Chapter I

1

Radar Principles

Chapter outline:

I. 1 Introduction

A RADAR (**RA**dio **D**etection **A**nd **R**anging) is an electrical system that transmits radiofrequency (RF) electromagnetic (EM) waves toward a region of interest and receives and detects these EM waves when reflected from objects in that region. The details of a radar system vary from one to another. Radar is placed among its surroundings in space, it sends, receives, and processes signals in time. These signals are described by their spectra and statistical distributions. Thus, radar is a detection system that uses radio waves to determine the range (distance), azimuth angle, and/ or radial velocity of objects of interest. It can be used to detect aircraft, ships, spacecraft, guided missiles, motor vehicles, weather formations, and terrain.

A radar system consists of a transmitter producing electromagnetic waves in the radio or microwaves domain, a transmitting antenna, a receiving antenna (often the same antenna is used for transmitting and receiving), a receiver and processor to determine properties of the objects. Radio waves (pulsed or continuous) from the transmitter reflect of the object and return to the receiver, giving information about the object's location and speed. Radar was developed secretly for military use by several nations in the period before and during World War II. A key development was the cavity magnetron in the UK, which allowed the creation of relatively small systems with sub-meter resolution [38].

This chapter is organized as follows. Section I. 2 presents different elements of monostatic radar system where radar cross section and radar equation that provide the maximum range are also given. Section I. 3 describes the two types of radar clutter (i.e., surface clutter and volume clutter) and then presents statistical models characterizing low and high resolution radar echoes. Section I. 4 outlines target models found in the open literature. Finally, a conclusion is drawn in Section I.5.

I. 2 Radar Systems

As discussed earlier, radar is an object-detection system that uses radio waves to determine the range, angle, or velocity of objects.

I. 2. 1 Main monostatic radar components

A typical arrangement of stages for a basic monostatic radar is shown in Figure I. 1. The radar timing is contained in the coherent oscillator and trigger generator box. The coherent oscillator provides the phase reference for the radar and the basic timing clock [1, 39]. Radar components cover a wide range of sizes and use a number of different special techniques so that they are normally developed by specialists in their own field.

A number of common factors must be observed throughout the design of radar, such as the avoidance of signal distortion, which requires a wide dynamic range, and the best arrangement of the stages using the components at hand. As long as no signals are distorted or suppressed, linear signal processing may take place in any order, and the processes used in analogue processing (mostly at intermediate frequency), and digital processing (digital representations of a two-phase video signal) are equivalent [1, 2, 39].

- Transmitter:

The transmitter converts mains power into radio frequency power, which leaves the radar by the antenna to illuminate its surroundings in the same way as a searchlight. The waveguide or transmission line system connects the transmitters and receivers to a common antenna.

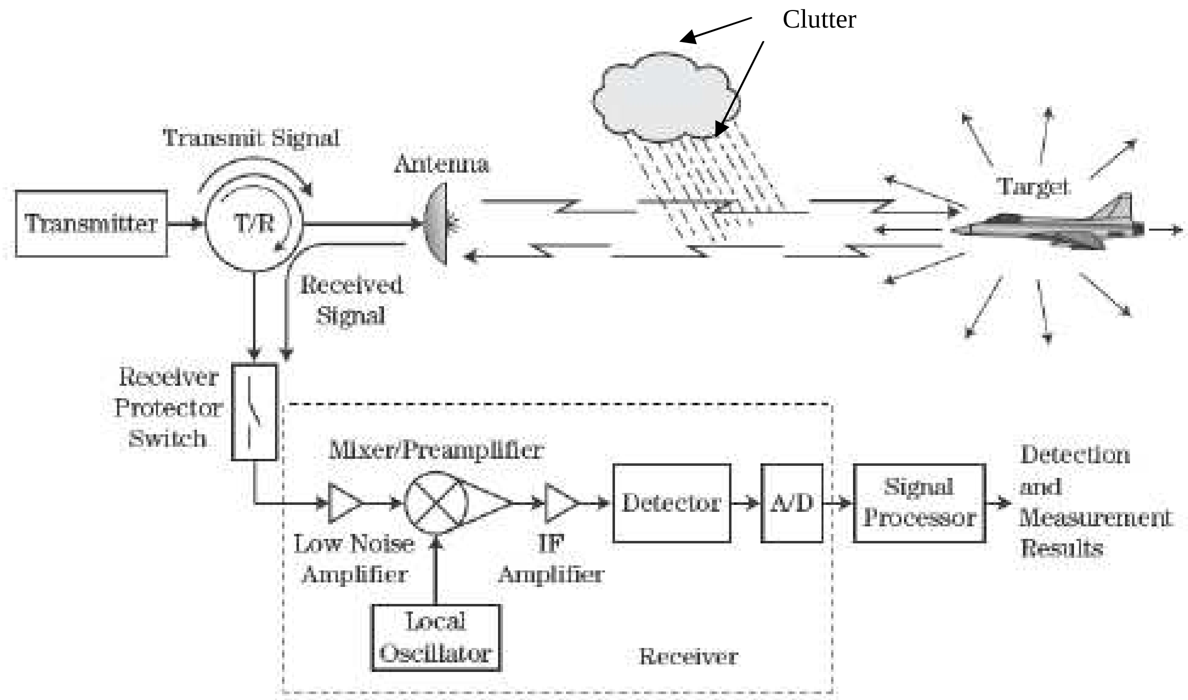


Figure I. 1: Major elements of the radar transmission/reception process [1]

- Antenna:

The antenna directs the transmitter energy into a beam that illuminates the radar's surroundings. The echoes of the illumination are gathered by the antenna for the receivers. The antenna is the principal filter to attenuate signals (interference or jamming) coming from other directions. Once the radio frequency energy leaves the antenna, it is subject to atmospheric refraction and attenuation.

- Receiver:

The receiver is normally a super heterodyne receiver with one or more intermediate frequencies. The first stage of the receiver is the principal component that defines the noise level and thus the sensitivity of the radar. The signals that arrive at the signal processor must not be distorted so they may be separated into the original components without the distortion components. The use of sensitivity time control (STC) reduces the necessity for a very wide dynamic in the receiver circuits. The matched filter has a shape and a bandwidth that gives best selection of signal energy out of the mixture of signals and noise coming from the receiver. These filters are often difficult to produce, so commonly simpler filters are used, called matching filters.

- Detector:

The intermediate frequency signals need to be detected before they can be displayed. Simpler detectors reject either phase or amplitude information and change the statistics of the thermal noise on a theoretical carrier from the receiver. Coherent signal processors, which follow detectors, require the full amplitude and phase information in the echo signals. This information is preserved in vector detectors. The most common detector circuit is a synchronous detector that develops the in-phase (I) component of the vector and the quadrature (Q) phase component.

- Analog-to-digital converter:

Digital signal processors perform arithmetic on trains of binary numbers that represent the signals. Analogue to digital converters convert the signals, normally from a vector detector, to digital form. The side effects are the limiting of the dynamic range, quantization noise, and distortion. Even in more modern systems in which the signal is sampled at the intermediate frequency (IF) with a single analog-to-digital converter (ADC), an algorithm implemented in the system firmware constructs the I and Q components of the signal for processing the envelop, $V = \sqrt{I^2 + Q^2}$.

- Signal processor:

Signal processing may take place during one sweep, many sweeps, and many scans. Radar echoes are a mixture of wanted echoes (for example, aircraft) and clutter echoes (often from land, sea, weather, or birds), which are generally of no interest. Signal processing tries to filter the echoes for the user and match them to his display. Modern digital processing often causes the echoes to be displayed as synthetic shapes that show only the information for which it has been preprogrammed. In contrast, radar operators who use older equipment are used to identifying echoes by size, shape, and movement. The evaluation of these criteria takes time and greatly reduces the number of echoes that an operator may follow, but it may be critical in unusual or unforeseen situations.

- Detection and measurement results:

After the signals have been filtered to exclude out-of-band noise, the pulse has been compressed (when necessary), and the clutter and interference have been reduced to the noise level, a decision is made as to whether the echo signal represents an object of interest. The decision may be made automatically or by an operator. Once the echo signals have been detected, the position, radial velocity and classification of the object must be estimated. The echo signals are combined with noise and the measurement accuracy depends on the signal-to-noise ratio (SNR) [39].

I. 2. 2 Radar classification

The concept of radar emerged in 1886, when Hertz discovered that metallic and dielectric objects reflect radio waves. Though substantial progress in radar technology has been made since, the most rapid development of radar systems has occurred during the Second World War, which is also the time when the term Radar was coined by the US Navy. Although originally only meant for target detection and early warning, today radar is being used in a countless number of applications, such as acquisition, detection, height finding, homing, mapping, navigation,…etc. Figure I. 2. shows the different types of radar systems available. Radars can be classified as ground based, airborne, space borne, or ship based radar systems. They can also be classified into numerous categories based on the specific radar characteristics, such as the frequency band, antenna type, and waveforms utilized. Another classification is concerned with the mission and/or the functionality of the radar. This includes: weather, acquisition and search, tracking, track-while-scan, fire control, early warning, over the horizon, terrain following, and terrain avoidance radars. Phased array radars utilize phased array antennas, and are often called multifunction (multimode) radars [40].

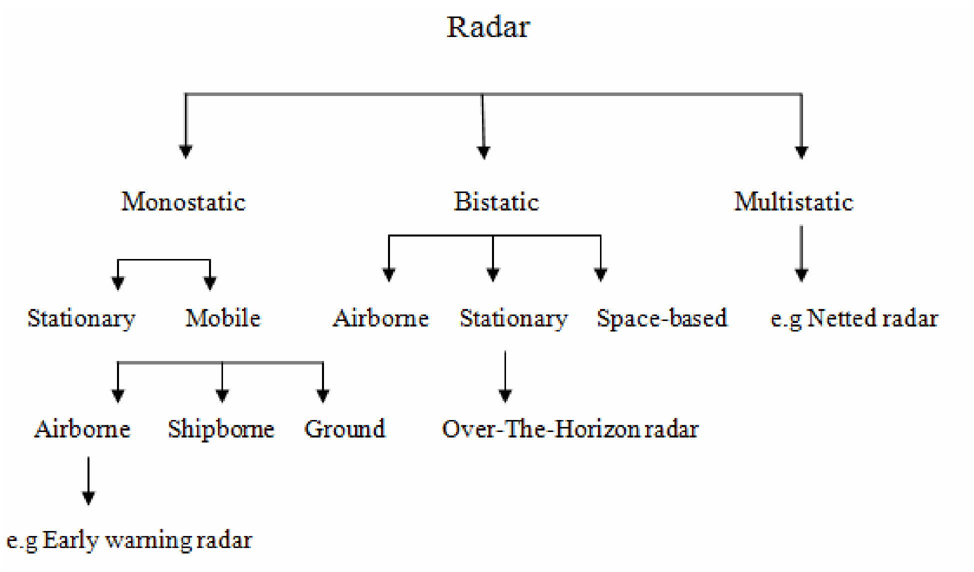


Figure I. 2: Different types of radar systems

I. 2. 3 Radar cross section

The term Radar Cross Section (RCS) was used to describe the amount of scattered power from a target towards the radar, when the target is illuminated by RF energy. At that time, RCS was referred to as a target-specific constant. This was only a simplification and, in practice, it is rarely the case [40]. The RCS is a measure of how detectable an object is by radar. A larger RCS indicates that an object is more easily detected. An object reflects a limited amount of radar energy back to the source. The factors that influence this include:

- The material of which the target is made;
- The absolute size of the target;
- The relative size of the target (in relation to the wavelength of the illuminating radar);
- The incident angle (angle at which the radar beam hits a particular portion of the target, which depends upon the shape of the target and its orientation to the radar source);
- The reflected angle (angle at which the reflected beam leaves the part of the target hit; it depends upon incident angle);
- The polarization of the transmitted and the received radiation with respect to the orientation of the target.

Assume the power density of a wave incident on a target located at range R away from the radar is P_{Di} . The amount of reflected power from the target is

$$P_r = \sigma P_{Di} \tag{I.1}$$

where σ denotes the target cross section. Define P_{Dr} as the power density of the scattered waves at the receiving antenna. It follows that

$$P_{Dr} = \frac{P_r}{4\pi R^2} \tag{I.2}$$

Equating (I.1) and (I.2) yields

$$\sigma = 4\pi R^2 \frac{P_{Dr}}{P_{Di}} \tag{I.3}$$

and in order to ensure that the radar receiving antenna is in the far field (i.e., scattered waves received by the antenna are planar), (I.3) is modified

$$\sigma = 4\pi R^2 \lim_{R\to\infty}\left(\frac{P_{Dr}}{P_{Di}}\right) \tag{I.4}$$

The RCS defined by (I.4) is often referred to as either the monostatic RCS, the backscattered RCS, or simply target RCS.

The backscattered RCS is measured from all waves scattered in the direction of the radar and has the same polarization as the receiving antenna. It represents a portion of the total scattered target RCS σ_t , where $\sigma_t > \sigma$. Assuming spherical coordinate system defined by (ρ,θ,φ), then at range ρ the target scattered cross section is a function of (θ,φ). Let the angles (θ_i,φ_i) define the direction of propagation of the incident waves. Also, let the angles (θ_s,φ_s) define the direction of propagation of the scattered waves. The special case, when $\theta_s = \theta_i$ and $\varphi_s = \varphi_i$, defines the monostatic RCS. The total target scattered RCS is given by

$$\sigma_t = \frac{1}{4\pi} \int_{\theta_s=0}^{2\pi} \int_{\varphi_s=0}^{\pi} \sigma(\theta_s, \varphi_s) \sin\theta_s \, d\theta_s \, d\varphi_s \tag{I.5}$$

The amount of backscattered waves from a target is proportional to the ratio of the target extent (size) to the wavelength, λ, of the incident waves. In fact, a radar will not be able to detect targets much smaller than its operating wavelength [40].

I. 2. 4 Radar equation

Consider a radar with an omni directional antenna (one that radiates energy equally in all directions). Since these kinds of antennas have a spherical radiation pattern, we can define the peak power density (power per unit area) at any point in space as

$$P_D = \frac{Peak\ transmitted\ power}{area\ of\ a\ sphere} \tag{I.6}$$

The power density at range R away from the radar (assuming a lossless propagation medium) is

$$P_D = \frac{P_t}{4\pi R^2} \tag{I.7}$$

where P_t is the peak transmitted power and $4\pi R^2$ is the surface area of a sphere of radius R. Radar systems utilize directional antennas in order to increase the power density in a certain direction. Directional antennas are usually characterized by the antenna gain G and the antenna effective aperture A_e. They are related by

$$A_e = \frac{G\lambda^2}{4\pi} \tag{I.8}$$

where λ is the wavelength. The relationship between the antenna's effective aperture A_e and the physical aperture A is $A_e = \rho A$, $0 \le \rho \le 1$. ρ is referred to as the aperture efficiency, and good antennas require $\rho \rightarrow 1$. In this case we will assume, unless otherwise noted, that *A* and A_e are the same. We will also assume that antennas have the same gain in the transmitting and receiving modes. In practice, $\rho = 0.7$ is widely accepted. The power density at a distance *R* away from a radar using a directive antenna of gain *G* is then given by

$$P_D = \frac{P_t G}{4\pi R^2} \tag{I.9}$$

when the radar radiated energy impinges on a target, the induced surface currents on that target radiate electromagnetic energy in all directions. If we set $\sigma = P_r / P_D$, the total power delivered to the radar signal processor by the antenna is

$$P_{Dr} = \frac{P_t G \sigma}{\left(4\pi R^2\right)^2} A_e \tag{I.10}$$

Substituting (I.8) into (I.10), (I.10) becomes

$$P_{Dr} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 R^4} \tag{I.11}$$

Let S_{min} denote the minimum detectable signal power. It follows that the maximum radar range R_{max} is

$$R_{\max} = \left(\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 S_{\min}} \right)^{1/4} \tag{I.12}$$

(I.12) suggests that in order to double the radar maximum range, one must increase the peak transmitted power P_t sixteen times; or equivalently, one must increase the effective aperture four times [40].

I. 3 Radar clutter and related distributions

Clutter is a term used for unwanted echoes in electronic systems, particularly in reference to radars. Radar clutter echoes consist of radar returns from reflectors that are not of interest and often obscure the signals from targets that are of interest. Radar clutter signals are typically caused by things such as rain, chaff, sea, woods, mountains and atmospheric turbulences, and can cause serious performance issues with radar systems. Clutter in some applications might be reflectors or targets of interest in other applications. This is illustrated by ground-mapping radar where reflections from the ground are of interest. Often clutter returns are much stronger than target returns and radar processing is required to improve the signal-to-clutter ratio (SCR). Several techniques are available to achieve this goal. One method is to reduce the resolution cell size in angle and range in order to decrease the amount of clutter return that competes with the target. Another method is to take advantage of differences between polarization characteristics of the target and the clutter. A third method is to filter the signals to improve the SCR based on the differences in Doppler frequency because echoes from desired targets are generally moving at a high radial velocity than clutter signals. Clutter can be classified into two main categories: surface clutter and airborne or volume clutter. Surface clutter changes from one area to another, while volume clutter may be more predictable [1, 2, 3, 39, 40].

Clutter echoes are random and have thermal noise-like characteristics because the individual clutter components (scatterers) have random phases and amplitudes. In many cases, the clutter signal level is much higher than the receiver noise level. Thus, the radar's ability to detect targets embedded in high clutter background depends on the SCR rather than the SNR. White noise normally introduces the same amount of noise power across all radar range bins, while clutter power may vary within a single range bin. Since clutter returns are target-like echoes, the only way a radar can distinguish target returns from clutter echoes is based on the target RCS σ_t , and the anticipated clutter RCS σ_c (via clutter map). Clutter RCS can be defined as the equivalent radar cross section attributed to reflections from a clutter area, A_c. The average clutter RCS is given by $\sigma_c = \sigma^0 A_c$, where σ^0 is the clutter scattering coefficient, a dimensionless quantity that is often expressed in dB. Some radar engineers express σ^0 in terms of squared centimeters per squared meter. In these cases, σ^0 is $40dB$ higher than normal. Figure. I. 3 represents the envelop detector of the clutter with an intermediate frequency. The received echo $q_r(t) = \tilde{A}\cos(\omega_c t + \tilde{\varphi})$ has random amplitude and phase. Note that, the emitted signal is $q_e(t) = A\cos(\omega_c t)$

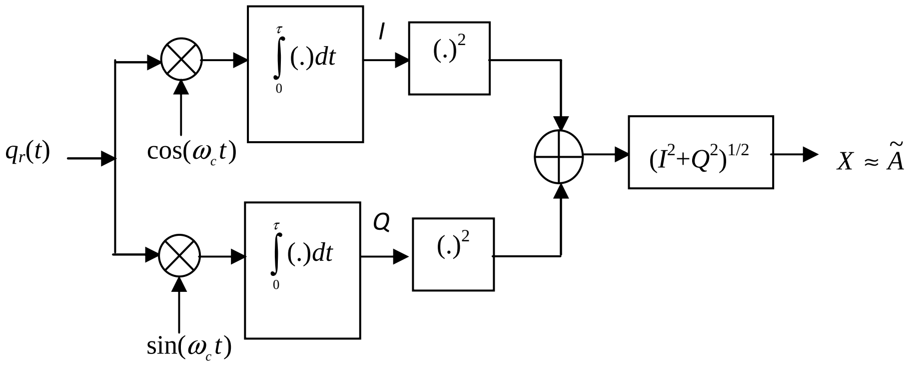


Figure. I. 3: Envelop detector of radar echoes with intermediate frequency.

I. 3. 1 Surface clutter

Surface clutter includes both land and sea-clutter, and is often called area clutter. Surface clutter includes trees, vegetation, ground terrain, man-made structures, and sea surface (sea clutter). Area clutter manifests itself in airborne radars in the look-down mode. It is also a major concern for ground-based radars when searching for targets at low grazing angles. The grazing angle ψ_g is the angle from the surface of the earth to the main axis of the illuminating beam, as illustrated in Figure I. 4.

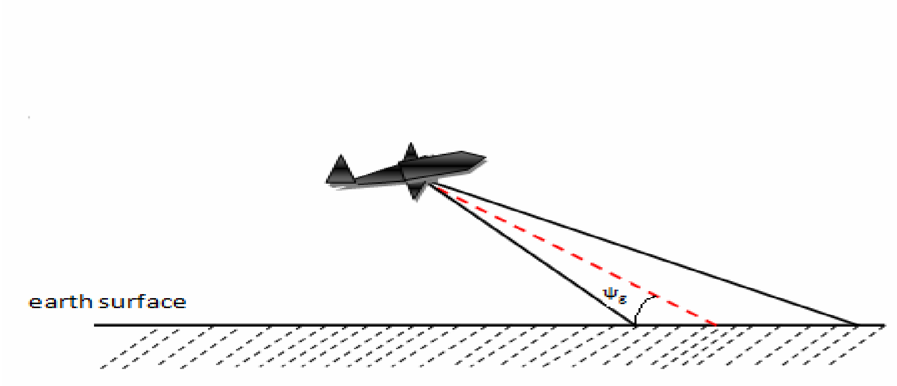


Figure I. 4: Definition of grazing angle [40].

Three factors affect the amount of clutter in the radar beam. They are the grazing angle, surface roughness, and the radar wavelength. Typically, the clutter scattering coefficient σ^0 is larger for smaller wavelengths. Figure I. 5 shows a sketch describing the dependency of σ^0 on the grazing angle. Three regions are identified; they are the low grazing angle region, flat or plateau region, and the high grazing angle region.

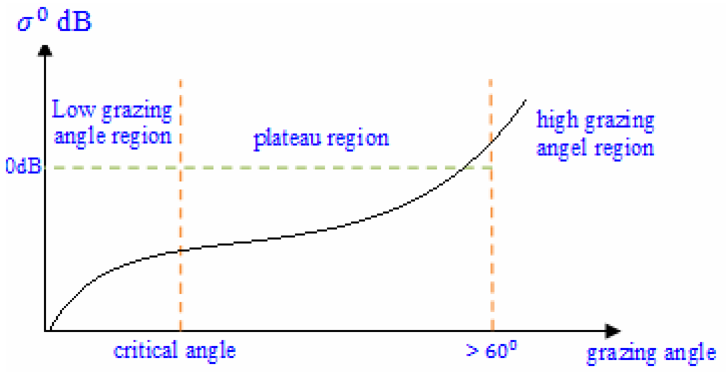


Figure I. 5: Clutter regions [40].

Clutter at low grazing angles is often referred to as diffuse clutter, where there are a large number of clutter returns in the radar beam (non-coherent reflections). In the flat region the dependency of σ^0 on the grazing angle is minimal. Clutter in the high grazing angle region is more specular (coherent reflections) and the diffuse clutter components disappear. In this region the smooth surfaces have larger σ^0 than rough surfaces, opposite of the low grazing angle region.

Consider airborne radar in the look-down mode as shown in Figure I. 6. The intersection of the antenna beam with the ground defines an elliptically shaped footprint. The size of the footprint is a function of the grazing angle and the antenna 3dB beam width θ_{3dB} , as illustrated in Figure I. 7. The footprint is divided into many ground range bins each of size $(c\tau/2)\sec\psi_g$, where τ is the pulse width, c is speed of light. From Figure I. 6, a resolution area A_c is

$$A_c \approx R\theta_{3dB}\frac{c\tau}{2}\sec\psi_g \qquad \text{(I.13)}$$

where $\sec(x) = 1/\cos(x)$

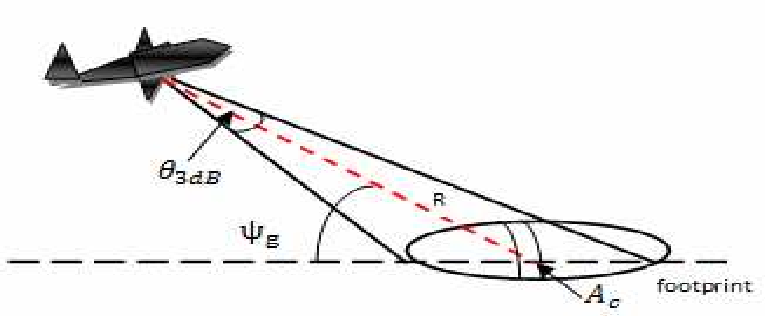


Figure I. 6: Airborne radar in the look-down mode [40].

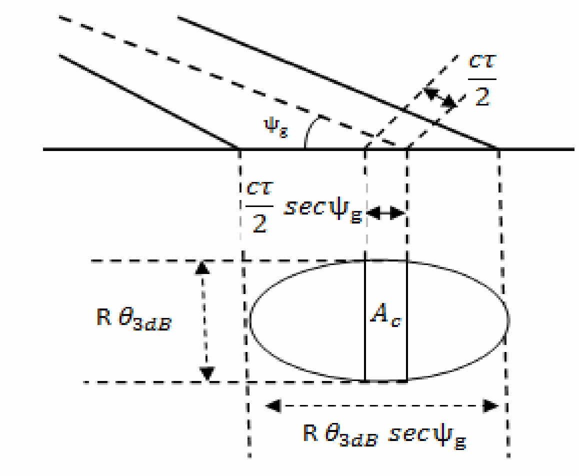


Figure I. 7: Footprint definition [40].

The SCR for area clutter is given by [40].

$$SCR_c = \frac{2\sigma_t \cos\psi_g}{\sigma^0 \theta_{3dB} R c\tau} \tag{I.14}$$

where σ_t is the target RCS.

I. 3. 2Volume clutter

Volume clutter normally has large extent and includes chaff, rain, snow, hail, birds, and insects and other flying particles. Weather or rain clutter is easier to suppress than chaff, since rain droplets can be viewed as perfect small spheres. A resolution volume is shown in Figure I. 8. and is approximated by

$$V_W \approx \frac{\pi}{8} \theta_a \theta_e R^2 c\tau \tag{I.15}$$

Where θ_e and θ_a are, respectively, the antenna beam width in azimuth and elevation.

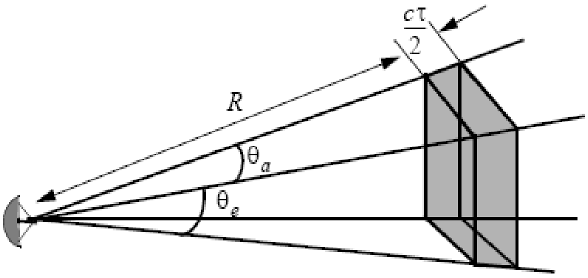


Figure I. 8: Definition of a resolution volume [40].

The SCR_c for weather clutter is computed as

$$SCR_c = \frac{8\sigma_t}{\pi\theta_a\theta_e c\tau R^2 \sum_{i=1}^{N}\sigma_i} \tag{I.16}$$

where σ_i is the i^{th} rain droplet RCS approximation.

I. 3. 3 Clutter models

Since clutter within a resolution cell or volume is composed of a large number of scatterers with random phases and amplitudes, it is statistically described by a PDF. The type of distribution depends on the nature of clutter itself (sea, land or volume), the radar operating frequency, and the grazing angle. Typically, clutter is non stationary in that its statistical characterization varies with time. The power spectrum of sea clutter is therefore a function of two variables: time and frequency. As discussed earlier, clutter could be so strong so that the targets are difficult or even impossible to be detected. The modeling of clutter has been investigated in depth because a proper model is essential in clutter suppression, and there are several widely adopted statistical models fitting reality quite well, such as the Rayleigh, log-normal, Weibull, non-central Chi-square, and *K* distributions [3, 40, 41].

If sea or land clutter is composed of many small scatterers when the probability of receiving an echo from one scatterer is statistically independent of the echo received from another scatterer, then the clutter may be modeled using a Rayleigh distribution. Generally weather clutter or smooth surface clutter is modeled by a Rayleigh PDF where either the in-phase *I* or quadrature *Q* component follows the following Gaussian distribution

$$p(I) = p(Q) = \frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{I^2}{2\sigma^2}\right) \tag{I.17}$$

where σ^2 is the variance. The output of the envelop detector, $X = \sqrt{I^2 + Q^2}$ is Rayleigh distributed.

$$p(x) = \frac{x}{\sigma^2}\exp\left(-\frac{x^2}{2\sigma^2}\right) \tag{I.18}$$

where $2\sigma^2$ is the mean squared value of *X*.

In modern high resolution adaptive thresholding radar CFAR, the clutter (sea clutter, weather clutter, or land clutter) returns may not follow the Gaussian or Rayleigh model, since the amplitude distribution develops a “larger” tail that may increase the false alarm rate. The log-normal distribution best describes land clutter at low grazing angles. It also fits sea clutter in the plateau region. It is given by [33]

$$p(x) = \frac{1}{\sigma\sqrt{2\pi x}} \exp\left(-\frac{(\ln(x) - \mu)^2}{2\sigma^2} \right) \quad , \tag{I.19}$$

where μ and σ are the median and the standard deviation of the random variable ln(x)(x> 0, $\mu \in [-\infty, +\infty])$ respectively. The Weibull PDF is used to model clutter at low grazing angles (less than five degrees) for frequencies between 1 and 10GHz. The Weibull PDF is determined by the Weibull slope parameter a and a median scatter coefficient $\overline{\sigma}_0$, and is given by [32]

$$p(x) = \frac{c}{b}\left(\frac{x}{b}\right)^{c-1} \exp\left(-\left(\frac{x}{b}\right)^{c} \right) \tag{I.20}$$

where $c = 1/a$ is the shape parameter and $b = \overline{\sigma}_0^{1/c}$ is the scale parameter.

CG models are often used to characterize heavy tailed clutter distributions in high-resolution radar. The key problems in CG clutter modeling are choosing the texture distribution and estimating its parameters. Previous work on the modeling of the envelope of sea clutter returns have shown that excellent agreement with observed data can be achieved form the K-distribution at low grazing angles (less than one degree) [15]. The latter consists of two components of the envelope amplitude of the clutter returns. The first is the local mean level y with a PDF $p(y)$ (texture component) which has been found to be a good fit to the Chi family of amplitude distributions [15]. This local mean level characterizes the mean level variation of clutter spikes. The second component is termed the “speckle” component which follows Rayleigh distribution indicating a return from multiple scatters. For the K distribution, the speckle and the texture components are respectively given by the following laws

$$p(x|y) = \frac{\pi x}{2y^2} \exp\left(-\frac{\pi x^2}{4y^2} \right) \tag{I.21}$$

and

$$p(y) = \frac{2b^{2\nu} y^{2\nu-1}}{\Gamma(\nu)} \exp(-b^2 y^2) \tag{I.22}$$

Using (I.21) and (I.22), the overall amplitude distribution is a K-distribution

$$p(x) = \int_0^\infty p(x|y)p(y)dy = \frac{4c}{\Gamma(\nu)}(cx)^\nu K_{\nu\text{-}1}(2cx) \tag{I.23}$$

where $K_{\nu\text{-}1}(2cx)$ is the modified Bessel function, c is a scale parameter ($c = b\sqrt{\pi/4}$) and ν is the shape parameter and $\Gamma(.)$ is the gamma function.

Another way to compute $p(x)$ is to present a CG model for a radar sea/land clutter $x(t)$ by a product of two components [7]

$$x(t) = \sqrt{\tau(t)}.y(t) \tag{I.24}$$

where t is a discrete time index, and $x(t)$ is samples from a given range cell at repetition frequency. $y(t) = y_I(t) + y_Q(t)$ is a stationary complex Gaussian process which accounts for local backscattering where $y_I(t)$ and $y_Q(t)$ are white Gaussian noises. The factor $\tau(t)$ is a nonnegative real random process, usually called the texture; it describes the variations of the local reflected power due to the tilting of the illuminated area. Another form of the compound Gaussian (CG) model can be obtained if the random variable τ follows the inverse gamma distribution [7]

$$p(\tau) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)}\tau^{-(\alpha+1)}\exp(-1/\beta\tau) \tag{I.25}$$

where α is the shape parameter and β is the scale parameter. Using (I.21) and (I.25), the magnitude or the amplitude of the clutter $R = |x| = \sqrt{\tau}|y|$ follows the Pareto type II model [7]

$$p(x) = \int_0^{\infty} p(x|y)p(y)dy = \frac{2x\beta\Gamma(\alpha+1)}{(\beta x^2+1)^{\alpha+1}\Gamma(\alpha)} \tag{I.26}$$

To provide an excellent description of sea clutter measurements, the generalized compound (GC) PDF is considered in the past [17]. The particularity of this PDF is the deviation of the speckle component from Rayleigh to Weibull or other PDF with longer tails. For this the GC PDF is formed using the generalized gamma (GΓ) law to characterize both the speckle and the modulation components of the radar clutter [17]

$$\begin{cases} p(x|y) = \dfrac{b_1}{y\Gamma(\nu_1)}\left(\dfrac{x}{y}\right)^{b_1\nu_1-1}\exp\left(-\left(\dfrac{x}{y}\right)^{b_1}\right) \\ p(y) = \dfrac{b_2}{y\Gamma(\nu_2)}\left(\dfrac{y}{a}\right)^{b_2\nu_2-1}\exp\left(-\left(\dfrac{y}{a}\right)^{b_2}\right) \end{cases} \tag{I.27}$$

where a is the scale parameter, $\nu_{1,2}$ are the shape parameters, and $b_{1,2}$ are the power parameters of the GΓ model. Using (I.27), the overall PDF of X yields [17]

$$
\begin{aligned}
p(x) &= \int_0^\infty p(x|y)p(y)dy \\
&= \frac{b_1 b_2}{\Gamma(\nu_1)\Gamma(\nu_2)} \frac{x^{b_1\nu_1-1}}{a^{b_2\nu_2}} \int_0^\infty y^{b_2\nu_2 - b_1\nu_1 - 1} \exp\left(-\left(\frac{x}{y}\right)^{b_1} - \left(\frac{y}{a}\right)^{b_2} \right)
\end{aligned}
\qquad \text{(I.28)}
$$

As shown in Table I. 1, several statistical models that are commonly used for radar clutter modeling can be inspired from the GC PDF given by (I.28).

I. 4 Targets models

Most objects of interest, such as aircraft, ships, and many other types of irregular shapes, consist of groups of scattering facets that interfere with each other, and only statistical estimations are valid. These vary from spherical objects, which give a constant reflection to an irregular cluster of equally sized reflectors. The reflections from such clusters are constant during the short radar pulse length. If the radar frequency changes, there are different interference effects that depend on the probability distribution of the scatterer. This is the same distribution as if the object were rotated when measured at a constant frequency. Steady echoes are the easiest to detect and measure. Fluctuating echoes must be observed during a number of fading cycles to obtain a reasonable mean value for detection and measurement. A number of probability distributions have been postulated (see Table I. 2) with decreasing degrees of dispersion [39].

Table I. 1: Distributions of sea clutter inspired from the GC PDF

Distribution	Parameters	Speckle	Texture
GC (General Compound)	ν_1, ν_2, b_1, b_2 and a	Generalized gamma	Generalized gamma
GK (Generalized *K*)	ν_1, ν_2, $b_1 = b_2 = b$ and a	Generalized gamma	Generalized gamma
K	$\nu_1 = 1$, $\nu_2 = \nu$, $b_1 = b_2 = b = 2$ and a	Rayleigh	gamma
WG (Weibull speckle, Gamma mean)	$\nu_1 = 1$, $\nu_2 = \nu$, $b_1 = b$, $b_2 = 2$ and a	Weibull	gamma
Weibull	$\nu_1 = 1$, $\nu_2 = 1/2$, $b_1 = b_2 = b$ and a	Weibull	Generalized gamma
Rayleigh	$\nu_1 = 1$, $\nu_2 = 1/2$, $b_1 = b_2 = b = 2$ and a	Rayleigh	-
Exponential	$\nu_1 = 1$, $\nu_2 = 1/2$, $b_1 = b_2 = b = 1$ and a	Exponential	-

HG (Hypergeometric gamma)	v_1, v_2, b_1, b_2 and a or b_1 and b_2 are integers	Generalized gamma	Generalized gamma

Table I. 2: A number of probability distributions used to describe scatterers [39].

Distribution	Used for
Log-normal	Ground clutter, ships
Weinstock	Aircrafts
Swerling I and II models	Aircrafts
Swerling III and IV models	Missiles
Rice	Satellites
Uniform for steady or Marcum model Towed spheres	Towed spheres

The radar equation uses the mean RCS to calculate the average echoed signal. Except for the log-normal case, the probability distributions are related to gamma distributions [39]. When a target is present, the amplitude of the signal at the receiver depends on the target RCS, which is the effective scattering area of a target as seen by the radar. In general, the target RCS fluctuates because targets consist of many scattering elements, and returns from each scattering element vary. The effect of the fluctuation is to require a higher SNR for high probability of detection, and lower values for low probability of detection than those required with non fluctuating signals. In addition, returns from the same scattering element are functions of the illumination angle, the frequency and polarization of the transmitted wave, the target motion and vibration, and the kinematics associated with the radar itself [41]. Target RCS fluctuations are often modeled according to the four Swerling target cases, Swerling case 1 to 4. These fluctuating models assume that the target RCS fluctuation follows either a Rayleigh or one-dominant-plus Rayleigh distribution with scan-to-scan or pulse-to pulse statistical independence.

I. 4. 1 Weinstock models

The Weinstock model uses the modified gamma distribution with η between 0.6 and 4 given by [39]

$$p(s) = \frac{\eta^{\eta}}{\Gamma(\eta)} s^{\eta - 1} e^{-\eta s} \tag{I.29}$$

I. 4. 2 Swerling models

Swerling Case 1: In this case, the returned signal power per pulse on any one scan is assumed to be constant, but these echo pulses are independent (uncorrelated) from scan to scan. A returned signal of this type is then a scan-to-scan fluctuation. The intensity of the entire pulse-train is a single exponential-distributed independent random variable given by [41]

$$p(s) = \frac{1}{m_s} \exp\left(- \frac{s}{m_s} \right) \tag{I.30}$$

where m_s is the average cross section (average of RCS or signal-to-noise power ratio S) over all target fluctuations.

Swerling Case 2: In this case, the fluctuations are more rapid than in Case 1, and are assumed to be independent from pulse-to-pulse instead of from scan-to-scan. This is pulse-to-pulse fluctuation where the voltages of the echoes from the scatterer are parts of a PDF given in (I.30).

Swerling Case 3: In this case, the fluctuations are scan-to-scan as in Case 1, but the PDF is given by

$$p(s) = \frac{4s}{m_s^2} \exp\left(- \frac{2s}{m_s} \right) \tag{I.31}$$

Swerling Case 4: In this case, the fluctuations are pulse-to-pulse as in Case 2, but the PDF is given by (I.31).

Note that in Cases 1 and 2, the targets are assumed to be composed of a large number of independent scatterers, none of which dominates (e.g., large aircraft). Cases 3 and 4 represent targets that have a single dominant nonfluctuating scatterer, together with other smaller independent scatterers (e.g., missiles). Observe that Cases 1 and 2 targets produce signals whose envelopes are Rayleigh distributed, while Cases 3 and 4 targets produce signals whose envelopes are chi-squared distributed [41].

Swerling Cases 1 to 4 are the models most commonly used, even though other models have been developed. They are summarized in the chi-square χ^2 target models family [41].

$$p(s) = \frac{1}{\Gamma(k)} \frac{k}{m_s} \left(\frac{ks}{m_s} \right)^{k-1} \exp\left(-\frac{ks}{m_s} \right) \qquad \text{(I.32)}$$

Swerling Case 5: Often, non fluctuating targets are said to have Swerling Case 5 or Swerling Case 0. In this case, the received signal amplitude is assumed unknown, and there is no amplitude or RCS fluctuation.

I. 4. 3 Rice models

The echoes from one large scatterer accompanied by several much smaller ones, such as a spherical satellite with antennas, are represented by the Rice distribution namely [39].

$$p(s) = (1+s)\exp\left(-s-(1+s)x\right) I_0\left(2\sqrt{s(1+s)x}\right) \qquad \text{(I.33)}$$

where S is the ratio of the power of the steady component to the total power in the random components, I_0 is the modified Bessel function of zero order. The Rice distribution may be approximated to the modified gamma distribution by equating the means and variances of the two distributions ($\eta = 1 + s^2 /(1+2s)$.

I. 4 Conclusion

In this chapter, we presented some basic concepts of the radar system. Radar components are described firstly, as well as its classification, radar cross-section and radar equation. As the modeling of radar clutter plays an important role in CFAR detection schemes, we gave some statistical models for high resolution radars. It is mentioned that radar echoes can be scattered from sea or land surface with different grazing angles. Finally, targets statistical models are also given using Rayleigh and other non-Gaussian distributions.

Questions

1- What is the meaning of the acronym ‘RADAR’ ?

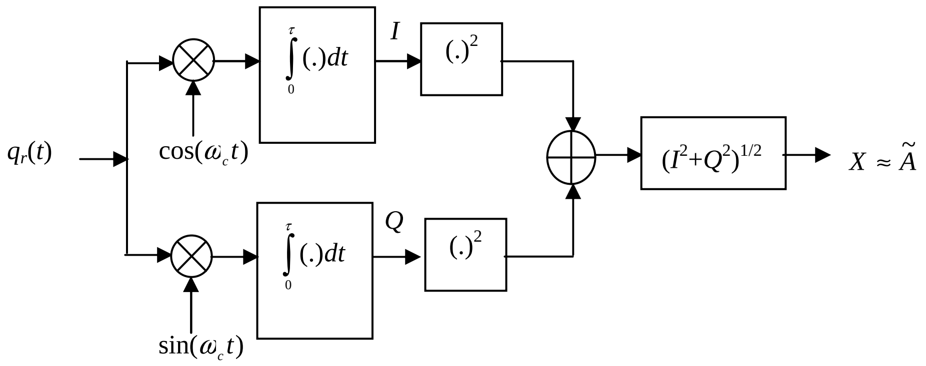
2- Cite some civil applications of radar system?

3- Write and explain the objective of radar equation?

4- What are the parameters influencing on volume and surface clutter resolutions?

5- From the following figure, demonstrate that the output of the envelop detector, X is exactly the amplitude of the received echo, $\tilde{A}$?

Emitted and received signals are $q_e(t) = A\cos(\omega_c t)$ and $q_r(t) = \tilde{A}\cos(\omega_c t + \tilde{\varphi})$ respectively.



6- What is the value of the shape parameter that gives the Rayleigh distribution from the following Weibull distribution?

$$p(x) = \frac{c}{b}\left(\frac{x}{b}\right)^{c-1} \exp\left(-\left(\frac{x}{b}\right)^{c}\right)$$

What is the distributed function of Weibull density?

7- Give the density function representing aircrafts?

8- Give the density function representing missiles?