Chapter 2
Radar Fundamentals

Radars are electronic systems that can detect and track objects. They can provide a highly accurate measurement of the distance, velocity and direction of the detected objects. In principle, every radar system (a) transmits electromagnetic energy to search for objects in a specific volume in space (b) detects the energy reflected from objects in that volume (c) measures the time between the two events, and (d) ultimately provides estimates of range, amplitude and velocity of the objects based on the detected energy and measured time. Several other conventional systems, including infrared and video sensors, have typically been used to perform the above functions, but radars have a significant advantage of being highly immune to environmental and weather conditions [10]. With technological advances leading to inexpensive radars, they are well-poised to replace existing low-functionality systems.

This chapter focuses on the basics of radars and reviews popular radar architectures, radar performance parameters and several performance enhancement techniques. The reader is referred to other texts for more detailed and comprehensive treatments of the subject [24, 25].

2.1 Radar Architectures

Several radar architectures have been studied and employed during the last century [1]. In the context of automotive radars, only a few architectures are of relevance, and can be classified into two categories: continuous-wave (CW) and pulsed. Performance of simple radars is seldom adequate for most applications and performance-enhancing techniques are almost always employed. One technique common to all radars is pulse compression, which is essentially frequency or phase modulation (FM/PM) of the radar signal for object detection at long range with adequate resolution, and will be described in a later section. Several architectures and techniques can be combined to form hybrid radars. Radar architectures are described in more detail in the following.

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2.1.1 Continuous-Wave Radars

Continuous-Wave (CW) radars transmit unmodulated or modulated frequency carrier as the radar signal. A simple unmodulated signal can only detect object velocity and not range, and hence is not useful in an automotive setting, which requires reliable detection of zero relative-velocity targets. In order to measure range, modulation of the radar signal is essential. Two popular modulation schemes in automotive CW radars are (a) Frequency chirp and (b) Pseudo-random Noise (PN) coding.

2.1.1.1 Frequency Chirped Radars

Frequency chirp architecture is the most popular for automotive radars, and has been employed traditionally in long-range high-power radar implementations. In frequency-chirped radars, the frequency of the radar signal is varied according to a pre-determined pattern. The most widely used patterns are (a) frequency-stepped, in which frequency is changed by a step in each time period and (b) linear frequency modulation (LFM), in which transmit frequency is changed continuously within each time period. This varying frequency essentially widens the bandwidth of the radar signal, which is equivalent to narrowing the signal in the time-domain. While detecting the velocity of the object, this pulse compression technique readily measures the range of the object. One of the main disadvantages of CW radars is that they suffer from limited dynamic range due to finite isolation between receive and transmit paths. In addition, the range resolution of frequency-chirped radars is dependent on the speed and bandwidth of the chirp, leading to stringent requirements on local-oscillator phase noise.

2.1.1.2 Pseudo-Random Noise Coded Radars

Pseudo-Random Noise (PN) codes are extensively used in communication systems for increased data-rate and superior interference-resilience [26]. A PN code is basically a binary periodic sequence with noise-like properties. It can readily be generated using a feedback shift register implemented with conventional digital circuits. Pulse compression in the context of PN coded radars is the same as coding or processing gain of the PN code [24]. PN codes are also known as spreading codes, and PN coded radars as direct-sequence spread spectrum (DSSS) radars, in conformity with their communications counterpart. While PN coded radars are robust to interference, their dynamic range is limited by the auto-correlation properties of the PN code. Furthermore, typical implementations of PN coded radars require complex frequency generation circuitry. Dynamic range limitations restrict the operating range of PN coded radars to 10 m typically [2]. A 79-GHz PN coded BPSK transmitter for short-range applications was recently presented [11], but no range performance was reported.

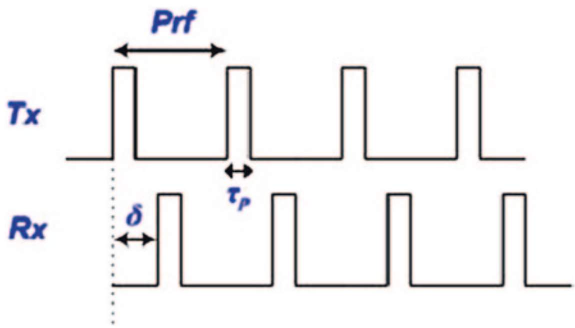

Fig. 2.1 Typical transmit and receive waveform envelopes in a pulsed-radar

2.1.2 Pulsed Radars

A pulsed-radar transmits modulated pulses at periodic intervals of time (i.e., a train of modulated pulses) as illustrated in Fig. 2.1. Range is readily extracted by measuring the time delay between the instants of pulse transmission and reception. Object velocity can be determined by measuring the rate of change of range, or by employing a bank of Doppler filters [24]. Pulse radar waveforms are characterized by three main parameters: (a) pulse-width, τ_p (b) carrier frequency, f_0 and (c) pulse repetition frequency, prf. The prf must be chosen to avoid range and Doppler ambiguities and to maximize average transmitted power. Range ambiguity decreases with decreasing prf, while Doppler ambiguity decreases with increasing prf. Radars with high prf are usually called pulsed Doppler radars. Intentional pre-determined jitter is sometimes introduced in the prf in order to avoid blind speeds and range and Doppler ambiguities.

In a pulsed-radar, the transmitter (TX) and the receiver (RX) essentially operate in a time-duplexed manner, and hence a high dynamic range can be attained. Although a complex timing engine with delay circuitry is required, pulsed radar is the simplest architecture to implement. Pulse compression is usually achieved using Binary Phase Shift Keying (BPSK) with Barker codes (more details in Sect. 2.7). In most of the following discussion, a pulsed-radar architecture is assumed.

2.2 Radar Range

The maximum target distance that radar can detect is usually referred to as the radar range. The target range, R, for a given pulse is determined by measuring the time delay, δ, it takes the pulse to travel the two-way path between the radar and the target. It is given by,

$$R = \frac{c\delta}{2}, \tag{2.1}$$

where $c = 3 \times 10^8$ m/s is the speed of light.

In order to avoid range ambiguity, after a pulse is transmitted, a pulsed radar must wait sufficiently long before it can transmit another pulse. This ensures that any returns from the targets at maximum range are detected. Then, for a given prf, the maximum unambiguous range can be determined as

$$R_u = \frac{c}{2 \cdot prf}. \tag{2.2}$$

2.3 Range Resolution

Range resolution is a radar performance metric, which measures the ability of the radar to detect objects in close proximity as distinct objects. The range resolution of radar determines the width of range gates or bins. It is easily observed that two objects need to be separated by at least $\tau_p/2$ in order to produce two distinct echo signals. Hence, the radar range resolution, ΔR, is given by

$$\Delta R = \frac{c\tau_p}{2} = \frac{c}{2B}, \tag{2.3}$$

where $B = 1/\tau_p$ is the signal bandwidth.

Short-range sensors demand high range resolution radars, implying wide signal bandwidth, and thus narrow pulses. This results in reduced average transmitted power. To maintain adequate range resolution without sacrificing transmitted power, pulse compression techniques must be employed.

2.4 Doppler Frequency

When a target is moving relative to the radar, the center frequency of the returned pulses is different from that of the incident pulses. The difference between the two is known as the Doppler shift or velocity, or just Doppler. It is given by

$$f_d = \pm\frac{2v}{\lambda} = \pm\frac{2v f_0}{c}, \tag{2.4}$$

where v is the target relative velocity, and λ is the radar wavelength. The shift is positive for an approaching target and negative for a receding target. If the target velocity is not in the radar line of sight, the Doppler shift becomes

$$f_d = \pm\frac{2v}{\lambda}\cos\theta = \pm\frac{2v f_0}{c}\cos\theta, \tag{2.5}$$

where $\cos\theta = \cos\theta_e \cos\theta_a$, μ_e is the elevation angle, and μ_a is the azimuth angle of the radar antenna.

2.5 Signal-to-Noise Ratio

Much of the determination of radar specifications depends on the required signal-to-noise ratio (SNR) at the radar receiver output, as will be shown theoretically in the next section. SNR itself depends on the required probability of detection and probability of false alarms for the radar. Probability of detection is the probability that the receiver output is above the detector threshold (i.e., the level above which an object is said to be detected) in the presence of signal and noise. Similarly, probability of false alarm is the probability that the receiver output is above the threshold in the presence of noise only. Determination of SNR from the aforementioned probabilities is complicated. A very accurate approximation is given by [27]

$$P_d \approx 0.5 \times erfc(\sqrt{-\ln P_{fa}} - \sqrt{SNR + 0.5}), \tag{2.6}$$

where P_d is the probability of detection, P_{fa} is the probability of false alarm, and erfc is the complementary error function.

2.6 The Radar Equation

The radar equation relates various radar system parameters to its range performance. It can be used to determine the required parameters from a given set of radar specifications. The power density at a distance R from a radar employing a directive antenna with gain G is given by Friis power transmission equation [28],

$$P_D = \frac{P_t G}{4\pi R^2}, \tag{2.7}$$

where P_t is the transmitter output power. When the radar signal is incident upon an object or target, it is scattered or radiated back. The amount of this radiation depends on the target size, orientation, shape and material, which are accounted for by an equivalent parameter called the radar cross section. It is the ratio of the power reflected by the target to the power density incident on it, and is denoted by σ. Thus, the total power received by the radar antenna is

$$P_r = \frac{P_t G \sigma A_e}{(4\pi R^2)^2}, \tag{2.8}$$

where A_e is the effective antenna aperture. A_e is related to the antenna gain by

$$G = \frac{4\pi A_e}{\lambda^2}. \tag{2.9}$$

Substituting A_e from (2.9) in (2.8),

$$P_r = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4}. \tag{2.10}$$

(2.10) can be re-arranged to determine target distance, R, as

$$R = \left(\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 P_r} \right)^{1/4}. \tag{2.11}$$

Given the minimum detectable signal power, P_{min}, at the receiver, the radar maximum range, R_{max}, is readily obtained as

$$R_{\max} = \left(\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 P_{\min}} \right)^{1/4}. \tag{2.12}$$

P_{min} can be written as

$$P_{\min} = kT_e B_n F (SNR_o)_{\min}, \tag{2.13}$$

where $k = 1.38 \times 10^{-23}$ Joules/Kelvin is the Boltzmann's constant, T_e is the effective noise temperature, B_n is the receiver noise bandwidth, F is the receiver noise factor (the ratio of input signal-to-noise ratio to output signal-to-noise ratio), and $(SNR_o)_{min}$ is the minimum required signal-to-noise ratio (SNR) at the receiver output. The radar range is then

$$R_{\max} = \left(\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 k T_e B_n F (SNR_o)_{\min}} \right)^{1/4}. \tag{2.14}$$

Equivalently, the minimum output SNR is given by

$$(SNR_o)_{\min} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 k T_e B_n F R^4}, \tag{2.15}$$

which is widely known as the radar equation (no radar losses and pattern propagation factors have been included for brevity). Usually, minimum output SNR is first determined from the probabilities of detection and false alarm. Then, the other parameters are calculated for a desired range performance. Due to implementation problems, most pulsed radars can not achieve sufficient output SNR for a desired range performance, with a single-pulse. This limitation is often resolved by integrating (coherently or incoherently [24]) several pulses returned from an object. Ideally, coherent integration of N pulses results in an N-times improvement in SNR, but system imperfections cause some amount of integration loss. The radar range can then (ideally again) be written as

$$R_{\max} = \left(\frac{P_t G^2 \lambda^2 N \sigma}{(4\pi)^3 k T_e B_n F (SNR_o)_{\min}} \right)^{1/4}, \tag{2.16}$$

where N is the number of integrated pulses.

Fig. 2.2 Barker codes

Code length	Code elements	Sidelobe level (dB)
2	+ −, + +	−6.0
3	+ + −	−9.5
4	+ + − +, + + + −	−12.0
5	+ + + − +	−14.0
7	+ + + − − + −	−16.9
11	+ + + − − − + − − + −	−20.8
13	+ + + + + − − + + − + − +	−22.3

2.7 Pulse Compression

It was shown in Sect. 2.3 that short pulses exhibit better range resolution. But, this leads to a reduced average transmitted power, thereby reducing the radar range. In order to obtain average transmitted power of a long pulse and a range resolution of a short pulse, the signal can be frequency or phased modulated. This process is known as pulse compression.

Linear FM, PN coding and phase-coding are the most commonly used pulse compression techniques. High code-sidelobes are undesirable because noise and jammers located in the sidelobes may interfere with the target returns in the main lobe. While linear FM is easily implemented, its first sidelobe is approximately 13.2 dB below the main peak [24], which may not be sufficient for most radars. In phase-coding, a pulse is divided into sub-pulses, each of which has a particular phase selected according to a code sequence. The length of the code is known as the compression ratio. The most popular codes are the binary sequences, which have two phases. For binary sequences, it is highly desirable that the peak sidelobe of the autocorrelation function is the minimum possible for a given code length. One class of binary codes is the Barker code, which has optimal autocorrelation properties, and hence, is widely used in pulsed radars. All known Barker codes are listed in Fig. 2.2 with the corresponding sidelobe levels [24]. No Barker codes longer than 13 have been found to exist, and hence the maximum achievable compression ratio is 13. However, two or more Barker codes can be combined to generate higher compression ratios, although with sub-optimal autocorrelation. Barker codes (or binary codes in general) can be easily implemented using BPSK modulation.

For compression ratios larger than 13, PN coding is usually employed. PN codes and their generation were discussed in Sect. 2.1.1.

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