering will correctly reduce SQI if no weather is present.

3.3 Clear Air Echoes

These are not an issue with clutter suppression in reflectivity measurement, but velocity is sometimes taken from clear air. In this case, due to the low target reflectivity, CSR is large even for side lobes ground clutter which contaminates vast areas close to the radar site. Thus, by virtue of fig.5, clear air velocities are seriously affected by clutter, and major improvement can be achieved by highpass filtering, see 3.5 and fig. 7 for an example in which velocity is improved by a factor of three.

3.4 IIR Filter Velocity Bias

Whenever the filter notch asymmetrically removes part of the spectrum (see 2.3), its first moment is shifted away from zero, and the radar estimate of mean radial velocity v' will be biased (to a lesser extent than by clutter), this time towards the folding boundaries $\pm v_N$. Filter bias will be zero at high absolute values of V, but will attain a maximum on both sides of zero velocity. At zero (true) velocity V, the retrieved filtered velocity v' becomes noisier with SNR decreased by the filter and should be thresholded for bad SQI. Wider filters will deteriorate signal quality at zero velocity and expand the range around zero that will be biased. Values can be read from fig. 6; e.g., choosing one of the narrow filters (4% or even 3%) will limit filter bias to the interval [-0.1 v_N, +0.1 v_N] or even [-0.05 v_N, +0.05 v_N], while sufficiently reducing CSR. Anyhow, velocity filter bias is not overly critical as it occurs at low wind speed.

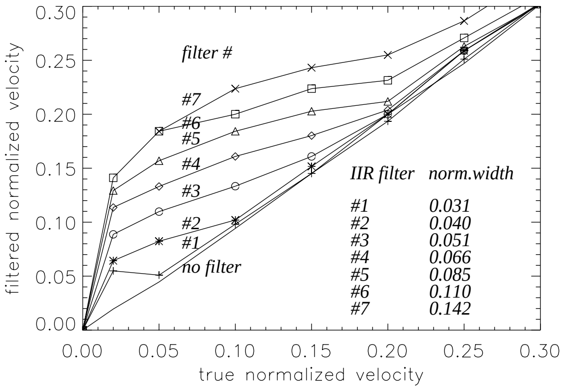

Fig. 6. *Quantitative effect of IIR-filtering simulated precipitation without clutter, showing the dependence of retrieved velocity on model input velocity for different filter widths. The retrieved velocity v' is biased towards the folding boundary whenever the signal spectrum is asymmetrically overlapped by the filter notch. For filter #1 (#2), this occurs if V < 0.05 (0.1).*

3.5 True Wind -VAD

In the well known VAD algorithm, the true wind vector is estimated from a sine fit to the radial components over some circular region. As the clutter distribution may be very inhomogeneous over this circle, the fit will be distorted by the azimuthally changing clutter bias. Thus, not only the modulus of the wind vector, but also its direction will be biased and maybe thresholded. Recovering precipitation range bins that without filtering would have been discarded and correcting valid clutter contaminated data improves true wind vector estimates and availability, as demonstrated by fig. 7.

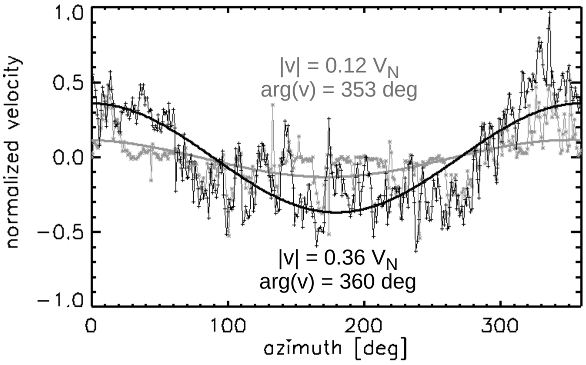

Fig. 7. *VAD sine at about 1 deg elevation, 19 km radial distance, under "clear air" conditions. The unfiltered (gray) curve with a maximum velocity $v = 0.11\ V_N$ is markedly shallower than the black one from IIR (#2) filtered data yielding a maximum velocity of $v' = 0.36\ V_N$. There is only little difference (7 deg) in wind direction because of the clutter symmetry.*

4 SUMMARY

By highpass filtering, the clutter bias CCOR in radar reflectivity measurements and hence in radar precipitation amount can be eliminated. For quantitative application, it is essential to balance against losses due to unwanted filter effects in precipitation. It was found that with both kinds of Doppler filters, most pixels are left unchanged, followed by a major number of 0.5 to 1 dB corrections which seems tolerable. In contrast, uncoherent LOG filter #2 produced a frequency maximum at CCOR = 7.5 dB and, as a consequence, but 25 % of the rain amount with respect to Doppler filters #2. Therefore, LOG amplitude filters are considered too aggressive towards precipitation to be applied for quantitative correction at 600 Hz but may be used to threshold uncorrected data. If feasible, FFT is recommended with a slowly revolving antenna at a constant PRF.

The number frequency of Doppler clutter correction as a function of velocity is over 85% at high velocities with a notch at V=0, where 60% are corrected by more than 1 dB, most of them pertaining to precipition with zero velocity (tangential and folded included).

Clutter also biases precipitation velocity v. At high CSR (~ 15 dB), clutter forces v = 0. At CSR ~ -15 dB, the correct velocity is retrieved. By Doppler filtering, CSR can be reduced by theoretically the filter width, in practice, efficiency of clutter filtering depends on scan rate and may well decrease from 30 dB at 0.6 rpm to 10 dB at 5.1 rpm for a pure clutter target. As clear air echoes have a high CSR, radial wind can easily be improved by a factor of 3. VAD wind direction is corrected, too.

On the other hand, a velocity bias may arise at low mean precipitation velocity, but this will not occur beyond the interval $\pm\ 0.1\ V_N$ for the two narrower filters.

5 REFERENCES

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