10

PULSE COMPRESSION

When we discussed pulse radar in Chapter 2, we described a number of advantages associated with radar operating with very short pulse widths. These advantages included superior range resolution and range accuracy, and small blind and minimum range.

In addition to these advantages, narrow pulse widths also assist radar when operating in a cluttered environment in Chapter 14. Radar also has an ability to perform limited target classification if operating with sufficiently narrow pulse widths [1], or sufficiently fine range resolution [2].

Chapter 5 described why pulse widths cannot be reduced indefinitely. Extremely narrow pulse widths result in wide receiver bandwidths and the associated problems with noise. Large receiver bandwidths effectively de-sensitise the radar receiver and either force the transmitter to transmit higher levels of peak power to compensate, or accept the consequential reduction in range. There are always limits on the amount of peak power available from the transmitter, and invariably a reduction in pulse width leads to a reduction in the maximum range of the radar.

In short, narrow pulse widths are desirable, but they are not always feasible. Pulse-compression radars make use of specific signal processing techniques to provide most of the advantages of extremely narrow pulses widths whilst remaining within the peak power limitations of the transmitter.

There are numerous waveforms suitable for use with pulse compression including binary or phase coding and linear frequency modulation. This chapter concentrates on linear frequency modulation (or the chirp pulse) which is the most prevalent of compression waveforms. Chapter 18 discusses the use of phase coding in an EW context but shows phase coding as a valid form of pulse compression.

10.1 CONCEPT OF OPERATION

10.1.1 Block Diagram

The block diagram for a pulse-compression radar is very similar to that of the standard pulse radar introduced in Chapter 2, and a simplified block diagram is shown in Figure 10.1.

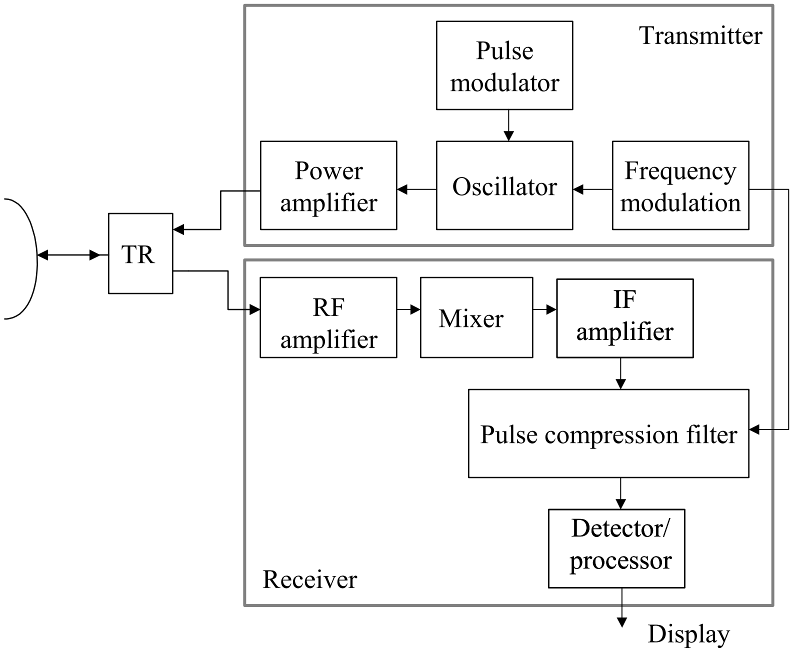


Figure 10.1. Block diagram of a simple pulse radar system.

The block diagram shows the frequency modulator responsible for generating the frequency-modulated (chirp) pulse. In addition to generating the transmitted pulse, the frequency modulator also plays a role in the design of the *pulse-compression filter*. The pulse-compression filter is an example of a *matched filter* because the filter is specially designed to recognise the characteristics of the transmitted pulse as they are returned to the receiver in the form of reflected pulses. To that end, the filter has been *matched* to the transmitted waveform. Received pulses with similar characteristics to the transmitted pulse are recognised by the matched filter where other received signals pass relatively unnoticed by the receiver.

10.1.2 Linear Frequency-Modulated Waveforms

The power of the pulse compression concept comes from the waveforms used. We concentrate on a popular pulse compression waveform called the linear frequency-modulated (or chirp) pulse.

The actual pulse train from a pulse-compression radar is the same as for any pulse radar. To the casual observer, the pulse train looks like an amplitude-modulated sinusoidal signal. To an extent, this is true, however the sinusoidal signal has now been frequency-modulated as well as amplitude-modulated. The modulation within each pulse (in this case, frequency-modulation) is the critical element of the pulse compression waveform. The modulation provides the basis and power of the compression concept. As stated earlier, the same modulation provides the basis for the design of the pulse-compression filter.

Figure 10.2 shows two ways to represent the pulses in a pulse train from a linear FM pulse-compression radar.

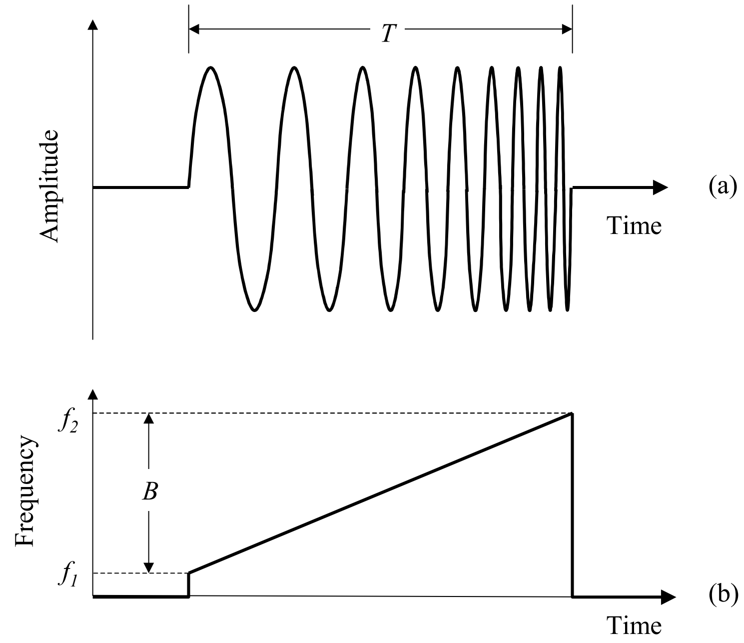


Figure 10.2. The amplitude of (a) a frequency-modulated pulse over time and (b) the frequency of the same pulse over time.

Figure 10.2 (a) shows the modulated sinusoidal signal that is transmitted by the pulse-compression radar. The pulse is characterised by its pulse width, which in the case of a pulse-compression radar is called the *uncompressed pulse width, T*. This pulse width is one of the critical characteristics of the pulse-compression radar. Figure 10.2 (b) shows the frequency change within the pulse as a function of time. The characteristic of interest in Figure 10.2 (b) is the bandwidth of the modulation within the pulse, *B*. The bandwidth is simply the difference between the highest and lowest frequencies within the uncompressed pulse.

To recognise the presence of the uncompressed pulse, the pulse-compression filter performs a *correlation* between the received pulse and the transmitted pulse. In this context, correlation is a signal processing term but it is directly analogous to the common English use of the term. The pulse-compression filter is simply looking for a strong correlation between what was transmitted and what was received. When a waveform similar to the waveform shown in Figure 10.2 (a) is passed through the matching pulse-compression filter, an interesting pulse called a *sinc* pulse results as the output of the filter. We have already encountered the sinc pulse in Chapter 3 and, therefore know that a sinc has a shape described by ($\sin x/x$). An example of a sinc pulse as it applies to the output of the pulse-compression filter is shown in Figure 10.3 and is characterised by a very narrow and tall central pulse surrounded by gradually decaying signals. The height and the width of the central pulse of the sinc pulse from the pulse-compression filter are dependent upon the bandwidth and pulse width of the uncompressed pulse.

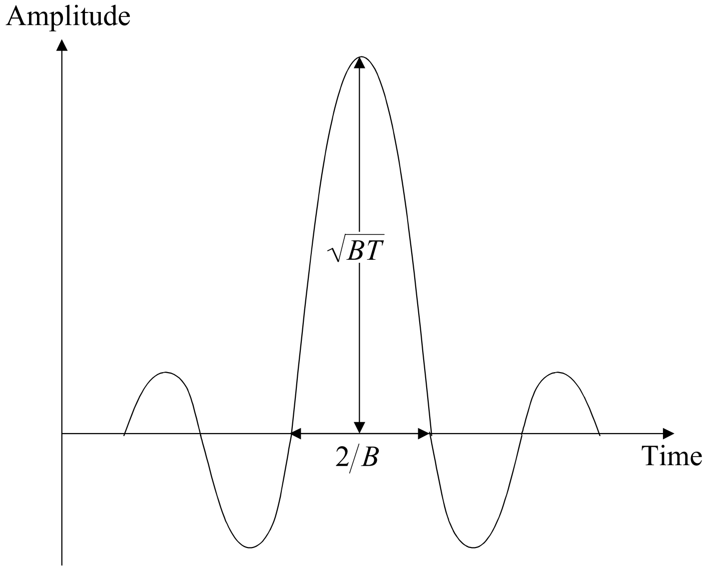


Figure 10.3. Typical output from a pulse-compression filter.

From Figure 10.3, the width of the sinc pulse is inversely proportional to the bandwidth of the uncompressed pulse and the height is proportional to the product of the bandwidth and uncompressed pulse width.

The output of the pulse-compression filter forms the input into the detector section of the pulse-compression radar. It is therefore desirable to have a very narrow and tall pulse (just as it is in a standard pulse radar system). The main points to note from Figure 10.3 are that the input to the filter is a relatively broad and low-power pulse. The output pulse, however, is very narrow and strong; two very desirable characteristics from a pulse radar.

The output of the pulse-compression filter shown in Figure 10.3 represents the amplitude of a signal rather than its power. To be consistent with the radar range equation, the output of the pulse-compression filter is converted into power that is taken as the square of the amplitude. When the signal in Figure 10.3 is converted into power, we see that the peak value of the pulse becomes the product of the modulation bandwidth, B and the uncompressed pulse width, T. This is known as the *pulse-compression ratio* of the pulse-compression radar.

$$\text{Pulse compression ratio} = B \times T \tag{10.1}$$

where B is the bandwidth of the modulation within each pulse in hertz and T is the uncompressed pulse width in seconds. As with radar antennas, we normally consider the usable portion of the sinc pulse to be half the null-to-null points in Figure 10.3. To that end, the width of the compressed pulse is simply the inverse of the modulation bandwidth, B.

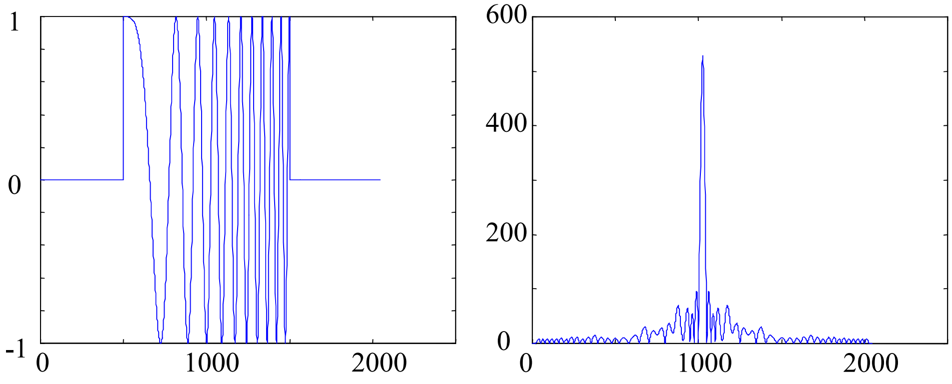
$$\text{Compressed pulse width} = \frac{1}{B} \tag{10.2}$$

where B is the bandwidth of the modulation within each pulse in hertz.

Pulse compression ratios in the hundreds are common in modern pulse-compression radar. For example, the AN/APS-134 is an airborne maritime surveillance radar that makes use of pulse-compression techniques especially when searching for submarine periscopes. In this mode of operation, the AN/APS-134 has a pulse compression-ratio of two thousand [3].

An elementary pulse-compression radar has been simulated using the MATLAB® to demonstrate the real power of the signal processing technique behind pulse compression.

Figure 10.4 shows an uncompressed chirp pulse representing the transmitted pulse, and the output of the corresponding pulse-compression filter when that pulse is processed. Note that the two graphs in Figure 10.4 are drawn on the same time scale (horizontal axis) to show how the process has compressed Figure 10.4 (b) into a very narrow pulse. Unfortunately, it is not possible to draw the amplitude axes (vertical axis) on the same scale due to the magnitude difference between Figure 10.4 (a) and (b). The amplitude of the pulse in Figure 10.4 (b) is approximately 500 times larger than Figure 10.4 (a).



(a) (b)

Figure 10.4. Real example of (a) an uncompressed and (b) compressed pulse.

It is fair to say that the results in Figure 10.4 are not realistic because the pulse passed through the matched filter has not suffered from noise or attenuation. Noise and attenuation are a real problem when operating radar systems, so the exercise has been repeated incorporating both random noise and signal attenuation, and is shown in Figure 10.5.

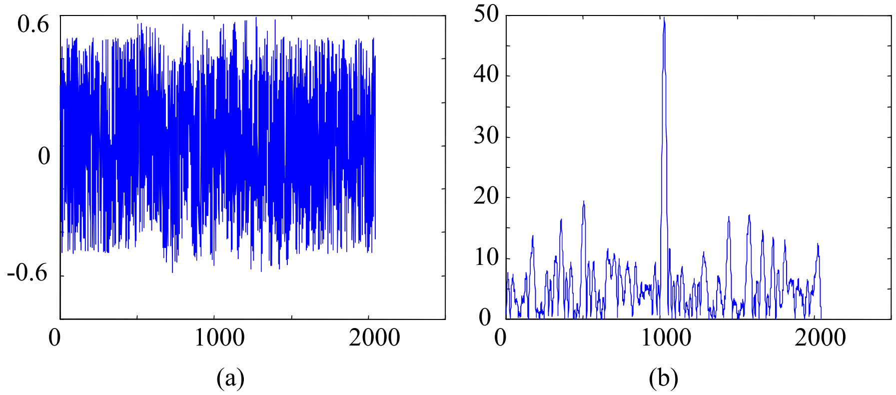


Figure 10.5. (a) Noise and attenuation and (b) its effect on the pulse compression process.

The output of the matched filter in Figure 10.5 (b) is now much noisier than the matched filter output in Figure 10.4 (b), which reflects the effects of the noise and attenuation of the input pulse. With that said, the output is still impressive from a peak amplitude and pulse-width perspective and the target is clearly visible.

10.2 REVISED RADAR RANGE EQUATION

The pulse-compression ratio measures the effective increase in the transmitted power of the pulse radar and the effective compression of the transmitted pulse. If the uncompressed pulse is transmitted with an actual peak power of, say, 1 MW and the pulse compression ratio, *BT*, is 100, the radar is effectively transmitting a peak power of 100×1 MW which is 100 MW. It is critical to note that 100 MW is the *effective radiated power* (ERP) of the radar, not the *actual* radiated power. The effective increase in power comes after the reflected pulse is received and processed by the pulse-compression filter. An ES system monitoring the radar transmission sees the results of the *actual* peak transmitted power, not the effect of the *effective* peak transmitted power.

When calculating the range performance of pulse-compression radar, the effective transmitted power (rather than the actual transmitted power) must be used as follows:

$$R_{\max} = \left(\frac{(BT) \times P_t \times G^2 \times \lambda^2 \times \theta \times n}{(4\pi)^3 \times S_{\min} \times L_s} \right)^{1/4} \qquad (10.3)$$

It may appear from (10.3) as though the pulse-compression radar is suddenly achieving much greater ranges due to the increase in the effective transmitted power. Unfortunately, the increased effective transmitted power (in the numerator of (10.3)) is accounted for by a related increase in S_{min} on the denominator. S_{min} increases with pulse compression ratio because the bandwidth of the receiver must be wide enough to handle at least the bandwidth, B, of the modulation within the pulse.

The main power-related benefit of pulse-compression radar is that it is able to achieve the maximum range performance of an equivalent narrow-pulse pulse radar with a much lower peak power level. This has a number of benefits. First, radars that are traditionally power-limited such as airborne radar can achieve impressive maximum ranges by using pulse compression. Secondly, radar systems that would traditionally involve the transmission of large peak power levels such as long-range air surveillance radars on warships can reduce their peak power levels without loosing range performance. From an EW perspective, radars that transmit low power levels are more difficult to detect and therefore more difficult to counter which is discussed further in Chapters 16 and 17 respectively. From a safety perspective, lower peak power also reduces the risks to personnel, fuel and ordnance associated with electromagnetic energy at radar (microwave) frequencies.

10.3 RANGE RESOLUTION

The range resolution of pulse-compression radar is a function of the compressed pulse width, not the uncompressed pulse width. The effective pulse width of the pulse-compression radar is given by (10.2). By substituting the compressed pulse width into the expression for range resolution (2.2), the range resolution of the pulse-compression radar is:

$$R_{res} = \frac{c}{2 \times B} \tag{10.4}$$

where R_{res} is the range resolution of the pulse-compression radar in metres, c is the speed of light (3×10^{8} ms^{-1}) and B is the bandwidth of the modulation within the pulse in hertz.

The range resolution of the pulse-compression radar is a major advantage of this type of radar, and is much better than that of traditional pulse radar systems. With that in mind, the pulse-compression radar is classified as a *high-resolution radar* within the context of this text.

The MATLAB code used to create Figures 10.4 and 10.5 is used to demonstrate the improvements in range resolution possible using pulse compression. Two returns have been positioned very close together (approximately one tenth of the uncompressed pulse width apart). Using conventional radar techniques, these two targets are unresolvable and would appear as one target following conventional processing. Figure 10.6 however demonstrates the output of the pulse-compression filter under these circumstances, where the two targets are clearly resolvable.

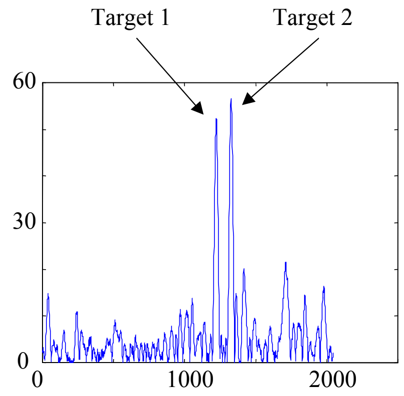


Figure 10.6. Two clearly resolved targets separated by one-tenth of the uncompressed pulse width.

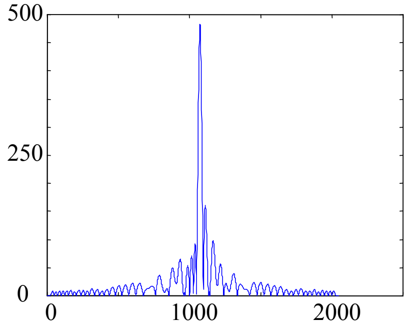


Figure 10.7. Output of the pulse-compression filter following a positive Doppler shift of the input.

10.4 MINIMUM OR BLIND RANGE

Minimum range or blind range is caused by the fact that the monostatic pulse radar cannot transmit and receive simultaneously. Whenever the radar is transmitting, therefore, it is blind. Pulse-compression radar is no exception. When calculating blind or minimum range for a pulse-compression radar, the uncompressed pulse width must be used in (2.2). This makes sense, as the radar has to transmit the entire uncompressed pulse before it is able to switch its duplexer and listen for reflections. Due to their relatively lengthy uncompressed pulse widths, pulse-compression radars normally have poor minimum and blind ranges.

The compressed pulse width is not used for the calculation of minimum or blind range.

10.5 DESIGN CONSIDERATIONS

Pulse-compression radar is not without its problems including increased complexity in both receiver and transmitter design, and undesirable results of the compression process known as *range sidelobes*.

10.5.1 Design Issues

By revisiting the preceding sections on pulse-compression radar, it is clear that the most impressive results come from radars transmitting extremely long uncompressed pulses with a high rate of modulation across them. These sort of pulses produce the largest pulse compression ratios. There is a limit on the extent to which radar designers can incorporate these features into their radar designs.

Broad pulse widths cause problems with respect to blind range or minimum range of the radar. Broad pulse widths can also fall victim more easily to enemy EW efforts as the EW equipment has increased time to prepare and attack the radar.

Large frequency deviations across the pulse place considerable load on both the transmitter and receiver equipment. The transmitter needs to be capable of producing the large frequency variation over a short period of time and the receiver needs to have the bandwidth to process the reflections.

The frequency issues are becoming less of an issue as equipment technology improves, however the physical limitations associated with broad pulse widths remain regardless. To that end, pulse compression ratios are most likely to be increased by improvements in the bandwidth of the uncompressed pulse rather than by increasing the uncompressed pulse width.

10.5.2 Range Sidelobes

When looking at the output of the pulse-compression filter, the sidelobes either side of the central pulse are reasonably large. These sidelobes are called *range sidelobes* (as opposed to *antenna sidelobes*). The range sidelobes are a direct consequence of the pulse-compression filtering process. They are undesirable because they can lead to false alarms and range ambiguity.

The solution to the range sidelobe problem is to use a weighting factor in the pulse-compression filter that effectively *detunes* or *mismatches* the filter and consequently attenuates the sidelobe levels. Unfortunately, the advantages of the pulse compression process are slightly reduced by this technique in that the compressed pulse will have a reduced amplitude and an increased pulse width.

10.5.3 Doppler Shift

Large Doppler shifts in the transmitted pulse may be caused by high velocity targets. This shift may adversely affect some pulse-compression filters in that the received pulse may fall outside the range of the pulse-compression filter. This means that the received pulse no longer "matches" the pulse expected by the filter.

A possible solution is to use a bank of filters to ensure that the reflected pulse is processed by at least one filter. Fortunately, research has shown that the Chirp pulse explained in this chapter is extremely Doppler tolerant. Even if the pulse suffers substantial Doppler shift, the pulse-compression filter still processes the pulse.

A received pulse has been up-shifted in frequency (simulating a closing target) and passed through the original pulse-compression filter. The result shown in Figure 10.7 demonstrates the Doppler tolerance of the chirp pulse as Figure 10.7 is very similar to Figure 10.4 (b).

10.5.4 EW Susceptibility

The relatively long uncompressed pulse length associated with pulse-compression radars restricts the minimum range of the radar. A potentially more critical weakness caused by long pulse widths is the additional time they provide adversary EW efforts to sample, replicate and deceive the radar system. This is discussed further in Chapters 16, 17 and 18.

10.5.5 Receiver Design

Pulse-compression radars necessarily require sophisticated receivers that incorporate the pulse-compression filter to match the transmitted pulse. To put this comment into context, however, the pulse-compression radar results in extremely narrow compressed pulses. To match the performance of this narrow pulse width with conventional radar would require exceptionally capable receivers.

Although the pulse compression receiver is complex, therefore, it is not as complex as the conventional receiver would need to be to process a pulse of the width of the compressed pulse.

10.6 WORKED EXAMPLE

Recall the worked example (Example 5.3) that discussed the situation of a submarine periscope and a shipborne radar system. The submarine's ES mast has an RCS of 3 m^2 and the radar operates at 5 GHz. The submarine was 15 km from a ship, and the radar had the following operating characteristics:

Type = Simple pulse radar with pulse integration

Peak transmitted power = 1 MW

Antenna gain = 4000

Antenna scan rate = 10 RPM

Antenna beamwidth = 1.25^o

PRF = 528 Hz

S_{min} = 0.095 μW

System losses = 12 dB

In this case, the radar had a maximum range of only 5 km against the submarine’s periscope.

Example 9.1. Instead of being a simple pulse radar with integration, the radar is now known to be a pulse-compression radar with pulse integration. It has an uncompressed pulse width of 100 μsec and a pulse modulation bandwidth of 2 MHz.

Recalculate with the additional information and reassess the safety of the submarine.

$$
\begin{aligned}
R_{\max} &= \left(\frac{(BT) \times P_t \times G^2 \times \lambda^2 \times \theta \times n}{(4\pi)^3 \times S_{\min} \times L_s} \right)^{1/4} \\
&= \left(\frac{200 \times 1 \times 10^6 \times 4000^2 \times 0.06^2 \times 3 \times 11}{(4\pi)^3 \times 0.095 \times 10^{-6} \times 15.85} \right)^{1/4} \\
&\approx 19{,}000\text{m} \\
&= 19 \text{ km}
\end{aligned}
$$

Clearly the additional information regarding the presence of pulse compression has changed the outcome of the scenario. With this additional information, the crew of the submarine would definitely consider themselves in danger of detection and take appropriate action. The radar system did not increase its transmitted power levels, but the presence of pulse compression gave the radar additional effective power previously unaccounted for.

10.7 SUMMARY

The concept of pulse-compression was introduced in this chapter using the linear FM (or chirp) pulse as an example. Pulse-compression results in increased ERP of the radar system and a compression of the effective pulse width of received pulses, leading to range advantages and range resolution improvements. The effectiveness of pulse-compression is determined by the width of the uncompressed pulse and the bandwidth of the modulation within the uncompressed pulse. The most impressive results come from broad uncompressed pulse widths containing a modulated pulse with a large bandwidth.

The concepts introduced in Chapter 2 and Chapter 5 were revisited as the impact of pulse-compression on range resolution, minimum or blind range, and maximum range (as determined by the RRE) was discussed.

Problems associated with pulse-compression radar including range sidelobes and receiver complexity were also discussed.

10.8 REVISION QUESTIONS

1. A pulse-compression radar uses linear FM as the modulation method. The modulation has a bandwidth of 2 MHz and the uncompressed pulse width is 200 μsec. Calculate the pulse-compression ratio and the compressed pulse width of this radar. (400, 500 ns)
2. Explain four advantages or strengths enjoyed by pulse radars with very narrow-pulse widths. What practical considerations limit the implementation of such narrow-pulse radars? Describe in very general terms how pulse compression achieves very narrow pulse widths whilst staying within practical design limitations.
3. From the equations relating to pulse compression, it appears beneficial to have as wide an uncompressed pulse as possible (to achieve very narrow compressed pulses of enormous amplitudes). Why can't uncompressed pulse widths be increased indefinitely?

ENDNOTES

1 Skolnik, M.I., *Introduction to Radar Systems*, Sydney: McGraw-Hill, 1988, p. 434.

2 Stimson, G.W., *Introduction to Airborne Radar*, New Jersey: SciTech Publishing Inc., 1998, p. 393.

3 Jane's Radar and Electronic Warfare Systems 1999-00, *AN/APS-134(V)/-134 (Plus) Maritime Surveillance Radars*, Jane's Information Group, 1999.