Proceedings of ERAD 2006

On the Performance of NLFM Pulse Compression with Polarimetric Doppler radar

T. Puhakka[1], P. Puhakka[1], and F. O'Hora[2]
[1]University of Helsinki, [2]Sigmet, Part of Vaisala Group

1 Introduction

Pulse compression radar transmits modulated (coded) long pulses and compresses the corresponding echo signals, resulting in fine range resolution. Frequency modulation is typically used, however binary phase modulation codes represent an alternative technique. For a given range resolution, pulse compression results in increased sensitivity over that of a none-compressed pulse. It is also evident that in addition to increased sensitivity and finer range resolution, pulse compression provides the possibility of obtaining independent weather echo samples 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 number of pulses per estimate. This facilitates the use of higher scan speeds, for instance for more rapid volumetric coverage. On the other hand, with an equal number of pulses, a pulse compression radar would provide superior quality and sensitivity as compared with a conventional radar. This is invaluable in investigating weak and noisy signals such as those found in clear air or non-precipitating clouds or in the depolarization channel with polarimetric measurements.

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, have been a disadvantage compared to normal measurements. However it is demonstrated that range side lobes may be suppressed considerably using new techniques (Keeler et al 1999).

Correspondance To: Pekka Puhakka
pekka.puhakka@helsinki.fi

Furthermore, as requirements for lower average power, higher sensitivity and higher scanning speed have become more common, pulse compression techniques are more attractive. The purpose of this paper is to evaluate the performance and possibilities of non-linear frequency modulation (NLFM) pulse compression (O'Hora, F., and Bech, J. 2005) using the fully coherent polarimetric high power weather radar of the University of Helsinki.

2 Radar

The new klystron based fully coherent C-band polarimetric Doppler weather radar located at the University of Helsinki (Kumpula radar) was used in the present analysis and tests. The main characteristics of the radar are given in table 1.

Table 1. Main characteristics of the University of Helsinki radar. (* value measured with the radome).

Transmitter	Klystron Power Amplifier
Frequency	C-Band
Peak Power	250 kW
Pulse Lengths	0.5 – 20 μs
Duty Cycle (Max)	0.004
Polarizer	3 dB H/V splitter, possibility of entire power into H channel
Antenna	Parabolic
Diameter	4.2 m
Polarization	Linear Horizontal, Vertical
Beamwidths (3 dB)	1 degree
Gain	43 dBi *
Side Lobe Levels (H&V)	<-33 dB * (horizontal and vertical planes)
Worst Side Lobes (H&V)	<-27 dB * (along struts)
Lowest Measured LDR	-39 dB *

Receiver	Analog RF, Digital IF (RVP8)
Polarization	Horizontal, Vertical
Dynamic Range	85 to 100+ dB (dependant on pulse width)
Z_0(τ=0.9 μs)	-41.75 dBZ at 1 km

The high duty cycle (0.004) and high pulse power of the radar makes it unique for pulse compression. Pulses as long as 20 μs can be used with PRF = 200 Hz with the full power of 250 kW. The NLFM pulse compression technique (O'Hora, F., and Bech, J. 2005) is implemented.

3 Analysis

3.1 Increase of sensitivity

Calibration is critical for evaluating the dynamic range and sensitivity of the radar. However, as the frequency is not constant with NLFM pulse compression, the radar cannot be calibrated using the traditional method of injecting known power levels from a microwave signal generator into the receiver and observing the system response. Instead a method is required to base the calibration of pulse compression signals on traditional non-modulated signals, referred to hereafter as the "reference pulse".

The calibration constant $Z_0(\tau)$ associated with pulse length τ is defined as the minimum detectable value of the radar reflectivity factor Z at the reference range r_0 (typically 1 km). In terms of the radar equation this can be written as:

$$Z_0(\tau)(mm^6m^{-3}) = k\frac{\lambda^2 r_0^2}{P_t G^2 \Theta\Phi g_r g_t}\frac{N}{\tau} \qquad (1)$$

where N is the noise power associated with the pulse length τ, g_r and g_t are the gains of the receiver and transmitter respectively, k is a numerical constant and other symbols have their standard meanings in the radar equation. We see that $Z_0(\tau)$ includes two parameters which should be changed with pulse compression. These are the pulse length τ and the corresponding noise power N. By replacing N and τ by the noise power N_C associated with the compression filter, and by the pulse length to be compressed τ_l, respectively, we obtain approximate calibration constant for the compression. Formally this can be done by dividing (1) by N/τ and multiplying it by N_C/τ_l. As a result we get the Z_0 value for the pulse τ_l compressed using a frequency modulation bandwidth of B_C.

$$Z_0(\tau_l B_C)(mm^6m^{-3}) = Z_0(\tau)(mm^6m^{-3})\cdot\frac{\tau}{\tau_l}\cdot\frac{N_C}{N} \qquad (2)$$

Note that in pulse compression, range resolution is not defined by τ_l but it is defined by the inverse of the bandwidth B_C of the frequency modulation.

In logarithmic units (2) is:

$$Z_0(\tau_l B_C)(dBZ) = Z_0(\tau)(dBZ) - 10\log\frac{\tau_l}{\tau} + 10\log\frac{N_C}{N} \qquad (3)$$

Since N =kTB and N_C=kTB_C , where k is Bolzman constant, T is absolute temperature, and B and B_C are the bandwidths associated with the reference pulse τ and the pulse τ_C corresponding to the compressed resolution respectively, equation (3) can also be written in following form:

$$Z_0(\tau_l B_C) = Z_0(\tau)(dBZ) - 10\log\frac{\tau_l}{\tau} + 10\log\frac{B_C}{B} \qquad (4)$$

Furthermore, since $B \sim 1/\tau$ and $B_C \sim 1/\tau_C$, (4) is also approximately:

$$Z_0(\tau_l B_C)(dBZ) \approx Z_0(\tau)(dBZ) - 10\log\frac{\tau_l}{\tau} + 10\log\frac{\tau}{\tau_c} \qquad (5)$$

In all alternative forms (3), (4) and (5) the first term on the right hand side is the normal calibration constant of the reference pulse length. The second term represents the increase of sensitivity, compared with the reference pulse, resulting from the effective increase of power due to the compression. The last term is associated with the decrease of sensitivity due to the larger bandwidth (higher noise power) of the compression filter compared to the bandwidth (noise power) of the reference pulse.

With the Kumpula radar we can use two long pulse lengths, τ_l =21.4 μs or τ_l =9.8 μs, for pulse compression. Shorter pulse lengths $\tau = 0.6$ μs $\tau = 0.9$ μs and $\tau = 2.2$ μs are also used with normal measurements, and as the basis of the calibration of pulse compression.

It is easy to estimate the final increase of sensitivity due to pulse compression e.g. from equation (4).

Example 1: Estimation of the increase of sensitivity due to compression:

Length of the reference pulse	$\tau = 0.6$ μs
Length of the pulse to be compressed	$\tau_l = 21.4$ μs
Modulation bandwidth of compression	B_C=3 MHz
Resolution after compression	τ_C =1/B_C = 0.33 μs
Bandwidth of reference pulse	B = 1/τ = 1/0.6 = 1.67 MHz
Z_0 obtained using normal calibration for $\tau = 0.6$ μs	Z_0(0.6 μs) = -38.46 dBZ

Increase of sensitivity (decrease of Z_0) due to compression of long pulse:

$$10\log\frac{\tau_l}{\tau} = 10\log\frac{21.4}{0.6} = 15.5 \text{ dB}$$

Decrease of sensitivity (increase of Z_0) due to the bandwidth of the compression filter:

$$10\log\frac{B_c}{B} = 10\log\frac{3}{1.67} = 2.6 \text{ dB}$$

Z_0 obtained for compression:

$Z_0\,(21.4\mu s)$ = -38.46 - 15.5 + 2.6 = -51.37 dBZ.

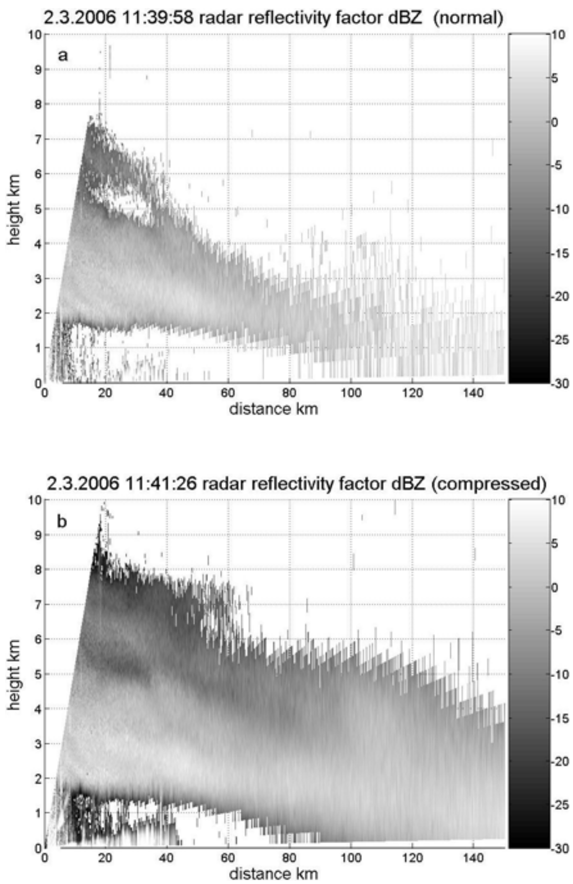

Fig. 1. RHI cross section of radar reflectivity factor a) Normal measurement with τ = 0.6 μs b) Pulse compression measurement with τ_l = 21.4 μs and B_C = 3 MHz.

This example indicates a total increase of about 13 dB in the sensitivity due to compression compared to a normal measurement with $\tau = 0.6$ μs. (Compared to normal measurement with $\tau = 0.9$ μs the increase in sensitivity would have been about 10 dB). In addition to the increase of sensitivity the range resolution is also improved (made finer). In this example the resolution obtained with compression is close to 0.33 μs while the best resolution without compression would have been only 0.6 μs (and with a 13 dB lower sensitivity). Range resolution can be increased further by increasing the bandwidth of the modulation, but this decreases sensitivity gained with compression.

To be accurate, it should be finally noted that Z_0 does not include receiver losses in this formulation. Receiver loss should be estimated and added separately like the matched filter loss in normal measurements. After adding this correction, the calibration applied to pulse compression produced consistent results with the conventional measurement (Fig 1).

3.2 Increase of scanning speed

The fundamental reflectivity parameter measured is the radar reflectivity factor Z. Accurate estimation of Z requires estimation of the average power received. For that we need enough independent samples of the backscattered signal. Independent echo samples are obtained if the time between samples is long enough to allow the drops reshuffle in an independent configuration within the pulse volume. The time needed for independence depends on the relative radial velocities of the drops and on the wavelength used. At C band the time needed for total independency is on the order of 10 ms (Marshall and Hitschfeld, 1953). To obtain reliable estimates for the average power received, many independent samples should be averaged. For an accuracy of 0.5 dB about 100 such samples are needed. Thus a relatively long dwell time is needed for an accurate estimate. This makes the scanning speed of the radar rather slow.

It is possible to obtain independent samples even from a fixed drop population if the frequency of the transmitted signal is changed at least by the amount $1/\tau$ from pulse to pulse, where τ is the pulse length (Marshall and Hitschfeld, 1953). One way of accomplishing this is through FM pulse compression. If the frequency of the transmitted microwave pulse is changed by B_C Hz during the pulse τ_l, echo signals from this pulse are independent at intervals of $\tau_C = 1/B_C$ independently of the length τ_l of the pulse. If for example, a 10 μs pulse is frequency modulated by a linear change of 9 MHz, theoretically $\tau_l/\tau_C = 10/(1/9) = 90$ independent samples would be obtained from a single pulse. In a real case there are factors that make the number of independent samples somewhat lower than the theoretical maximum. However, FM pulse compression provides a way of obtaining many independent samples practically simultaneously, facilitating thus the use of higher scan speeds, and thus faster volumetric coverage.

Example 2. Potential increase of scanning speed with pulse compression.

- If a pulse τ_l = 10 μs is compressed using B_C = 9 MHz the resulting range resolution is 0.11 μs corresponding to 16.7 m.

- Samples taken at 0.11 μs intervals (=16.7 m range intervals) from the compressed echo are independent from each other.

- By averaging such independent samples from 10 consecutive ranges we get estimates for the average power received at range intervals of about 1.1 μs (167 m) from a single transmitted pulse.

- Since a corresponding 10 sample estimate requires with normal processing 10 pulses, the dwell time needed for equal estimates with pulse compression is only one tenth of the time needed with normal measurements.

Fundamental polarimetric reflectivity parameters are differential reflectivity Z_{DR}, linear depolarization ratio LDR, and co-polar correlation coefficient. As the differential reflectivity is the ratio of horizontal and vertical reflectivity factors, what is said about the radar reflectivity factor above is true for differential reflectivity as well.

As the cross-polar signal power is typically only a small fraction of the co-polar power, LDR measurements gain much from pulse compression. This is important especially in cases where the co-polar signal is also small, like at log distances and in non-precipitating clouds.

3.3 Velocity estimation

For the estimation of Doppler velocity the samples should not be independent. If they are independent, the estimation of phase change from pulse to pulse is not possible. In pulse compression we actually make the phases of the echoes from each resolution sub volume within the compressed long pulse uncorrelated. Thus we cannot derive velocity information from the phase differences between the sub volumes of a single long pulse. Actually, as the maximum time difference between such sub pulses is on the order of 20 us, the movements of the drops are negligible small, and the non-modulated phases from such an almost fixed configuration of drops would be constant. For that reason we obviously need at least two pulses in order to obtain velocity information. Though the phases within each resolution sub volume are independent, phases from pulse to pulse are coherent. This is because the FM modulation sequence is identical within every long pulse. As a result, by compressing two pulses and estimating phase changes between the respective sub volumes of these pulses, the number of independent velocity estimates obtained from a pair of pulses is equal to the number of sub pulses. Thus it should be possible to estimate velocities satisfactorily from only two pulses. Another benefit gained in velocity measurements with NLFM pulse compression is that as a result of increased sensitivity, a larger coverage area of high quality velocity data (even in clear air situations) is possible. In general, all radar measurables including polarimetric parameters gain from the increased of sensitivity provided by pulse compression.

4 Conclusions

The benefits gained by using the NLFM pulse compression scheme were studied in connection with the University of Helsinki full coherent dual polarization C-band radar. The results show that NLFM pulse compression can be used in connection with all conventional and polarimetric parameters. Compared with conventional uncompressed measurements, pulse compression yields as accurate estimates but with a considerable smaller number of pulses per estimate. This facilitates the use of higher scan speeds, for instance to obtain more rapid volumetric coverage. On the other hand, with an equal number of pulses, a pulse compression system delivers superior sensitivity and quality of moment estimates as compared with uncompressed estimates. This is invaluable in investigating weak and noisy signals such as found in clear air, with non-precipitating clouds, or in the depolarization channel with polarimetric measurements.

Acknowledgements: The authors acknowledge very helpful discussions with Dr. Jeffrey Keeler.

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