Radar Pulse Compression

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Outline

- Why is pulse compression needed?
- Pulse compression, the compromise
- How it works
- Simplified view of concept
- Pulse coding
    - Phase-coded pulse
    - Chirp (linear FM)
- Receiver signal processing
- Window functions and their effects

Why is pulse compression needed?

- Radar range resolution depends on the bandwidth of the received signal.

$$\rho = \frac{c\tau}{2} = \frac{c}{2B}$$

c = speed of light, ρ = range resolution,
τ = pulse duration, B = signal bandwidth

- The bandwidth of a time-gated sinusoid is inversely proportional to the pulse duration.
  - So short pulses are better for range resolution
- Received signal strength is proportional to the pulse duration.
  - So long pulses are better for signal reception

More Tx Power??

- Why not just get a transmitter that outputs more power?
- High-power transmitters present problems
  - Require high-voltage power supplies (kV)
  - Reliability problems
  - Safety issues (both from electrocution and irradiation)
  - Bigger, heavier, costlier, …

Pulse compression, the compromise

Transmit a long pulse that has a bandwidth corresponding to a short pulse

Must modulate or code the transmitted pulse

- to have sufficient bandwidth, B
- can be processed to provide the desired range resolution, ρ

Example:

Desired resolution, $\rho = 15$ cm (~ 6”)

Required bandwidth, B = 1 GHz (10^9 Hz)

Required pulse energy, E = 1 mJ

$E(J) = P(W) \cdot \tau(s)$

Brute force approach

Raw pulse duration, $\tau = 1$ ns (10^{-9} s)

Required transmitter power, P = **1 MW !**

Pulse compression approach

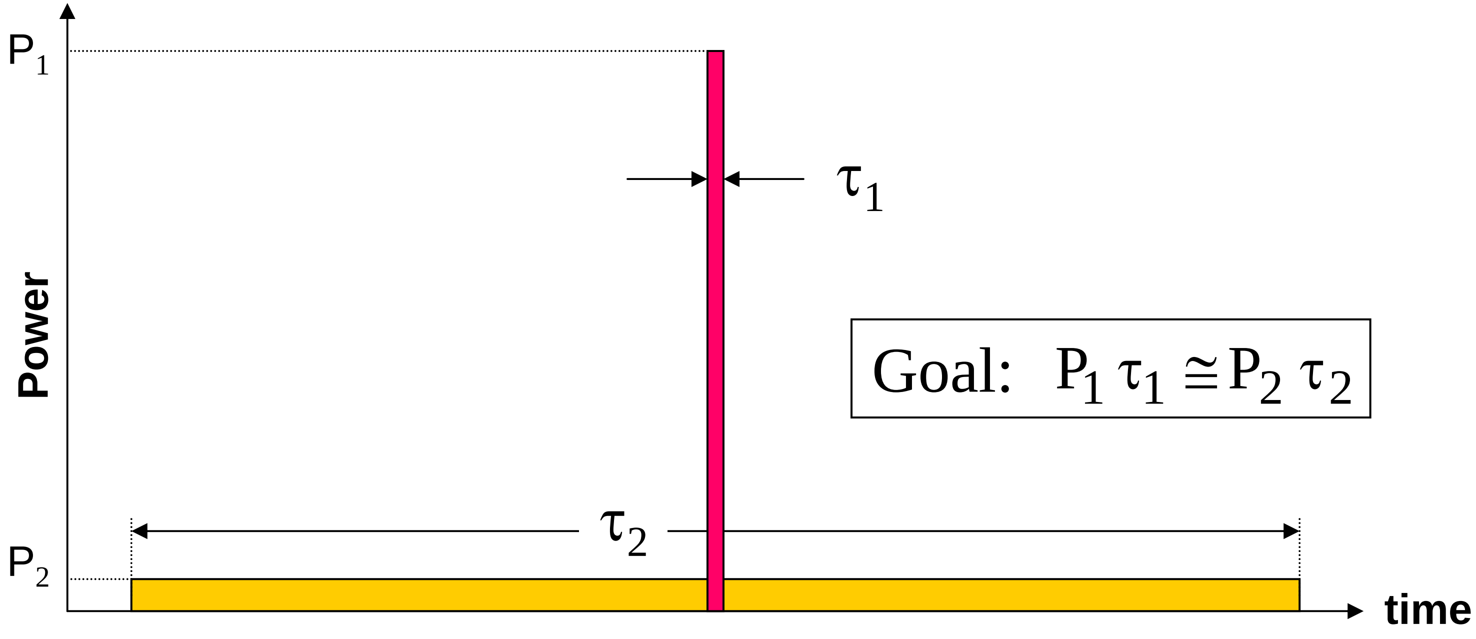
Pulse duration, $\tau = 0.1$ ms (10^{-4} s)

Required transmitter power, P = **100 W**

Simplified view of concept

Energy content of long-duration, low-power pulse will be comparable to that of the short-duration, high-power pulse

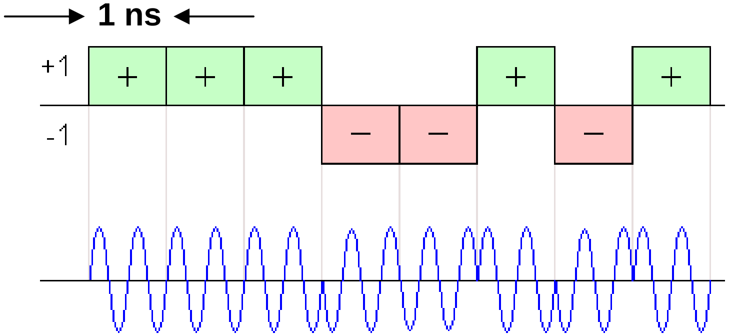
$$\tau_1 \ll \tau_2 \text{ and } P_1 \gg P_2$$



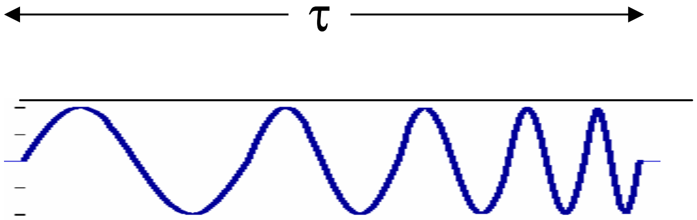
Goal: $P_1 \tau_1 \simeq P_2 \tau_2$

Pulse coding

- Long duration pulse is coded to have desired bandwidth. Various ways to code pulse.
  - Phase code short segments
    - Each segment duration = 1 ns



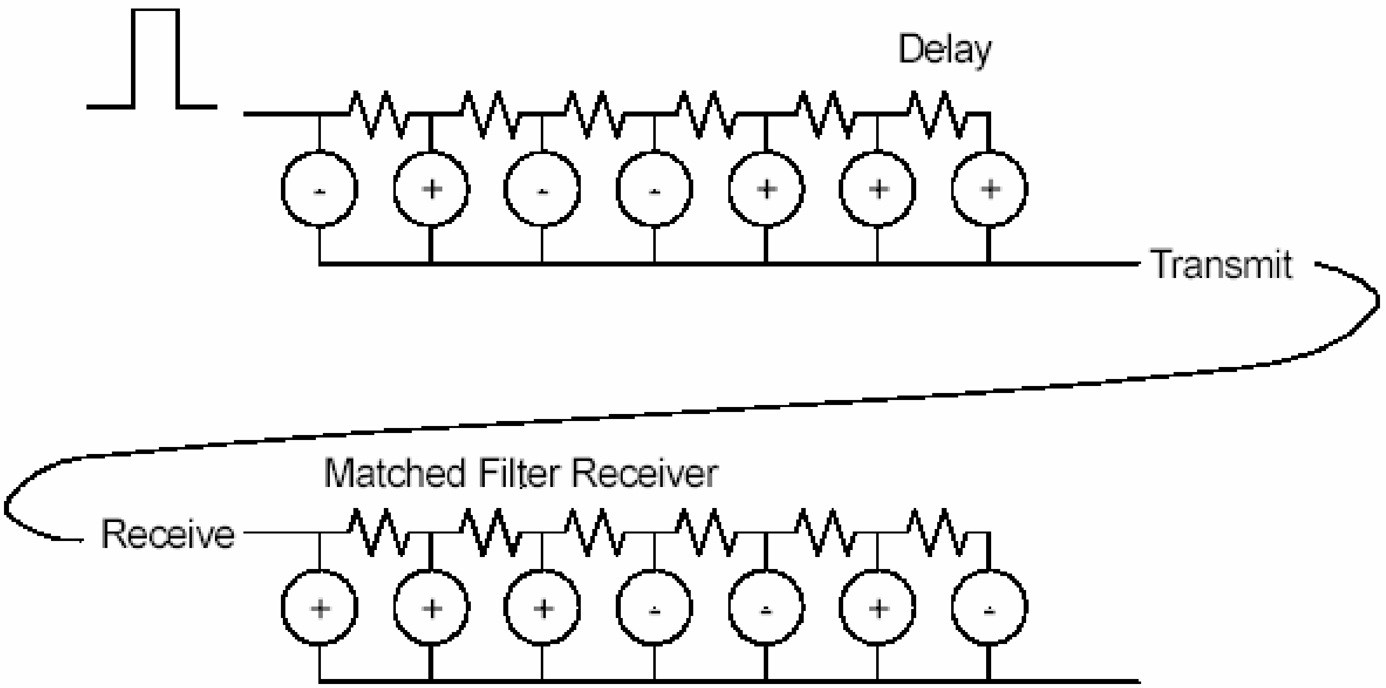
  - Linear frequency modulation (chirp)
    - $s(t) = A\cos(2\pi f_C t + 0.5\, k\, t^2 + \phi_C)$
    - for $0 \leq t \leq \tau$
    - f_C is the starting frequency (Hz)
    - k is the chirp rate (Hz/s)
    - $B = k\tau^2 = 1$ GHz



- Choice driven largely by required complexity of receiver electronics

Receiver signal processing

phase-coded pulse generation and compression



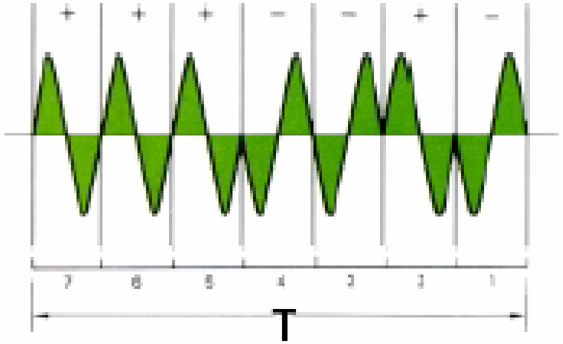
-							-1 = -1
+	-						+1-1 = 0
-	+	-					-1+1-1 = -1
-	-	+	-				-1-1+1+1 = 0
+	-	-	+	-			+1-1-1-1+1 = -1
+	+	-	-	+	-		+1+1-1+1-1-1 = 0
+	+	+	-	-	+	-	+1+1+1+1+1+1+1+1 = 8
	+	+	+	-	-	+	+1+1-1+1-1-1 = 0
		+	+	+	-	-	etc

Receiver signal processing

phase-coded pulse compression

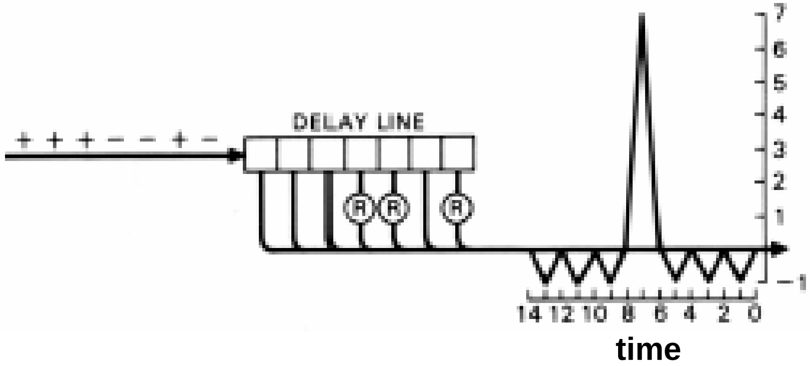
BINARY-PHASE CODED PULSE:

- Barker Code of Length N = 7



BINARY-PHASE DECODER FOR PULSE COMP. :

- For Barker Codes, PSL = -20log(N)

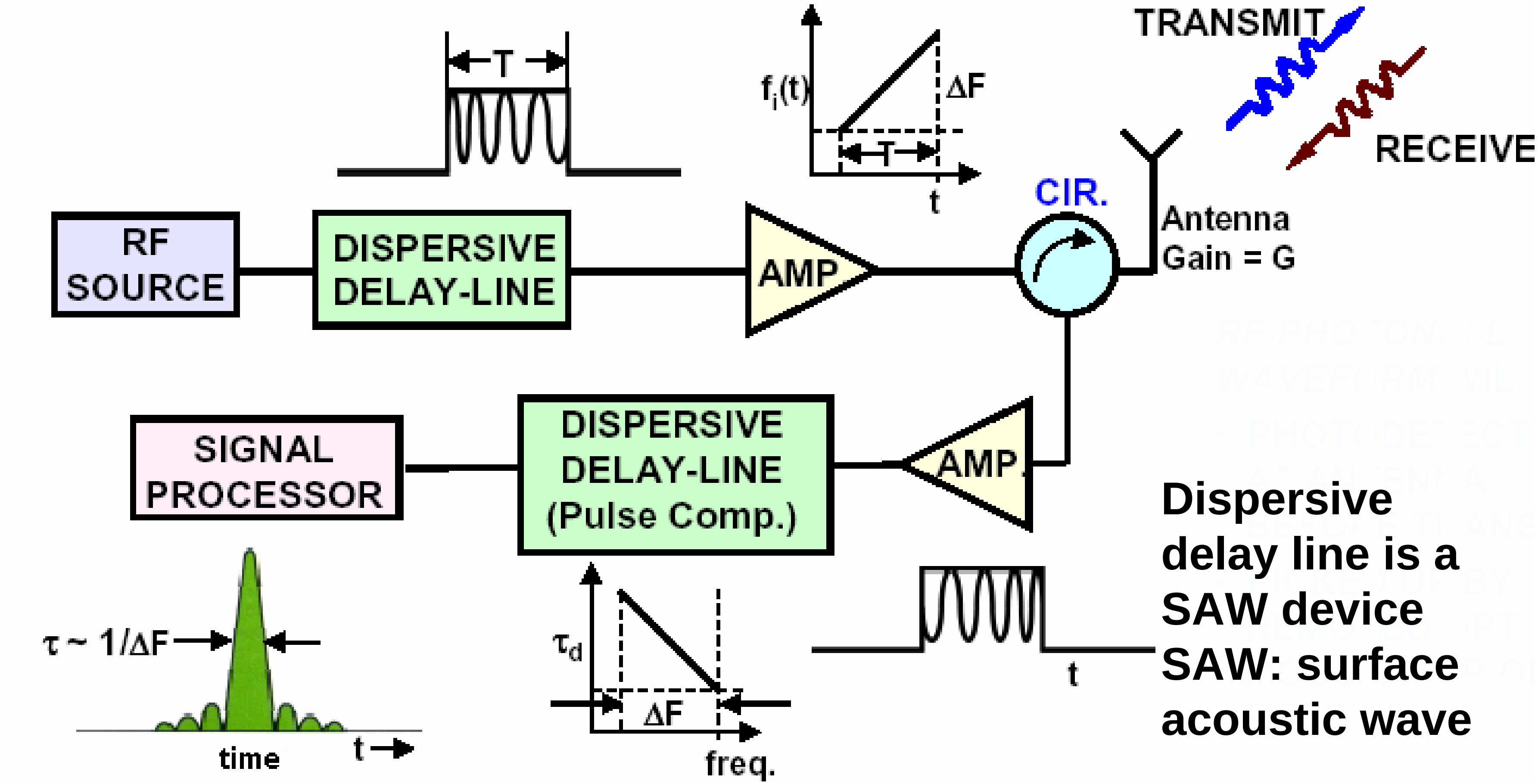


Correlation process may be performed in analog or digital domain. A disadvantage of this approach is that the data acquisition system (A/D converter) must operate at the full system bandwidth (e.g., 1 GHz in our example).

PSL: peak sidelobe level (refers to time sidelobes)

Receiver signal processing

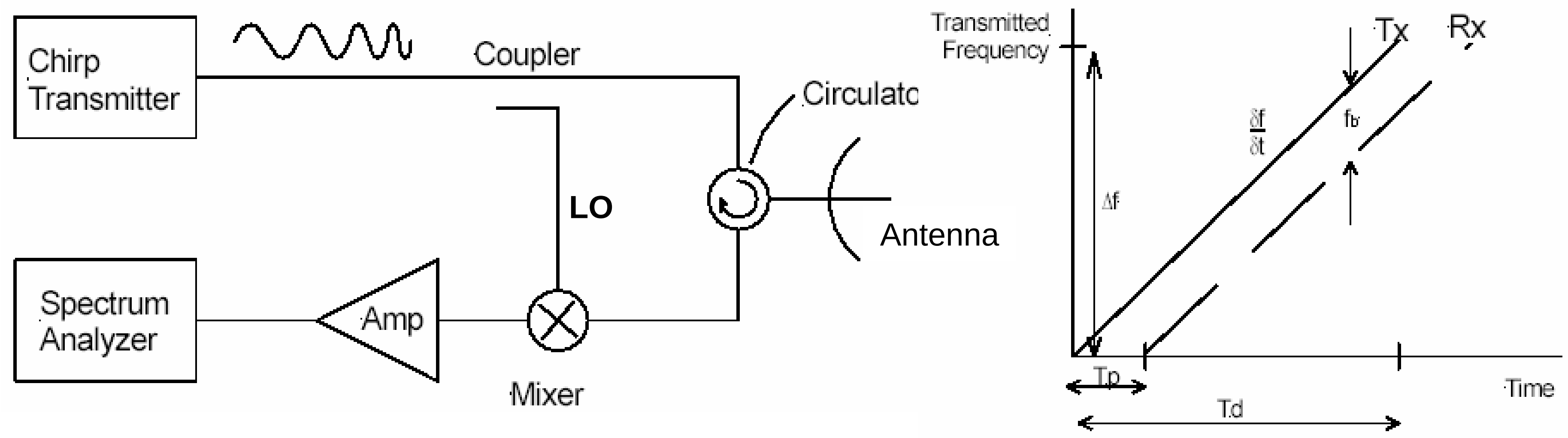
chirp generation and compression

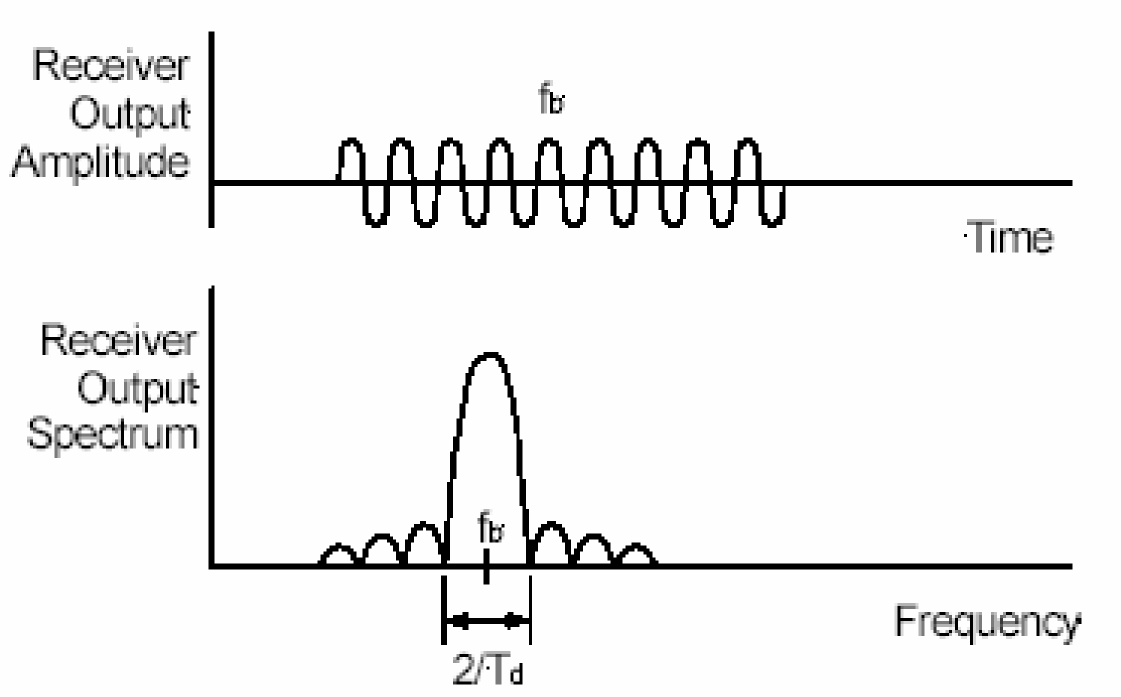


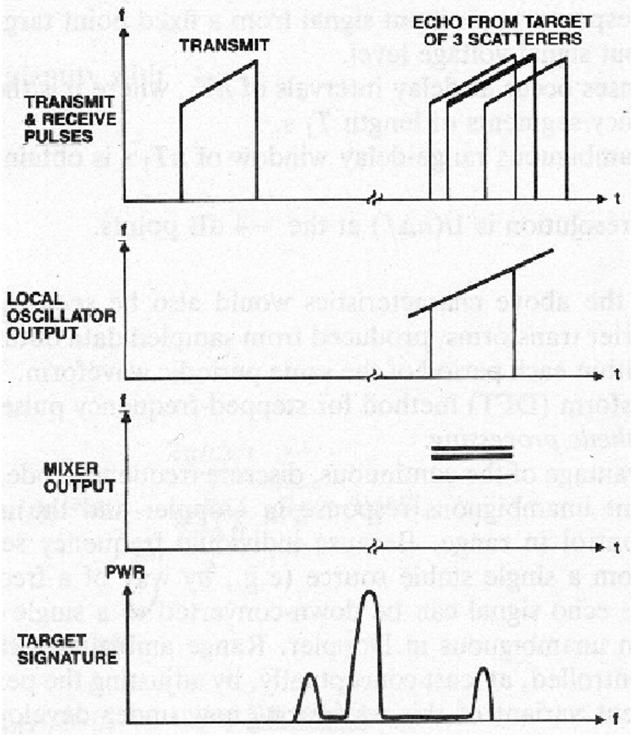
Dispersive delay line is a SAW device

SAW: surface acoustic wave

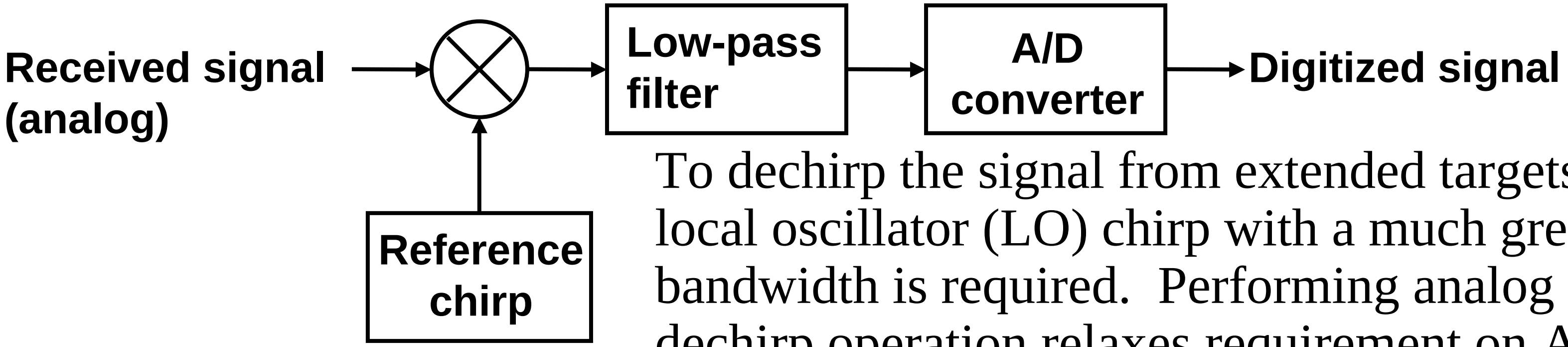
Stretch chirp processing





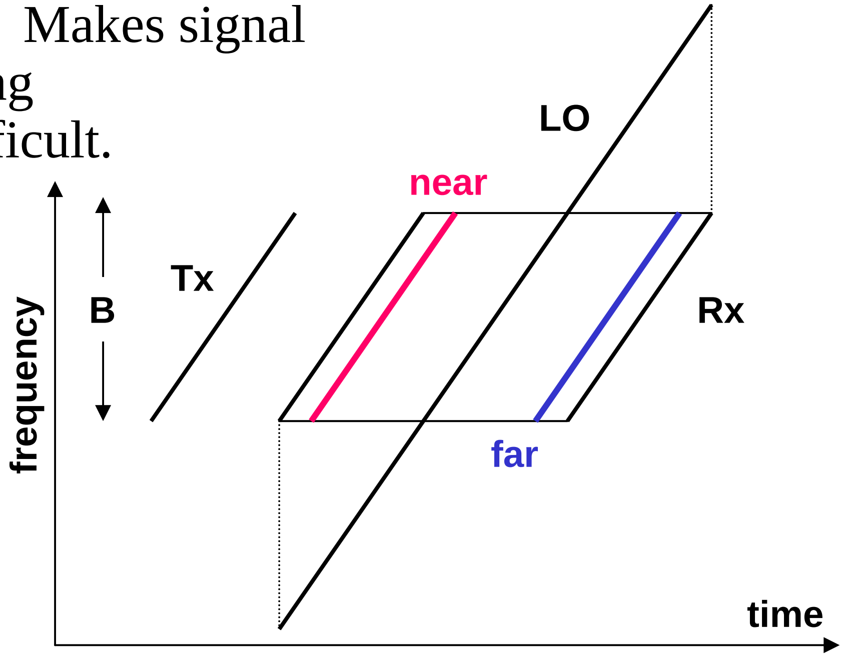


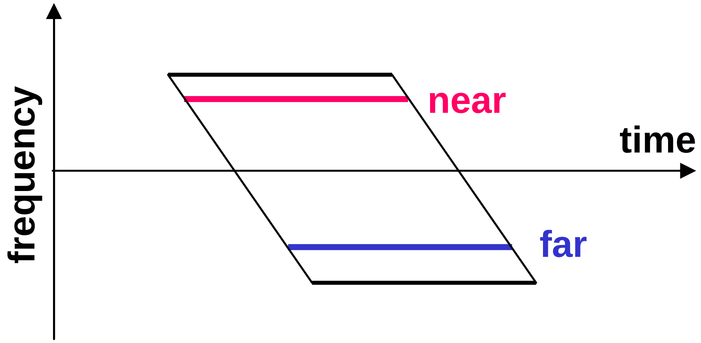
Challenges with stretch processing



To dechirp the signal from extended targets, a local oscillator (LO) chirp with a much greater bandwidth is required. Performing analog dechirp operation relaxes requirement on A/D converter.

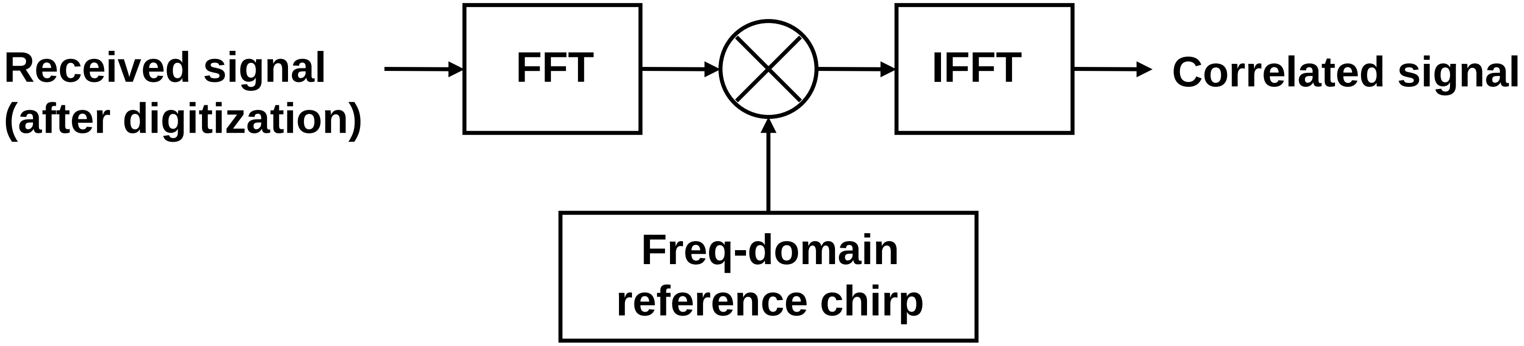
Echos from targets at various ranges have different start times with constant pulse duration. Makes signal processing
more difficult.





Correlation processing of chirp signals

- Avoids problems associated with stretch processing
- Takes advantage of fact that convolution in time domain equivalent to multiplication in frequency domain
  - Convert received signal to freq domain (FFT)
  - Multiply with freq domain version of reference chirp function
  - Convert product back to time domain (IFFT)



Received signal (after digitization)

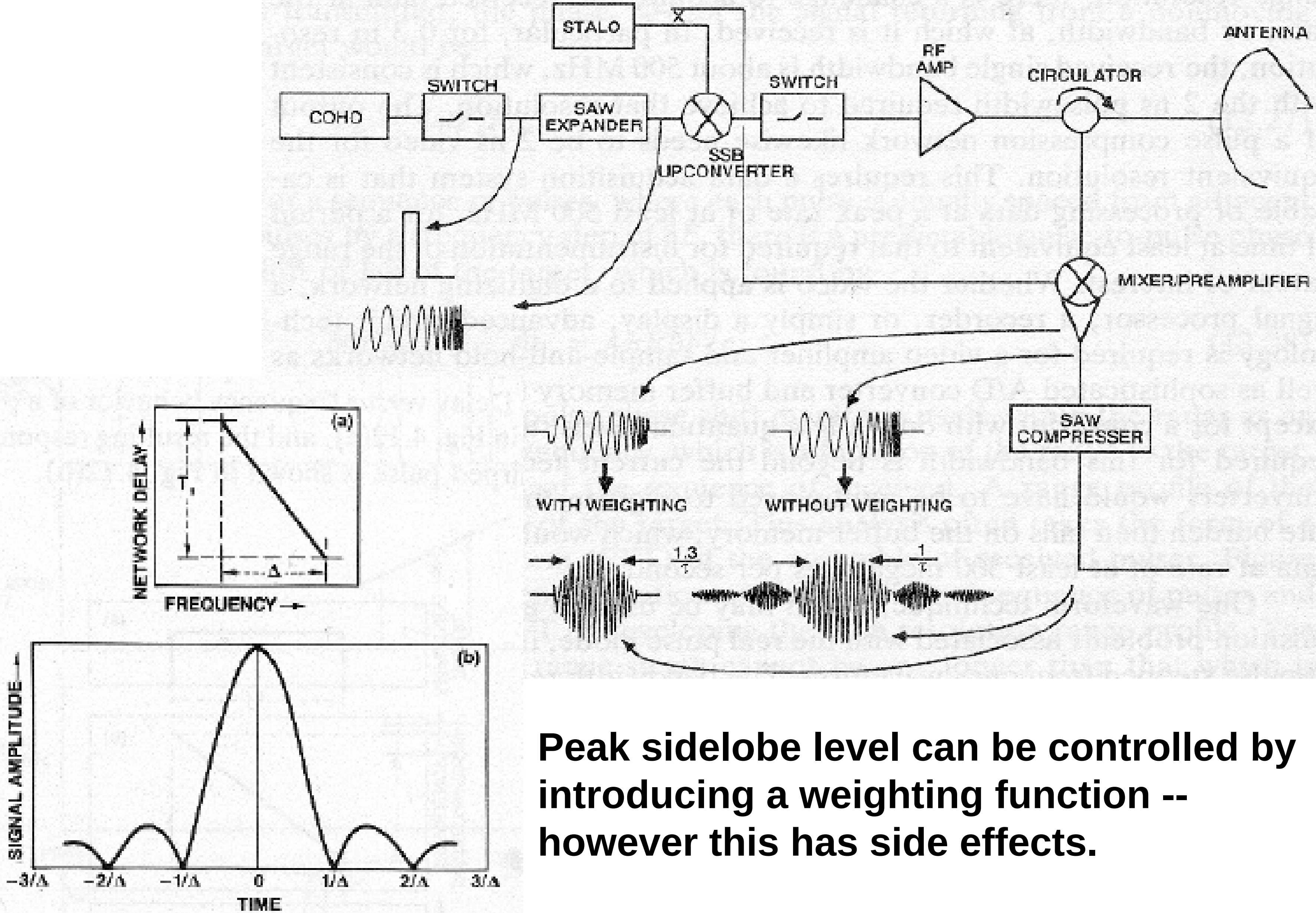
FFT

IFFT

Correlated signal

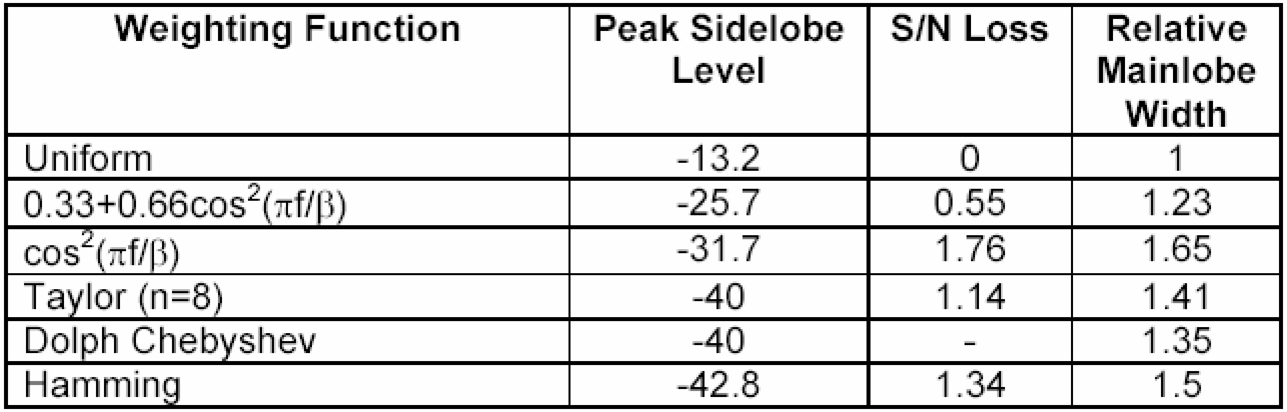
Freq-domain reference chirp

Chirp pulse compression and sidelobes



Peak sidelobe level can be controlled by introducing a weighting function -- however this has side effects.

Window functions and their effects



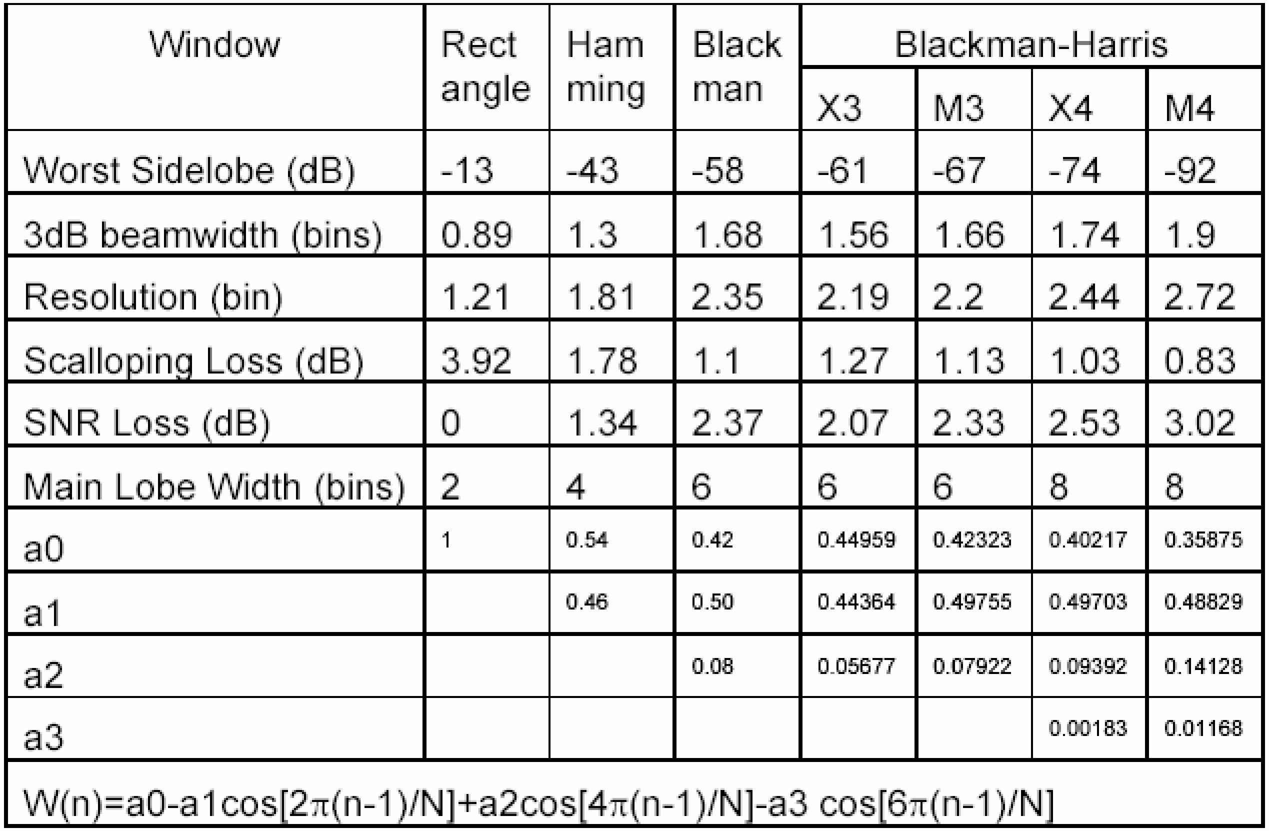
Weighting Function	Peak Sidelobe Level	S/N Loss	Relative Mainlobe Width
Uniform	-13.2	0	1
$0.33+0.66\cos^2(\pi f/\beta)$	-25.7	0.55	1.23
$\cos^2(\pi f/\beta)$	-31.7	1.76	1.65
Taylor (n=8)	-40	1.14	1.41
Dolph Chebyshev	-40	-	1.35
Hamming	-42.8	1.34	1.5

Time sidelobes are an side effect of pulse compression.

Windowing the signal prior to frequency analysis helps reduce the effect.

Some common weighting functions and key characteristics

Less common window functions used in radar applications and their key characteristics



Window	Rect angle	Ham ming	Black man	Blackman-Harris			
				X3	M3	X4	M4
Worst Sidelobe (dB)	-13	-43	-58	-61	-67	-74	-92
3dB beamwidth (bins)	0.89	1.3	1.68	1.56	1.66	1.74	1.9
Resolution (bin)	1.21	1.81	2.35	2.19	2.2	2.44	2.72
Scalloping Loss (dB)	3.92	1.78	1.1	1.27	1.13	1.03	0.83
SNR Loss (dB)	0	1.34	2.37	2.07	2.33	2.53	3.02
Main Lobe Width (bins)	2	4	6	6	6	8	8
a0	1	0.54	0.42	0.44959	0.42323	0.40217	0.35875
a1		0.46	0.50	0.44364	0.49755	0.49703	0.48829
a2			0.08	0.05677	0.07922	0.09392	0.14128
a3						0.00183	0.01168

$W(n)=a0-a1\cos[2\pi(n-1)/N]+a2\cos[4\pi(n-1)/N]-a3\cos[6\pi(n-1)/N]$

Window functions

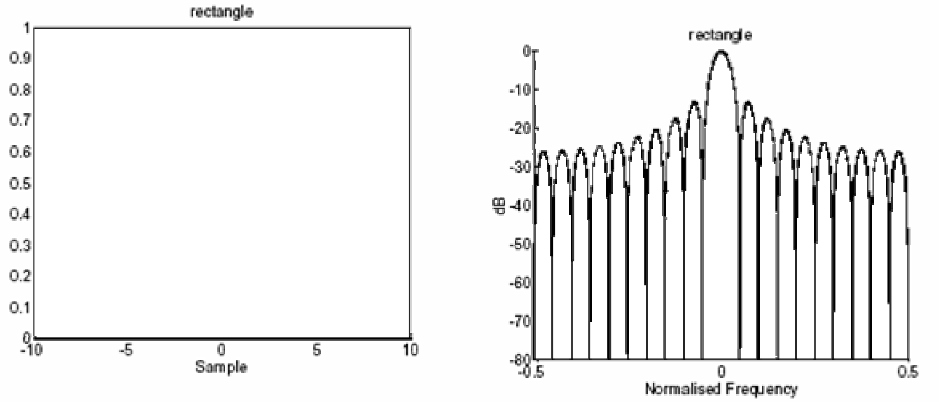
Basic function: $c_k = \cos\left(2k\pi(n - ½N) / N\right)$

a and b are the –6-dB and -∞ normalized bandwidths

Rectangular: $w(n) \equiv 1$

a=1.21, b=2

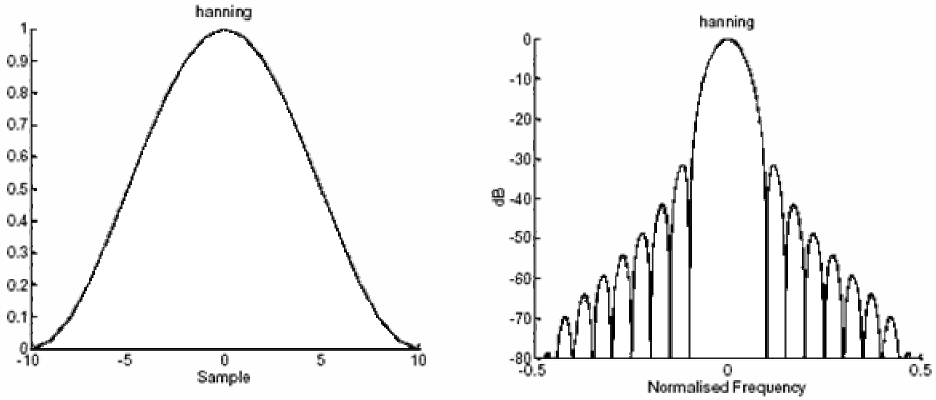
Sidelobe = -13dB



Hanning: $0.5 + 0.5c_1$

a=1.65, b=4

Sidelobe = –23dB

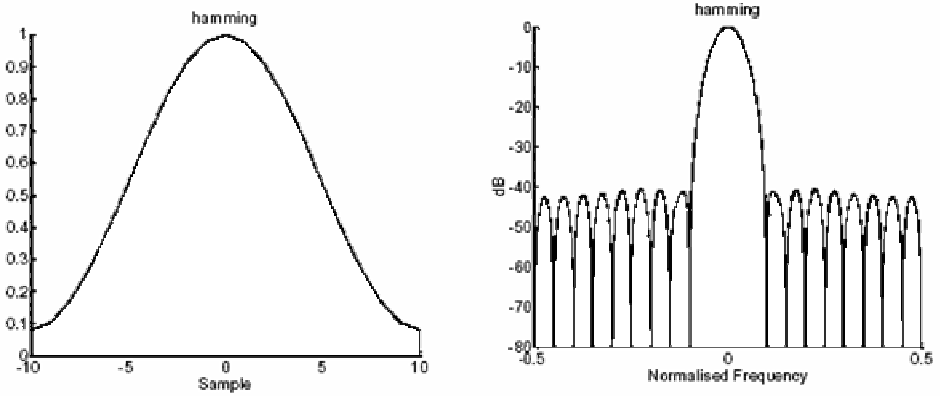


Window functions

Hamming: $0.54+0.46c_1$

a=1.81, b=4

Sidelobe = –43dB

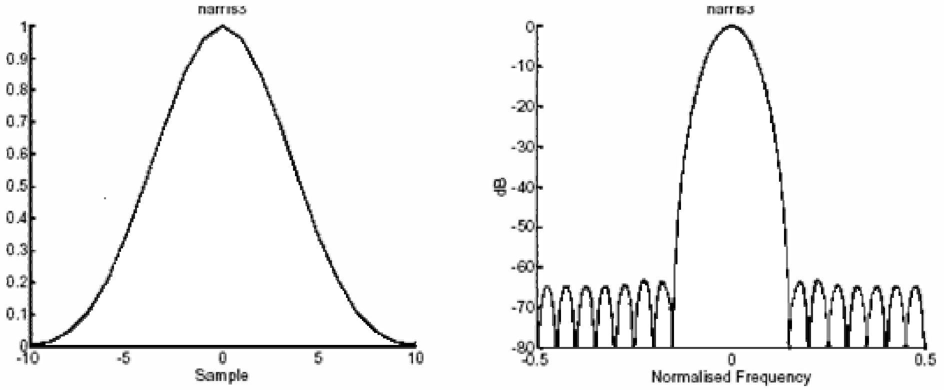


Blackman-Harris: 3 term

$0.423 + 0.498c_1 + 0.079c_2$

a=1.81, b=6

Sidelobe = –67dB

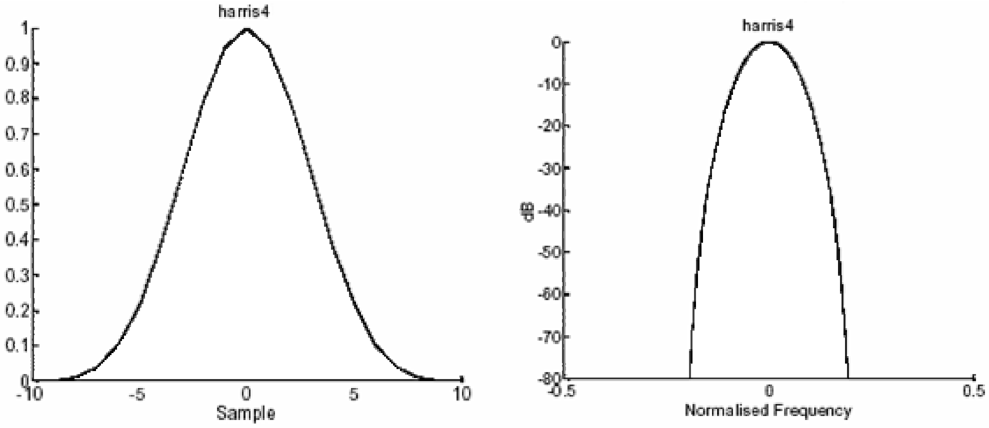


Blackman-Harris: 4 term

$0.359 + 0.488c_1 + 0.141c_2 + 0.012c_3$

a=2.72, b=8

Sidelobe = –92dB



Detailed example of chirp pulse compression

received signal

$$s(t) = a\cos(2\pi f_C t + 0.5\,k\,t^2 + \phi_C)$$

dechirp analysis

$$s(t)\,s(t-\tau) = a\cos(2\pi f_C t + 0.5\,k\,t^2 + \phi_C)\;a\cos[2\pi f_C(t-\tau) + 0.5\,k\,(t-\tau)^2 + \phi_C]$$

which simplifies to

$$s(t)\,s(t-\tau) = \frac{a^2}{2}[\cos(2\pi f_C\tau + k\,t\,\tau - 0.5k\,\tau^2)$$

sinusoidal term

$$+\;\cos(k\,t^2 + 2\pi\,2\,f_C t - k\,\tau\,t + 0.5k\,\tau^2 - 2\pi f_C\tau + 2\phi_C)]$$

chirp-squared term

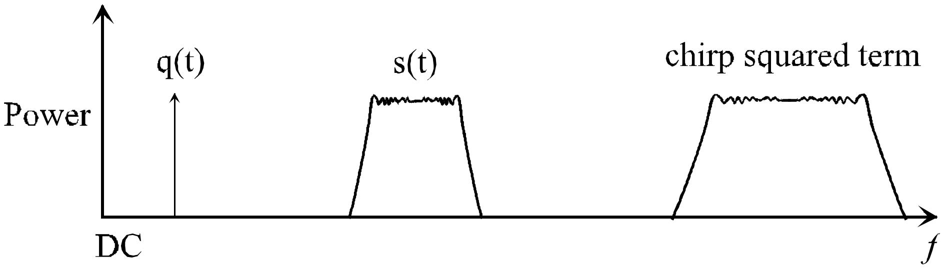
quadratic frequency dependence

linear frequency dependence

phase terms

after lowpass filtering to reject harmonics

$$q(t) = \frac{a^2}{2}\cos(2\pi f_C\tau + k\,\tau\,t - 0.5k\,\tau^2)$$



Conclusions

Pulse compression allows us to use a reduced transmitter power and still achieve the desired range resolution.

The costs of applying pulse compression include:

- added transmitter and receiver complexity
- must contend with time sidelobes

The advantages generally outweigh the disadvantages so pulse compression is used widely.