7.6 EVALUATION OF FM PULSE COMPRESSION FOR WEATHER RADARS

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1. INTRODUCTION

A radar using a Pulse compression waveform system transmits modulated (coded) long pulses and compresses the corresponding echo signals, resulting in finer range resolution and higher effective peak power. Frequency and phase modulation are typically used; For a given range resolution, pulse compression results in increased sensitivity. In a weather radar system pulse compression provides the possibility of obtaining lower measurement errors due to signal fading more rapidly than what is possible by non-modulated pulses. As a result, pulse compression yields estimates that are as accurate as conventional radar, but with a considerably smaller dwell time. This in turn facilitates the use of higher scan speeds, for instance for more rapid volumetric coverage.

Though the principles of pulse compression have been known for a long time, pulse compression has not been used widely in meteorological radars. There are two main reasons for that. First, the sensitivity and range-resolution of existing weather radars may have been adequate for most applications. Secondly, range side lobes generated with the compression, especially in the presence of strong gradients, has been a disadvantage compared to normal measurements. However it is demonstrated that range side lobes may be suppressed considerably using new techniques (Mudukutore et al. 1998; Keeler et al. 1999).

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The most important advantages of pulse compression for weather radars, depending upon how they are used are:

1) Increasing the effective peak power and sensitivity for a given resolution
2) Increasing range resolution
3) Increasing scan speed

Pulse compression techniques have recently become more attractive, as demands for lower average power, higher sensitivity and higher scanning speed without compromising resolution have increased. The purpose of this paper is to evaluate the Piecewise Linear Frequency Modulated Pulse Compression (FMPC) developed by Chandrasekar et al. (2004), (O'Hora and Bech 2005) using the coherent polarimetric C-band weather radar of the University of Helsinki. The ability of FMPC in increasing effective power and sensitivity, as well as producing good quality estimates of radar measurables was discussed in Puhakka et al. (2006).

2. BACKGROUND

Accurate estimation of the average echo power received from precipitation requires a large number of independent echo samples to be averaged. For an accuracy of 1 dB about 30 such samples are needed. In order to obtain independent samples, precipitation particles should have enough time to move into independent positions between pulses. The time needed for independence depends on the relative radial velocities of the precipitation particles and on the wavelength used. At C band the time needed for independency is on the order of 10 ms (Marshall and Hitschfeld, 1953). This implies long dwell times for accurate estimates (0.3 s for an accuracy of 1 dB). Consequently, scan speeds are too slow for high resolution volume scans. For example a volume scan consisting 360 azimuth angles at 10 elevations requires at least 18 min to be measured completely. Many methods of overcoming the dwell time problem have been suggested in the past (Smith et al. 1974, Krehbiel and Brook, 1979, Keeler and Passarelli, 1990, Keeler et al. 1999, Gossard and Strauch, 1983, Koivunen and Kostinski, 1999, Torres and Zrnic, 2003).

Independent samples are obtained from a single pulse at range intervals of half of the pulse length. The simplest method of reducing dwell time is to integrate these independent range samples, but this reduces range resolution as well. A more effective advanced way of reducing dwell time by averaging independent range samples is using pulse compression. Pulse compression compresses the resolutions of the pulses into a much finer scale. As this compressed scale can be made much smaller than the typical resolution available with conventional radars, compression yields many independent samples from each single pulse decreasing thus the dwell time required for given accuracy and range resolution of estimates.

The independency of the compressed resolution volumes produced by FMPC follows from the fact, that samples from even a fixed drop population are independent if the frequency of the transmitted signal is changed at least by the amount $1/\tau$, where τ is the pulse length (Marshall and Hitschfeld, 1953). The independency is achieved since frequency change makes the phases of the signals scattered from a distributed target independent, as $1/\tau$ corresponds to one cycle (2π) within the pulse τ. As the frequency of the transmitted pulse is changed linearly by B_C during the pulse τ_l in FMPC, compressed echo signals from this pulse are independent at intervals of $\tau_C = 1/B_C$ independently of the length τ_l of the pulse. Thus the number of independent samples per range interval increases as the sizes of the resolution volumes decrease by compression.

In our study a pulse τ_l =10 µs is frequency modulated by a linear frequency change of B_C=6 MHz. The width of the compressed pulse τ_C will be now 0.167 µs and $\tau_l B_C$= 60 independent samples would be obtained from a single τ_l =10 µs pulse. In other words independent samples are available at 25 m range intervals.

In the case of a piecewise linear approximation of nonlinear FMPC the compressed pulse length will be somewhat larger and the number of independent samples lower than the theoretical maximum values above. This is due to the frequency and amplitude tapering of the pulses transmitted, needed to suppress the range time side lobes (Chandrasekar et al. 2004). According to O'Hora and Keeler (2006) this filtering may increase the compressed pulse length τ_C by a factor of 1.5 roughly. According to theoretical calculations made for our radar system (Chandrasekar 2007, personal communication) this factor seems to be about 1.2. In our example this means a decrease in range resolution from 25 m to 30 m, and a decrease in the number of independent samples obtained using FMPC by an additional factor of about 0.83.

Furthermore, all independent samples obtained by FMPC from a single long pulse, cannot necessarily be used to improve the accuracy of reflectivity estimates as the samples should represent the precipitation at some suitable range resolution. In the above example, for instance, perhaps some 6-12 compressed 25 m samples can be integrated from each single pulse in order to keep the range resolution around 1-2 µs.

If we aim to 150 m range resolution corresponding to 1 µs pulse, FMPC with B_C=6 MHz gives 6 independent 25 m samples for each 150 m (1 µs) range interval from one pulse. As only one (or less) independent sample is obtained from one pulse with normal measurements, FMCP could in principle increase scan speed at least by

Table 1. Main parameters used in the measurements.

	Pulse width (μs)	FM band-width (MHz)	Range resolution (m)	PRF (Hz)	Sample size (pulses)
NM (normal)	2.3	-	345	350	512
FMPC (compr.)	10	6	25	350	512

a factor of 6. With the side lobe suppression filter the increase would still be at least 5 fold. In the present study we compare FMPC results with normal measurements where pulse length 345 m (2.3 μs) is used. If we aim to this final resolution FMPC can in principle increase scan speed by a factor of about 11.

For velocity estimates at least two consecutive pulses are needed with pulse compression (Gossard and Strauch, 1983) while normal measurements require several pulses. This condition is already met in the above example, since at least 3 pulses are required with FMPC for a reasonable estimate of reflectivity. Thus velocity estimation would not change the result with respect to the increase of scan speed. It should also be noted, that for velocity estimation, the pulses should not be independent. Thus for velocity estimation we have to transmit pulses at a higher PRF than what would be needed for reflectivity processing. As a consequence, 4 or even more pulses will be available for velocity estimation in the case of above theoretical example.

3. MEASUREMENTS AND ANALYSIS

3.1 Radar and Measurements

Description of the University of Helsinki full coherent polarimetric radar is given by Puhakka et al. (2006). The paper describes also the method of calibration used with FMPC as well as the results related to the increase in sensitivity due to FMPC. As for the pulse compression, the main features of the radar are the high duty cycle of about 0.004, and the piecewise linear FMPC implemented in the system. The high duty cycle makes it possible to use relatively long pulses even with reasonable high PRF's. FMPC is explained in more details by O'Hora and Bech (2005).

In order to compare signal statistics in compressed and non compressed measurements, pulse to pulse samples are needed. As the time interval between the FMPC and the corresponding normal measurement (NM) should be as short as possible, pairs of NM- and FMPC measurement taken from fixed direction were used. Parameters used in the normal measurements (NM) and the corresponding compressed measurements (FMPC) are given in Table 1.

Each measurement (either NM or FMPC) produced a data record consisting the values of the radar reflectivity factor at 25 m range intervals as well as raw values of the power received. The raw values of the power received are available separately for each pulse (i.e. 512 power values at each range), while the radar reflectivity factor at each range is estimated using the mean power obtained by averaging of the powers received from all 512 pulses (i.e. one reflectivity value at each range). The present analysis is based mainly on the raw pulse-wise values of the IF power. Time needed to switch between NM and FMPC was 1 to 2 min.

Bin spacing was set to 25 m both in NM and FMPC for convenience. In normal measurements, however, values from every 14th bin (at 350 m intervals) corresponding closely to the 345 m range resolution of the pulse length 2.3 μs were used. In FMPC the whole 25 m resolution was used. After averaging the FMPC IF power data in consecutive groups of 14 bins for each of the 512 pulses we had formally similar data records for both NM and FMPC, i.e. pulse-wise values of the power received at range intervals of 350 m.

The important difference between NM and FMPC records is that with NM the values represent instantaneous power values received from the 345 m long resolution volume of the 2.3 μs pulse, while with FMPC the values are averages of the 14 compressed consecutive 25 m long resolution volumes within each 350 m in range. As the FM bandwidth is 6 MHz compressed signals should be independent just at intervals of 25 m. Thus these one pulse estimates of the average power received obtained by FMPC should be as good as obtained by averaging echo powers from 14 consecutive independent pulses in normal measurements without range side lobe filtering. In following the method of testing this will be described.

3.2 Analysis Methods

The accuracy of the estimate of the average power is described by its standard deviation σ. If we have *N* power samples P_i, the standard deviation of an estimate consisting *k* samples can be calculated as the standard deviation of the all (*n=N/k*) different estimates available from the population *N*

$$\sigma_k = \left[\frac{\sum_{j=1}^{n} (\overline{P}_{k,j} - \overline{P})^2}{n-1} \right]^{\frac{1}{2}} \text{, where} \qquad (1)$$

$$\overline{P} = \frac{1}{N} \sum_{i=1}^{N} P_i \quad \text{, and} \qquad (2)$$

$$\overline{P}_{k,i} = \frac{1}{k} \sum_{i=1}^{k} P_{i+(j-1)\times k} \quad , \quad j = 1,2,3,...,n \qquad (3)$$

From *N*=512 pulses we can calculate *n*=256 estimates of 2 pulse averages, 128 estimates of 4 pulse averages, 64 estimates of 8 pulse averages etc. In order to improve the independence between pulses in the analysis, we may use only every second pulse for estimating averages. In this case the numbers of the estimates will also be halved. This decreases the quality of the estimates of the standard deviations with increasing values of *k*, as will be seen later.

As normal measurement and pulse compression measurement were not exactly simultaneous, the standard deviations should be normalized before comparison. This was done by dividing the standard deviations σ_k by the average power of all *N* samples. This "normalized" standard deviation is called as the relative dispersion *V* in statistics.

$$V_k = \frac{\sigma_k}{\overline{P}} \qquad (4)$$

According to Marshall and Hitschfeld (1953), the standard deviation of the estimated mean of *k'* independent values of signal power is theoretically

$$\sigma_{k'} = \frac{\overline{P}}{\sqrt{k'}} \qquad (5)$$

This means that if the *k* pulses used in estimating σ_k are independent, *k'* solved from (5) using estimated values $\overline{P}$ and σ_k, i.e.

$$k' = \left(\frac{\overline{P}}{\sigma_k} \right)^2 \qquad (6)$$

should be equal to *k*. Hence the degree of independence between samples may be estimated by comparing *k*, the actual number of samples averaged in estimating σ_k, and the corresponding value of *k'* solved from (5).

The number of pulses needed in normal measurement to reach estimates of equal quality as obtained by FMPC is the number of pulses which makes the relative dispersion of the NM-estimate equal or smaller than the relative dispersion of the FMPC-estimate.

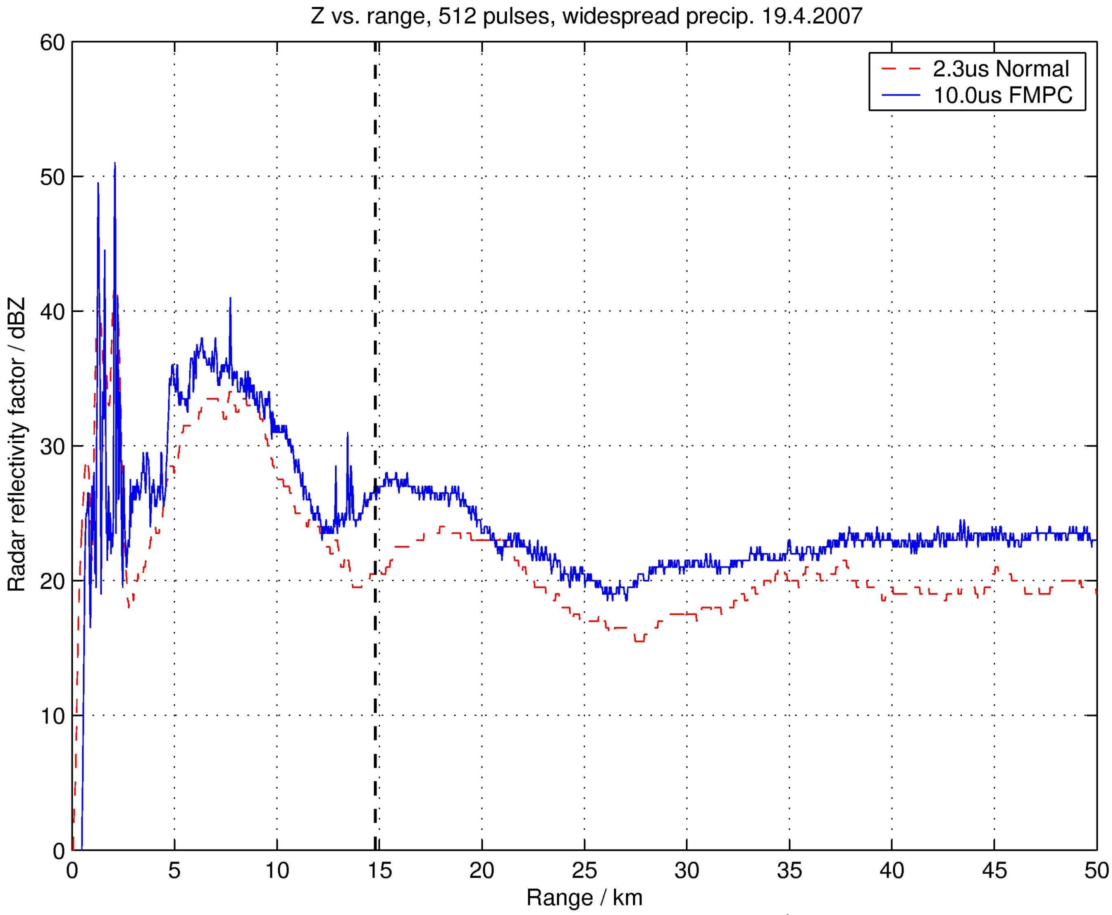

Figure 1. Radar reflectivity factor as a function of range on the 19th April 2007. Continuous lines show results based on 10 μs pulses compressed to 0.167 μs using Piecewise Linear FMPC with B = 6 MHz. Dashed line is corresponding normal measurement with 2.3 μs pulses closest to the FMPC measurement. In all measurements sample size was 512 pulses. The point of analysis is denoted by a vertical dashed line.

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4. RESULTS

4.1 Signal Statistics

The Piecewise Linear FMPC was evaluated in two rainfall cases. Figure 1 is an A-scope representation of the radar reflectivity factor using NM-estimates and FMPC-estimates in the rainfall case 19 April 2007. It was a relatively steady widespread rainfall with a good S/N. Time series data were available from 128 consecutive range bins spaced at 25 m from each other between ranges 14.8 km and 18 km.

In the present study values of received power corresponding to one 345 m resolution volume of the normal measurement were used. Thus only one power value was used from each pulse with NM, while 14 compressed power values were obtained corresponding to the same volume with FMPC (consecutive values with 25 m spacing within the same 345 m).

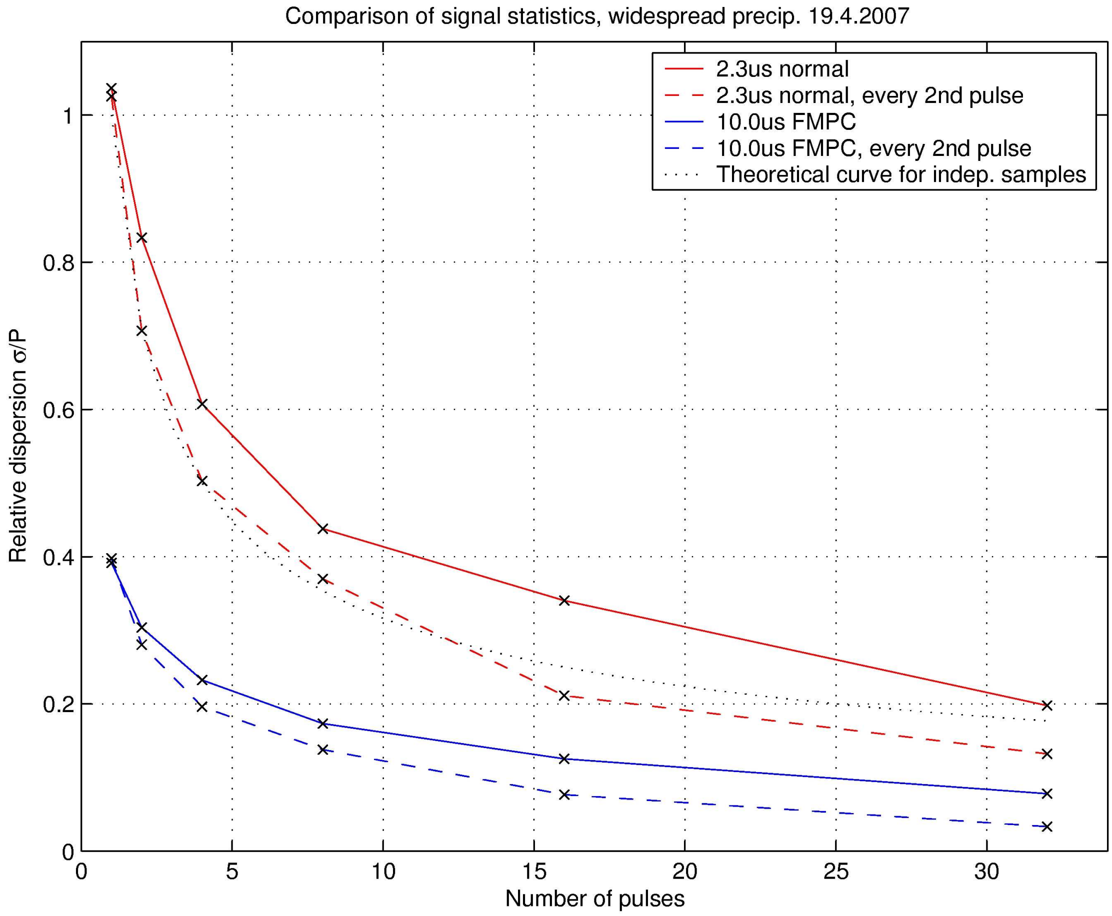

Figure 2. Relative dispersion σ_k/P of estimates of average power P as a function of k, the number of pulses used for the estimate. Upper and lower continuous lines represent the normal measurement (τ=2.3 µs) and the compressed measurement (τ_l=10 µs FMPC) respectively using PRF=350 Hz. Dashed lines are corresponding results obtained by using every second pulse, i.e. at PRF=175. Dotted curve is theoretical result according to equation (5) for totally independent samples.

Figure 2 represents main results of the analysis. Relative dispersions of the estimates of the average power received were calculated for *k* = 1, 2, 4, 8, 16 and 32 transmitted pulses. Comparing the relative dispersions obtained from NM (red line) and FMPC (blue line) measurements indicates, that FMPC produces with one pulse as good an estimate as 12.5 pulses in NM with PRF=350 Hz (see also Table 2). Further, 2 FMPC pulses seem to be as good as 21 pulses in NM (i.e. 10.5 normal pulses per each FMPC pulse).

As each 350 m range interval contains 14 range bins of 25 m, which in FMPC are averaged to form one power estimate, one could expect theoretically, that FMPC measurement with one pulse should be as good as 14 independent pulses in normal measurement.

According to the results one pulse with FMPC corresponds in this case to 12.5 pulses in normal measurement. If the echoes received from consecutive pulses were independent, this could

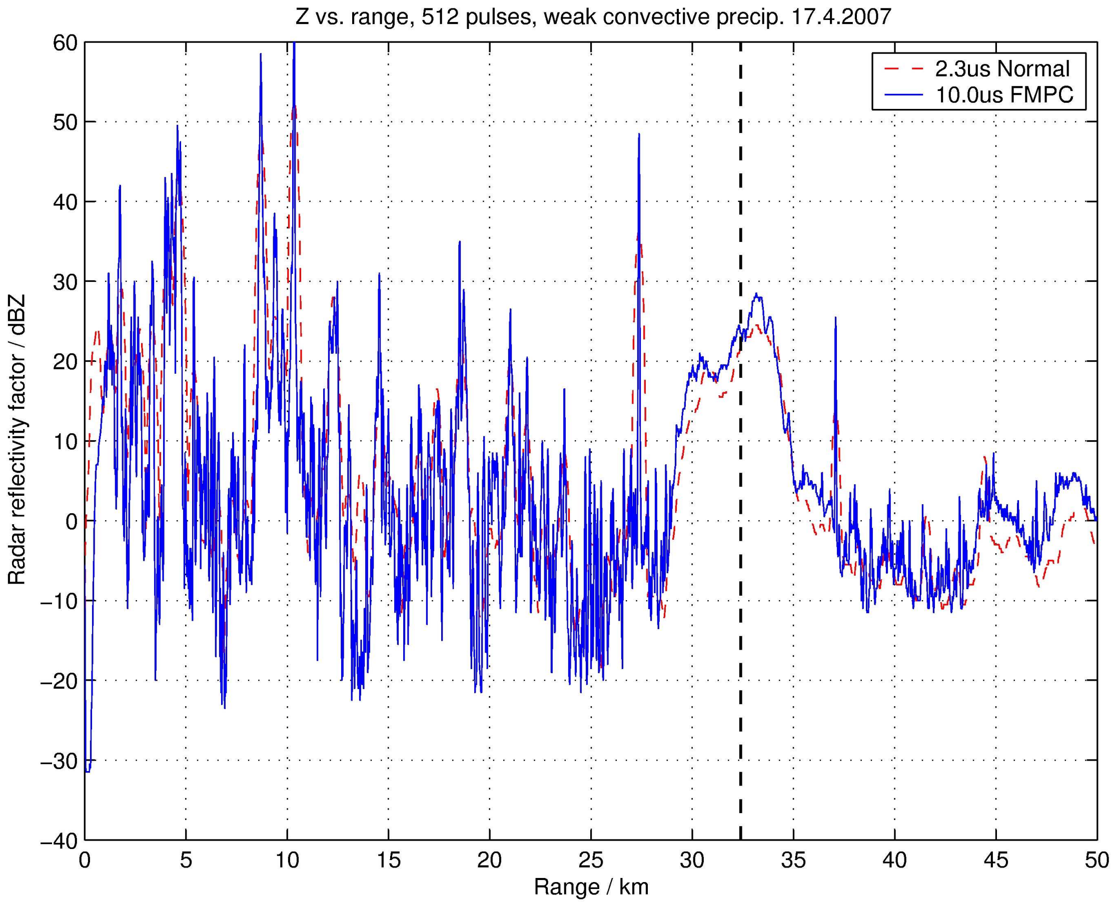

Figure 3. Same as Figure 1 but for the case 17 April 2007.

be interpreted that 89 % of the compressed 25m samples are independent, or equivalently, that the width of the compressed independent resolution volume is 28 m instead of 25 m. Correspondingly, 2 FMPC pulses are as good as 21 pulses in NM, which means that 75 % of the compressed samples seem to be independent (see Table 2) corresponding to a compressed resolution volume of 33 m instead of 25. These values would be in good agreement with the value 1.2 of the resolution widening factor due to the side lobe suppression filter.

As the pulse repetition interval of about 0.003 s with PRF=350 Hz is relatively short with respect of the typical pulse to pulse independence time of 0.01 s at C band, the figures given above for the resolution widening factor may be too optimistic. In the case of figure 2 pulses transmitted at a frequency of 350 Hz are indeed not totally independent. This can be observed from Figure 2 by comparing the result obtained using only every second pulse representing PRF=175 Hz (dashed line), and the dotted line representing theoretically total independence. At low number of pulses per estimate (k < 12) the lines are located closely together, and they differ considerably from the continuous line representing NM with PRF=350 Hz. This suggests that total independence between pulses would be reached close to PRF=175 Hz.

Comparing the dashed lines representing FMPC and NM at the PRF of independence (175 Hz)

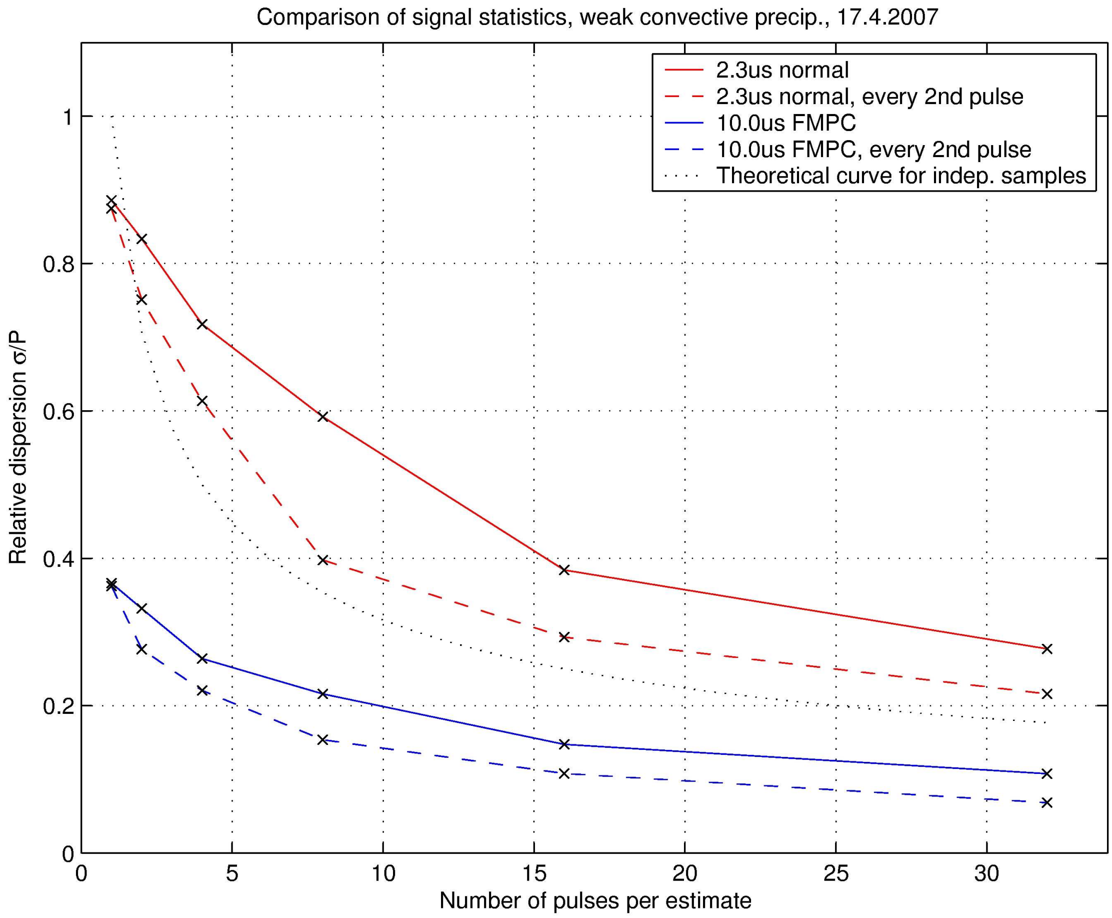

Figure 4. Same as Figure 2 but in the case 17 April 2007.

indicates, that one FMPC pulse corresponds to 7.5 independent normal pulses only. This suggests that the widening factor due to side lobe suppression filtering would in our case be considerably larger than what was estimated above using PRF=350 Hz.

However, the standard deviations of estimates with $k > 12$ at PRF= 175 Hz (dashed line) fall even below that of totally independent samples (dotted line) which is unrealistic. This is related to the small data set from which the standard deviations are calculated especially in the case of PRF=175 Hz. Thus the results based on PRF=175 should be treated as qualitative only. The same applies also at PRF=350 Hz in comparisons, where the sample size k in estimating standard deviations is greater or equal than say 16 pulses in NM.

The second case studied (17 April 2007) (Figures 3 and 4) was an echo received from a weak tiny convective shower at a distance of 32 km from the radar. In this case the S/N was somewhat smaller than in the first case, mainly due to the longer range of the point of analysis.

Echoes at PRF=350 Hz are in this case even less independent than in the first case. As a consequence, in this case PRF=175 Hz does not represent total independency, though this was true in the first case.

This can be seen immediately by comparing the steepness of the curves in Figures 2 and 4 at small sample sizes. Steeper decrease of the normalized standard deviation with increasing number of samples indicates higher percentage of independent samples in the case of Figure 2 than in the case of Figure 4 with a more gently sloping decrease. Since the theoretical independence line does not coincide with the dashed line representing PRF=175 Hz, but is far on the left from it, samples taken at PRF=175 Hz are not independent in this case.

As a result from this case one FMPC pulse corresponds now as many as 20 pulses in NM. This looks at first impossible as each FMPC pulse consists of 14 independent compressed 25 m resolution volumes at the most, but it can be easily explained by the high dependence between pulses; The more dependent consecutive pulses are, the larger number of these pulses is needed to reach an equal standard deviation as obtained by averaging compressed independent resolution volumes within a single FMPC pulse.

At PRF=175 one FMPC pulse corresponds still to 11 pulses in NM. This value is nearly the same as obtained in the first case studied with PRF=350 Hz indicating, that the echoes from consecutive pulses are not independent now at PRF=175. Comparing the relative dispersion of one FMPC pulse to the theoretical independence curve in Figure 4 we find again the same final result found already in the first case (Figure 2); One FMPC pulse corresponds to 7.5 independent pulses in NM.

These two cases illustrate also nicely how the performance of FMPC compared to the performance of NM improves with decreasing independence between pulses.

4.2 Potential Increase in Scan Speed

Main results from cases 19 April 2007 and 17 April 2007 are summarized in Tables 2 and 3 respectively. Tables give the numbers of pulses needed in normal measurements (k_{NM}) in order to obtain an estimate of the average power having a relative dispersion equal to the relative dispersion of the FMPC estimate with k_{FMPC}=1, 2, 4 or 8 pulses for both PRFs. The scan speed increase factor k_{NM}/k_{FMPC} is given for k_{FMPC}=1, 2 and 4.

Table 2. Number of pulses needed in normal measurements (k_{NM}) to obtain an estimate of the average power having the relative dispersion equal to the relative dispersion of the FMPC estimate with k_{FMPC}=1, 2, 4 and 8 pulses for PRFs 350 Hz and 175 Hz (19 April 2007).

2007-04-19	PRF	350 Hz	PRF	175 Hz
k_{FMPC}	k_{NM}	k_{NM}/k_{FMPC}	k_{NM}	k_{NM}/k_{FMPC}
1	12.5	**12.5**	7.5	**7.5**
2	21	**10.5**	13	**6.5**
4	28	7	20	5
8	-	-	32	4

Table 3. Same as table 2 but for the case 17 April 2007.

2007-04-17	PRF	350 Hz	PRF	175 Hz
k_{FMPC}	k_{NM}	k_{NM}/k_{FMPC}	k_{NM}	k_{NM}/k_{FMPC}
1	20	**20**	11	**11**
2	25	**12.5**	20	**10**
4	-	-	32	8
8	-	-	-	-

The decrease of the scan speed increase factor with increasing number of pulses in both cases can be explained partly by the fact that pulse to pulse dependence has no effect to FMPC if only one pulse is transmitted, while the corresponding NM with several pulses is always influenced by the pulse to pulse dependence. Another reason is the decreasing accuracy of the estimate of the standard deviations due to the small data in cases with high values of k_{NM}. This makes the comparisons of FMPC and NM unreliable in cases with k_{FMPC} > 2. For these reasons only the values indicated by bold numbers in Tables 2 and 3 were considered in estimating the potential increase in scan speed.

Table 4. Time needed for a volume scan consisting of 360 azimuths at 10 elevations using normal methods (NM), and FMPC with range resolutions of 150 m and 345 m. The accuracy required for reflectivity estimates is 1, 1.4 or 1.8 dB, corresponding to PRFs 100, 200 and 300 Hz respectively at C band when the sample size is 30 pulses.

	Accuracy of reflectivity estimates (dB)		
Method	1	1.4	1.8
NM	18 min	9 min	6 min
FMPC resol. 150 m	5.5 min	2.3 min	1.8 min
FMPC resol. 345 m	2 .5 min	1.5 min	0.8 min

In the case 19 April 2007 (Table 2) one FMPC pulse corresponds at PRF=350 Hz to 12.5 or 10.5 NM pulses. Thus it can be concluded that FMPC produces equal quality estimates for the average power as NM does, but at a speed 12.5 to 10.5 times faster than NM.

In the case 17 April 2007 (Table 3) one FMPC pulse corresponds at PRF=350 Hz to 20 pulses in NM. With 2 FMPC pulses this number decreases to 12.5. Thus it can be concluded that in this case FMPC produces equal quality estimates for the average power as NM does, but at a speed of 20 times faster than NM in case of one FMPC pulse, and 12.5 times faster than NM in cases with several FMPC pulses.

If our intention is to find out FMPC estimates which are as accurate as would be obtained by NM using a certain number of independent samples, we have to compare FMPC and NM at such a PRF which produces independent samples from pulse to pulse. In the case 19 April 2007 (Table 2) this happens at PRF=175 Hz. From Table 2 we can see that in this case one FMPC would be about 7.5 times faster than NM. In case of Table 3, the echo samples are not independent at PRF=175 Hz. However, by using the theoretical independence line in Figure 4 we may estimate the number of independent pulses required in NM to get equal accuracy as obtained by one FMPC pulse. The result is also in this case 7.5 pulses, like in the case of Table 2. Thus In both of the cases studied scan speed would increase by a factor of 7.5 by using FMPC. This result applies for the final range resolution of 345 m corresponding to the pulse length of 2.3 μs.

For an accuracy of 1 dB in reflectivity estimates about 30 independent samples should be averaged. As a consequence 30 independent pulses per estimate are needed in NM, while using the FMPC only 30/7.5 = 4 pulses are needed for such an estimate, and the scan speed increase factor is 7.5. If we aim to range resolution of 150 m corresponding to 1 μs pulse, scan speed increase factor would be 3.3, and 9 pulses are required using FMPC to reach the same accuracy of estimates as obtained with 30 independent pulses in NM.

Assuming that the time required for independence between pulses at C band is on the order of 0.01 s (corresponding to PRF = 100 Hz), a large volume scan consisting of 360 azimuths at 10 elevation angles would require as much as 18 min to be measured with an accuracy of 1 dB in reflectivity, when measured using normal methods. FMPC shortens the scan time to 5.5 min if the final range resolution is 150 m, and even to 2.5 min if the final resolution is 345 m as indicated in column 2 of Table 4.

In operational radar applications PRF is typically much higher than 100 Hz and do not vary according to the actual independence time for each situation. Thus pulses are not totally independent. This means that, compared to the second column of Table 4,

1) the accuracy of reflectivity estimates is lower, and
2) scan times are shorter, if the sample size stays constant.

If for example only every second pulse were independent (corresponding to PRF = 200 Hz) scan times would be reduced to half of what is indicated in column 2 of Table 4, but at the cost of increasing the standard deviation of reflectivity estimates from 1 dB to about 1.4 dB at the most (Table 4 column 3). If only every third pulse was independent (PRF=300 Hz), scan times would be reduced accordingly further by a factor of 0.7, while the standard deviation of reflectivity estimates would increase to 1.8 dB (Table 4 column 4). As high accuracy of estimates may not be critical in all operative products, compromises between the accuracy and scan time are typical. Thus volume scan times of about 6 min are common. FMPC will shorten also these scan times further as indicated in columns 3 and 4 of Table 4.

It should also be noted that the time to independence is not constant but increases with increasing wavelength and decreases with the increasing width of the Doppler spectrum. Thus the real accuracies of reflectivity estimates are in most cases better than the “worst case values” indicated in Table 4. Accuracies are expected to be higher in severe convective events, for example.

Dependence between pulses is necessary in order to extract radial velocities. Increasing the sample size by including dependent samples in the measurement does not increase scan times since dependent samples are obtained by transmitting extra pulses between independent. According to preliminary tests with the University of Helsinki radar 4 dependent pulses is enough for good velocity estimates with FMPC. As at least 4 pulses are needed in any case with FMPC to produce satisfactory estimates for reflectivity in these examples, velocity estimation does not change the result with respect to increase of scan speed. Same applies also for the polarimetric parameters (Puhakka et al. 2006).

A major increase in the scan speed over the present results may be achieved by increasing the width of frequency modulation. Improvements may also be obtained by optimizing range time side lobe filtering parameters.

5. SUMMARY AND CONCLUSIONS

The performance of the piecewise linear FMPC was studied using the University of Helsinki coherent C-band weather radar in two real precipitation cases. Test measurements used 10 µs high power (250 kW) pulses compressed by applying a piecewise linear FM modulation of B=6 MHz.

Theoretically a modulation bandwidth of 6 MHz corresponds to a compressed range resolution of 25 m, but the range side lobe suppression filtering is expected to increase the width of the compressed resolution volume (i.e. decrease the resolution) by a factor between 1.2 and 1.5. Corresponding theoretical values for the scan speed increase factors are 11 and 5 for final range resolutions of 345 m and 150 m respectively. These values assume that the width of the ideal compressed resolution volume would be increased by the factor 1.2 due to the range side lobe suppression filtering.

The increase in scan speed was estimated empirically also for two final resolutions; 345 m and 150 m corresponding to pulse widths 2.3 µs and 1 µs. To get estimates of the average power received with an accuracy of 1 dB requires averaging of 30 independent pulses with normal methods while FMPC requires for equal quality estimates only 4 pulses if the final resolution is 345 m (2.3 µs). In other words FMPC is at least 7.5 times faster than NM. Similarly, for the final resolution of 150 m (1 µs) scan speed could be increased by FMPC by a factor of 3.3. These values were obtained from both of the cases studied. According to the results the decrease in resolution due to the range side lobe filtering was in this case somewhat larger than 1.2. By optimizing the filtering parameters even better values may be reached.

However, FMPC as it is now, is able to increase scan speed such that a large high resolution volume scan, which requires 18 min to be measured with an accuracy of 1 dB using normal methods, requires using FMPC only 5.5 min if the final resolution is 150 m, and only 2.5 min if the final resolution is 345 m.

Correspondingly, the same volume scan measured with a reduced accuracy of about 2 dB, requires 6 min by normal methods, but using FMPC it is measured in less than 2 min (resolution 150 m) and in less than 1 min (resolution 345 m). Though only radar reflectivity factor was measured in this experiment, the results are valid for velocity and most polarimetric parameters as well. An open issue is the Doppler clutter cancelation which is degraded at high antenna rotation rates. To optimize clutter cancelation performance, it may be advantageous to scan at reduced rates at low elevation angles, and then use rapid scan at the high elevation angles.

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