CHAPTER 1

Introduction

1.1 SCOPE AND OBJECTIVES

This book describes the principles and design of sensor systems using nonionizing radio-frequency (RF) radiation for the detection of concealed targets. Nonionizing radiation (NIR) is the term used to describe the parts of the electromagnetic spectrum covering optical radiation [ultraviolet (UV), visible, and infrared] and electromagnetic fields (EMFs) (power frequencies, microwaves, and radio frequencies). Equipment and techniques using either ionizing radiation from sources such as x-rays and γ-rays or vapor or gas detection are not covered but clearly have capability for particular applications.

This book covers the following topics: radar systems and, in particular, ultra-wideband (UWB) radar, ground-penetrating radar, Doppler radar, millimeter and submillimeter systems, as well as passive (radiometric) millimeter, submillimeter, and terahertz systems. Nuclear quadrupole resonance has been included because it is an RF technique, albeit at relatively long wavelengths, and its design has many aspects common to radar systems and it offers high specificity to explosives and narcotics. The key elements of the subject of electromagnetic techniques for the detection of concealed targets are considered as well as the interrelationship between physical principles, system design, and signal processing that define system performance.

In many cases the system diagrams are shown in terms of function, and this should not always be interpreted to mean hardware components. Often digital signal processing hardware can be used for signal processing or antenna beamforming functions. This book does not cover the signal and image processing methods that can be used to extract maximum information from the radar or radiometer system as this topic could form a future volume in its own right.

EM Detection of Concealed Targets, by David J. Daniels

1.2 STRUCTURE

This Chapter provides a background to the market for security sensors and then identifies each of the main areas of application. Several key issues such as the statistics of detection performance and radiological and licensing considerations are described. Each chapter contains a short summary of its key points. The physics of propagation is, of course, fundamental to a proper understanding of the use of electromagnetic fields for detecting concealed targets, and the characteristics of EMFs as well as propagation of energy in a dielectric and absorption in water, man-made, and natural materials are described in Chapter 2. This also includes consideration of aspects of human and animal physiology relevant to the propagation of electromagnetic (EM) waves as well as the EM characteristics of certain materials.

Most sensing techniques need antennas to transmit and receive the signals from concealed targets, and Chapter 3 provides an introduction to the types of antennas often used in UWB short-range radar systems. Nuclear quadrupole resonance (NQR), despite the "nuclear" in its title, is a radio-frequency technique that can be used to interrogate specific substances, including explosives and narcotics and is described in Chapter 4. Generic radar systems are described in Chapter 5, which provides an understanding of the various modulation techniques that can be employed and some of the issues critical to successful implementation. This chapter covers the principles of operation of Doppler radar, frequency-domain radar, and time-domain radar systems. Chapter 6 discusses passive or radiometric systems as applied to concealed target detection. It is followed in Chapter 7 by a review of the applications and the radar technology for the detection of concealed targets. This contains a review of developments in Doppler radar systems, through-wall radar systems, ultra-wideband, microwave, millimeter, submillimeter, and terahertz radar systems. The material is then summarized in Chapter 8. References cited throughout the book are found following Chapter 8.

1.3 MARKET NEEDS FOR SECURITY

Various estimates from sources such as Beckner and Shaheen, [4], Shaheen [5], Barami [6], as well as Frost and Sullivan [298], suggest that the annual global security market will be on the order of £1000 million by the end of the first decade of the twenty-first century and will grow at a rate of around 10%. The largest market will be the United States, but the demand from the rest of the world will eventually exceed that, with Europe and the wealthy nations of the Middle East and Asia being the main markets. The market can be segmented into three main groups: transportation, civil and government infrastructure, and military. Many of the threats that are now active cross these market boundaries and the difference between the threat from terrorists and insurgents are not always easy to define. In addition the segments cover two different

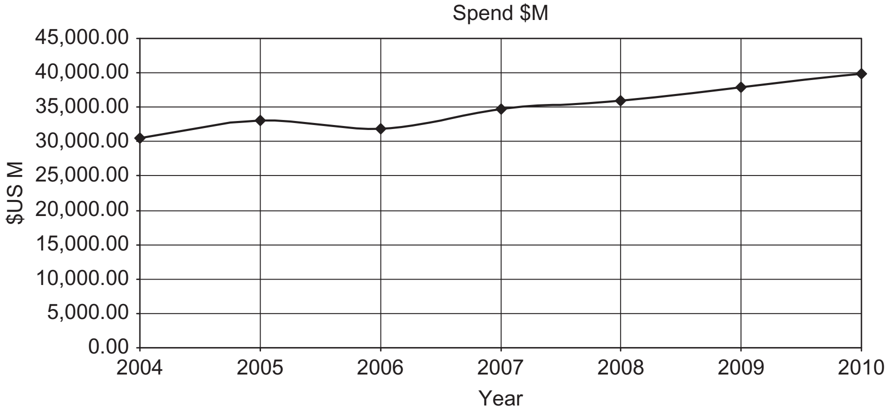

FIGURE 1.1 Estimated U.S. Department of Homeland Security: Spending forecasts 2004–2010.

customer bases: military and civilian. In the United States alone the estimated U.S. Department of Homeland Security spending forecasts for 2004–2010 is shown in Figure 1.1.

The products developed for these customer bases are, however, significantly different in that the civilian homeland security market has different requirements for the through-life costs associated with operation and support compared with the military requirements. The military has well-developed procedures for procurement, operation, and support and tends to expect significant equipment lifetimes and midlife upgrades. The civilian market views these aspects rather differently, and equipment replacement philosophy is more geared to shorter lifetimes due to product performance improvements. Manufacturers recognize that the civilian market does not have the same infrastructure as the military, and buyers expect products to be designed with this in mind. The civilian market is also more attuned to trading-off performance and cost in a way quite foreign to the military.

The market segments can be further subdivided represented as shown in Figure 1.2. Furthermore, each of these segments can be defined by the type of operation that is to be carried out, which then enables the type of equipment to be defined as shown in Figure 1.3.

The global market for homeland security, while enormous, is challenging because it is highly fragmented with decision makers having perspectives aligned to their own region, country, and segment. Competition from national suppliers is fierce, and technical edge, protection of market share, pricing, and national interest make for a keenly contested arena.

For example, in 2007, 61.3 million international passengers passed through London Heathrow (LHR), which handled 3.6% of the world's total international travelers and was at that date the largest international airport in the world. With 1702 million international passengers each year, the worldwide

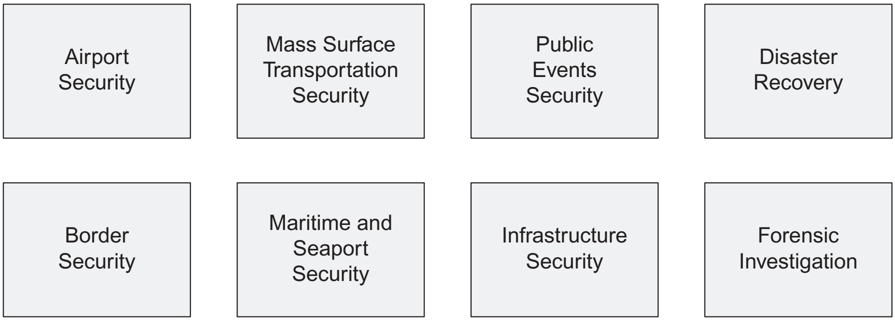

FIGURE 1.2 Market segments for security.

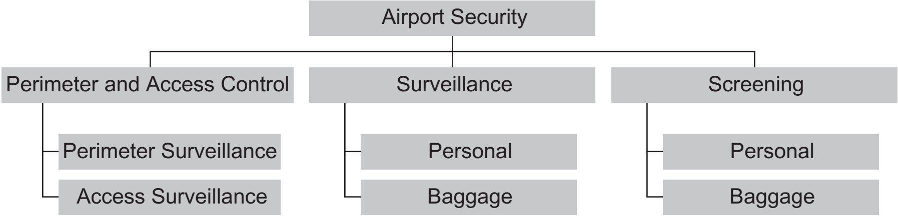

FIGURE 1.3 Types of operation for security processes.

requirement for surveillance and screening is clearly a major market. The market in one country is significant, and estimates of the UK homeland security market made by Frost and Sullivan [298], suggest this to be in excess of £5.40 billion across all eight threat domains by the year 2016 as shown in Figure 1.4.

The agencies that are responsible for security at ports of entry, security at airports, implementing customs regulations, and policing political, sporting, trade, and cultural events need to be able to detect concealed objects on suspects that are hidden in a variety of ways. These can range from:

Drugs inside body cavities
Explosives hidden on a person’s clothes or apparel
Metallic and nonmetallic weapons, knives, guns, and suicide bombers
Illegal immigrants and stowaways

The operational requirements for rapid passenger throughput and market push for technology advancement as well as governments and the public need for risk reduction, combined with strong internal drivers such as government and corporate spending, indicate that the homeland security market will continue to grow over the next decade. The market can be characterized by a period of rapid technological growth as the development and deployment of a generation of technologies designed specifically for the market are introduced.

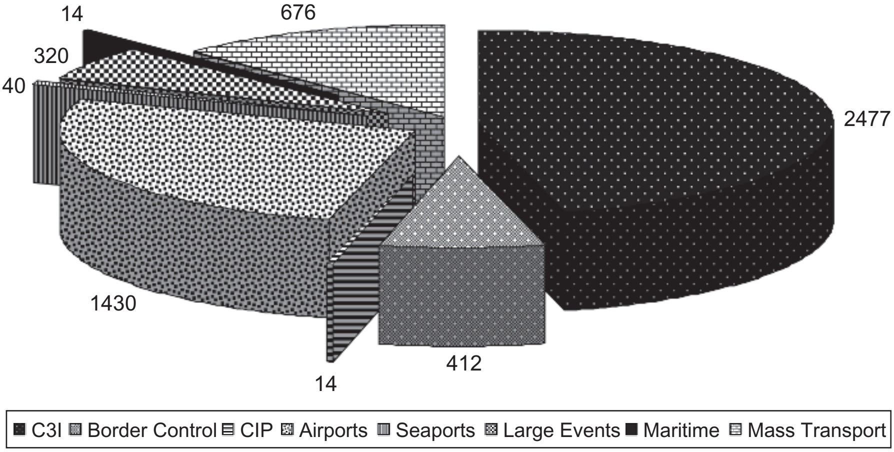

FIGURE 1.4 UK security market in £1,000,000 for, 2007–2016.

Researchers and developers are working swiftly to devise novel solutions and bring to market new generations of security technology. This environment should provide knowledgeable investors with good rewards provided there is a sound understanding of what can be achieved with physics and technology.

1.4 TARGETS INSIDE CONTAINERS

Explosives and weapons can be contained in hold baggage, suitcases, or any means of transportation. X-ray equipment is very successful in detecting anomalous material such as guns and concealed weapons. The main advantage of X-ray equipment is its capability to penetrate through conducting or metallic casing, which is not possible with EM techniques. However, X-ray techniques are not specific, and techniques such as NQR, which are highly specific, may be used to uniquely identify explosives and narcotics, provided the casing of the container is nonmetallic or has a sufficient amount of gapping to enable propagation of EM waves into the interior of the container. Provided the container casing is completely nonmetallic, then EM techniques can be used to image the interior of the case, and some reports suggest that terahertz systems can provide spectroscopic information on the suspect material.

1.5 BURIED LAND MINES

Ground-penetrating radar (GPR) is one of a number of technologies that has been extensively researched as a means of improving mine detection efficiency for both civil and military programs. The military programs are largely based on the requirement to maintain the pace of military operations and have different requirements in terms of speed and detection performance to civil or humanitarian programs. Land mines can be either buried or surface laid. They are emplaced by a variety of techniques, including being scattered on the surface by vehicles or helicopters. Thus, mines may be found in regular patterns or in irregular distributions. When environmental conditions caused by natural processes result in soil erosion and movement caused by rain over several seasons, the mines may be lifted and moved to new locations and can be covered or exposed. Mines are encountered in desert regions, mountains, jungles, as well as urban areas.

Land-mine detection equipment has to be designed to work in a wide range of physical environments, and the statement of operational requirements issued by end users will reflect this need. Detection equipment must be able to be operated in climatic conditions that range from arid desert, hillside scree, to overgrown jungle. Ambient operating temperatures can range from below −20 to 60°C. Rain, dust, humidity, and solar insolation, all must be considered in the design and operation of equipment. The transport conditions of equipment can be arduous, and these as well as human–machine interface issues are vitally important to the design of detectors.

In general, most pressure-sensitive mines are not designed to operate when buried deeply. The overburden ground material acts as a mechanical bridge and inhibits triggering of the detonator mechanism and also reduces the force of the explosion. This fact is often taken into account in the specification of performance for a mine detector, which typically has a depth range of 300 mm, although some land mines can be encountered at depths well beyond the range of current detection systems. Land-mine detection systems can be employed in several different roles: for close-in handheld detection, for vehicle-mounted standoff detection, or as a remote sensor mounted on low-flying fixed or rotary wing aircraft.

1.6 FORENSIC DETECTION OF BURIED BODIES

Forensic investigation using GPR has become a recognized method of forensic archeology because of some high-profile case histories. GPR techniques are one among a number of methods that can be used in forensic investigations and can greatly assist police investigations by pinpointing suspicious areas and thus saving unnecessary excavation. GPR provides the means to conduct rapid, nondestructive investigations that can alleviate the need to carry out extensive and expensive excavations. In skilled hands, GPR can be employed to search for and locate the types of target sought by forensic investigators. Unlike searching for utilities and services, where the radar signatures tend to be well defined, radar signatures of forensic targets are varied and, due to the wide variety of targets and scenarios, never the same. However, with experience an operator will begin to be accustomed to general patterns within the radar images. It must be emphasized that GPR cannot provide an image of the buried remains. Because of the variability of the sites, those without significant experience of GPR forensic surveying do not find it easy to carry out the interpretation of GPR B-scan images. For good GPR survey results it is also vital that the ground be undisturbed by either the passage of heavy vehicles (which tend to compress the soil and give rise to unwanted reflections) or by digging. Once digging has been carried out, the soil structure is disturbed and effective GPR surveying becomes extremely difficult. The golden rule is that the site should be in a virgin state for best GPR results.

Forensic investigations should be multidisciplinary, and the following aspects should be considered when dealing with GPR:

Availability of site plans of utilities
Availability of site information on burial sites of pet animals
Correct recording of scene and site evidence
Methods of removing surface vegetation and obstructing artefacts (note that GPR requires a reasonably flat surface to gather good data)
Time, manner, and cause of death (state of decay of corpse)
Identification of state of remains to aid GPR interpretation
Recovery procedures of remains

1.7 AVALANCHE AND EARTHQUAKE VICTIMS

Radar has been used for research into the detection of victims of earthquakes and avalanches. Tests in the French Pyrenees by Daniels [2] and in the Italian Alps by ERA Technology showed that GPR [299] has a potentially useful role in this application. Detection of humans buried in earthquake rubble has also been the subject of much research, and Doppler radar systems are an obvious choice to detect humans by means of their respiration and heartbeat, while simultaneously eliminating the clutter that ranging radar would also detect.

1.8 CONCEALED HUMANS

A prime concern of immigration authorities in most developed countries is the detection of stowaways in road vehicles. Such stowaways may be opportunistic or facilitated and hide in the cargo zones of heavy-goods vehicles. It is difficult to establish the number of illegal entrants to any country, but it is clearly a problem for the developed countries of the world and a variety of estimates have been made in the United Kingdom, Europe, the United States, and Canada as to the scale of the problem. The legal and ethical issues are not the subjects of this volume, but the RF and microwave techniques for detection will be considered. Stowaways are found concealed in the cargo zones of heavy-goods vehicles. These cargo zones may be encased by fabric or metal and may carry a variety of goods from electrical white goods through to cargos of fruits and vegetables. Stowaways are found in a variety of concealed positions.

1.9 CONCEALED TARGETS ON HUMANS

There is clearly a major need to detect concealed targets on humans, and this can range from the less dramatic knife and gun carriers to the hardened terrorist. The targets can range from drugs inside body cavities, through metallic and nonmetallic weapons, knives, guns, as well as explosives hidden under a suspect's clothes or in luggage. Note that radar has not been used to investigate searches of targets inside human beings. Following the tragic events of 911 and the attempt by a shoe bomber to compromise safety, air travel is now extensively protected both in terms of baggage screening and person screening and by techniques ranging from X-ray scanning through to passive millimeter-wave imaging. However, the airport is a controlled environment, and, while the measures have undoubtedly made life for the traveler more difficult, it is now a harder target for the terrorist to attack. Other means of mass transportation as well as major public events are softer targets, so concealed weapons and explosives on humans are still a continued threat to national security. This is evidenced by recent events in Europe.

On March 11, 2004, in Madrid four packed commuter trains heading into Madrid from working-class neighborhoods were bombed using 10 backpacks filled with dynamite and nails. This killed 191 and wounded more than 1800 people. In the United Kingdom a series of bomb attacks on London's transport network on Thursday July 7, 2005, caused significant casualties. Three explosions on the Underground system left 35 dead, while 2 victims died in a blast on a double-decker bus, a further 700 plus people were injured. These soft targets need better protection, and sensors to detect concealed targets are an essential means to provide this.

1.10 RADIOLOGICAL CONSIDERATIONS

Public exposure to nonionizing electromagnetic fields such as those associated with radar, broadcast transmitters, mobile phones, power lines, and domestic equipment come under guidelines incorporated into various national and international standards.

In the United Kingdom the Health Protection Agency's Radiation Protection Division (RPD) [7] [formerly the National Radiological Protection Board (NRPB)] advises on risks from radiation including electromagnetic fields. The UK Health Protection Agency (HPA) is an independent body that protects the health and well-being of the UK population and has published a series of reports [8–16]. There is a continuing program of research in the United Kingdom relevant to health concerns about exposures to RF fields. The RPD has responsibility for providing advice on appropriate restrictions on the exposure of people to electromagnetic fields and radiation. These include static, power frequency (50 Hz), and other extremely low-frequency (ELF) electric and magnetic fields, and RF fields and radiation. Guidance limiting exposure to time-varying electric and magnetic fields is issued at regular intervals. NRB recommendations are based on an assessment of the possible effects on human health derived from biological information [17–19], from dosimetric data [20, 21], and from studies of exposed human populations [22, 23]. They apply equally to workers and to members of the public but not to people who are exposed to electromagnetic fields and radiation for medical diagnostic or therapeutic purposes.

The RPD advise that for electromagnetic radiation of frequencies greater than 100 kHz and less than 300 GHz, both induced current and thermal effects are relevant, but above 100 MHz only thermal effects need to be considered. The specific absorption rates (SAR) are measured in units of watts per kilogram (W kg^{-1}) and are given in Table 1.1.

Guidance for the protection of patients and volunteers during clinical magnetic resonance diagnostic procedures has been issued separately by the American National Standards Institute (ANSI) [24]. These recommendations are intended to provide a framework for a system of restrictions on human exposure to these fields and radiation as described by Elder and Cahill [25].

In Europe the European Recommendation (EC/519/1999) sets a framework that deals with limiting public exposure, providing public information, and undertaking research. The European Commission (EC) supports an ongoing program of further research on the topic.

The U.S. Department of Labor, Occupational Safety and Health Administration (OSHA) General Industry [Part 1910.97(a) (2) (i)] [26] defines the following standard for normal environmental conditions and for incident electromagnetic energy of frequencies from 10 MHz to 100 GHz: The radiation protection guide is 10 mW cm^{-2} (milliwatt per square centimeter) as averaged

TABLE 1.1 RPD Permitted Absorption Levels in United Kingdom

Frequency Range	Quantity	Basic Restriction
100 kHz to 10 MHz	Current density in the head and trunk	$F/100$ mA m^{-2}
100 kHz to 10 GHz	SAR averaged over the body and over any 15-min period	0.4 W kg^{-1}
100 kHz to 10 GHz	SAR averaged over any 10 g in the head and fetus and over any 6-min period	10 W kg^{-1}
100 kHz to 10 GHz	SAR averaged over any 100 g in the neck and trunk and over any 6-min period	10 W kg^{-1}
100 kHz to 10 GHz	SAR averaged over any 100 g in the limbs and over any 6-min period	20 W kg^{-1}

TABLE 1.2 Recommended Levels of Electromagnetic Fields: A Comparison of NRPB and ICNIRP Guidelines

1993 NRPB Guidelines (the same for occupational and public)			1998 ICNIRP Guidelines	
			Occupational	Public
Basic restriction (the quantity which must not be exceeded)	Induced current density in the central nervous system	10 mA m^{-2}	10 mA m^{-2}	2 mA m^{-2}
Reference level	Magnetic field	1600 μT	500 μT	100 μT
	Electric field	12 kV m^{-1}	10 kV m^{-1}	2 kV m^{-1}

over any possible 0.1 h period. This is expanded as follows: The acceptable absorption is equal to a power density of 10 mW cm^{-2} for periods of 0.1 h or more with an energy density of 1 mW-h cm^{-1} (milliwatt hour per square centimeter) during any 0.1 h period.

The available evidence indicates that human beings can tolerate moderate absorption rates of approximately 1 W kg^{-1}. Some standards also provide data on maximum allowable partial body exposures and criteria for avoiding RF shocks and burns. It should be noted that SAR criteria do not apply to exposures at low frequencies (less than 100 kHz) for which nerve stimulation (shock) occurs, or at frequencies higher than 6 GHz for which surface heating prevails.

The Institute of Electrical and Electronic Engineers (IEEE) has published a number of studies dealing with the issue of biological effects, and further details can be gathered from the references provided by the IEEE/ANSI [27]. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) [28] is a body of independent scientific experts consisting of a main commission of 14 members, 4 scientific standing committees covering epidemiology, biology, dosimetry, and optical radiation, and a number of consulting experts. This expertise is brought to bear on addressing the important issues of possible adverse effects on human health of exposure to nonionizing radiation and their recommendations are given in Table 1.2.

1.11 LICENSING CONSIDERATIONS

Although compared with the number of mobile phones, Global Positioning System (GPS) users, and other occupants of similar bands, the number of radar/detection systems is very small with a very low potential for interference, and equipment must comply with regulatory requirements. A brief summary of the situation is provided in this section.

The International Telecommunication Union (ITU), based in Geneva, Switzerland, is the international organization within which governments coordinate global telecom networks and services. The United States is a member of the ITU. Therefore, the Federal Communications Commission (FCC) in the United States, the European Telecommunications Standards Institute (ETSI), and the national authorities in Region 3 define the key licensing requirements.

In the United States the FCC and the National Telecommunications and Information Administration (NTIA) jointly regulate radio spectrum use in the United States. Within the FCC, the Office of Engineering and Technology (OET) provides advice on technical and policy issues pertaining to spectrum allocation and use. OET also maintains the FCC's Table of Frequency Allocations. Further information can be found in EURO GPR [29] and Olhoeft [30].

In Europe the following requirements are relevant:

ETSI EN 302 066-1 Electromagnetic Compatibility and Radio Spectrum Matters (ERM); Short Range Devices (SRD); Ground- and Wall-Probing Radar Applications; Part 1: Technical Characteristics and Test Methods

ETSI EN 302 066-2 Electromagnetic Compatibility and Radio Spectrum Matters (ERM); Short Range Devices (SRD); Ground- and Wall-Probing Radar Applications; Part 2: Harmonized EN under Article 3.2 of the R&TTE Directive

ETSI EN 301 489-32 Electromagnetic Compatibility and Radio Spectrum Matters (ERM); Electromagnetic Compatibility (EMC) Standard for Radio Equipment and Services; Part 32: Specific conditions for Ground- and Wall-Probing Radar Applications

In addition to radio transmission regulations, all equipment in Europe must be CE marked to demonstrate that it satisfies the relevant directives of the European Union. (EU). The CE mark may only be applied when the requirements of all other relevant EU Directives, such as safety, have also been demonstrated. Europe has defined electromagnetic environments and agreed to European Norm (EN) specifications with test levels defined. These specifications have product, product family, and generic requirements with the application in that order of precedence. For commercial electromagnetic compatibility (EMC), there are emissions and immunity requirements. The emission requirements have been defined through the CISPR international committees and the immunity through the IEC committees.

In the United States the FCC document (*Federal Register* Vol. 67, No. 95/ Thursday, May 16, 2002/Rules and Regulations) defines the licensing requirements for various categories of equipment as listed below. Imaging systems under Part 15 of the FCC's rules are subject to certain frequency and power limitations.

GPR, which must be operated below 960 MHz or in the frequency band 3.1 to 10.6 GHz

Wall imaging systems, which must be operated below 960 MHz or in the frequency band 3.1 to 10.6 GHz

Through-wall imaging systems, which must be operated below 960 MHz or in the frequency band 1.99 to 10.6 GHz

Surveillance systems, which must be operated in the band 1.99 to 10.6 GHz

Medical systems, which must be operated in the band 3.1 to 10.6 GHz

Vehicular radar systems, which must be operated in the band 22 to 29 GHz

In response to various petitions, the FCC amended the rules to facilitate the operation of through-wall imaging systems by law enforcement, emergency, rescue, and firefighter personnel in emergency situations; eliminated the requirement that GPRs and wall-imaging systems operate with their -10dB bandwidths below 960 MHz or above 3.1 GHz; specified the limitations on who may operate GPR systems and wall-imaging systems and for what purposes; eliminated the requirement for nonhandheld GPRs to employ a dead man switch which requires the user to physically operate a switch for the equipment to transmit; clarified the coordination requirements for imaging devices; and clarified the rules regarding emissions produced by digital circuitry used by UWB transmitters.

The FCC also proposed additional new rules to address issues raised regarding the operation of low pulse repetition frequency (PRF) UWB systems, including vehicular radars, in the 3.1- to 10.6–GHz band; the operation of frequency hopping vehicular radars in the 22- to 29-GHz band as UWB devices; the establishment of new peak power limits for wideband Part 15 devices that do not operate as UWB devices; and the definition of a UWB device.

The designer, developer, or user of equipment must ensure compliance with existing national regulations. The changing nature of much of the ITU, European (ETSI), and U.S. standards is such that up-to-date information should be obtained. Other countries will have specific requirements, and proper advice should be sought from the appropriate national authorities.

1.12 STATISTICS OF THE DETECTION PERFORMANCE OF A SENSOR

A key issue in assessing the performance of any detection system is its probability of detection (PD), the probability of false alarm (PFA), as well as the confidence that can be placed in the claimed PD and PFA. This section describes the basic measures that are commonly used to describe the performance of a particular sensor and explains the most effective and commonly used description of sensor performance, which is the receiver operating characteristic (ROC).

A basic approach to describing a methodology for classifying the performance of a sensor is described by the confusion matrix reported by Provost and Kohavi [31], who use the descriptions as given in Table 1.3.

TABLE 1.3 Confusion Matrix

		Predicted	
		Negative	Positive
Actual	Negative	a	b
	Positive	c	d

a = number of correct predictions that an instance is negative
b = number of incorrect predictions that an instance is positive
c = number of incorrect of predictions that an instance negative
d = number of correct predictions that an instance is positive

Equation (1.1) gives the accuracy (AC), which is the proportion of the total number of predictions that were correct:

$$\mathrm{AC} = \frac{a+d}{a+b+c+d} \tag{1.1}$$

Equation (1.2) gives the recall or true positive (TP) rate, which is the proportion of positive cases that were correctly identified:

$$\mathrm{TP} = \frac{d}{c+d} \tag{1.2}$$

Equation (1.3) gives the false positive (FP) rate, which is the proportion of negative cases that were incorrectly classified as positive:

$$\mathrm{FP} = \frac{b}{a+b} \tag{1.3}$$

Equation (1.4) gives the true negative (TN) rate, which is defined as the proportion of negative cases that were classified correctly:

$$\mathrm{TN} = \frac{a}{a+b} \tag{1.4}$$

Equation (1.5) gives the false negative (FN) rate, which is the proportion of positive cases that were incorrectly classified as negative:

$$\mathrm{FN} = \frac{c}{c+d} \tag{1.5}$$

Equation (1.6) gives the precision (*P*), which is the proportion of the predicted positive cases that were correct, as calculated using the equation:

$$\mathrm{P} = \frac{d}{b+d} \tag{1.6}$$

The ROC curve is another way of understanding the performance of a sensor and plots the true positive rate as a function of the false positive rate for different levels of sensitivity of the sensor. Consider two populations, one due to true reports or detections and one due to false alarms, which are shown in Figure 1.5 and labeled true and false, respectively.

Their Gaussian population distributions have identical standard deviations but different mean values. If a detection threshold value were set to 5, then the majority of the true positive reports would be detected, and a small proportion of true negative (false positive) reports would be included. This threshold can also be plotted as a pair of true positive/true negative reports or sometimes termed sensitivity/specificity parameters, and this generates an ROC curve. The ROC curve for Figure 1.5 is shown in Figure 1.6, and it can be seen that at a 0.95 true positive detection the false positive proportion is 0.35.

A test with perfect discrimination (no overlap in the two distributions) has an ROC plot that passes through the upper left corner (100% sensitivity, 100% specificity). Therefore, the closer the ROC plot is to the upper left corner,

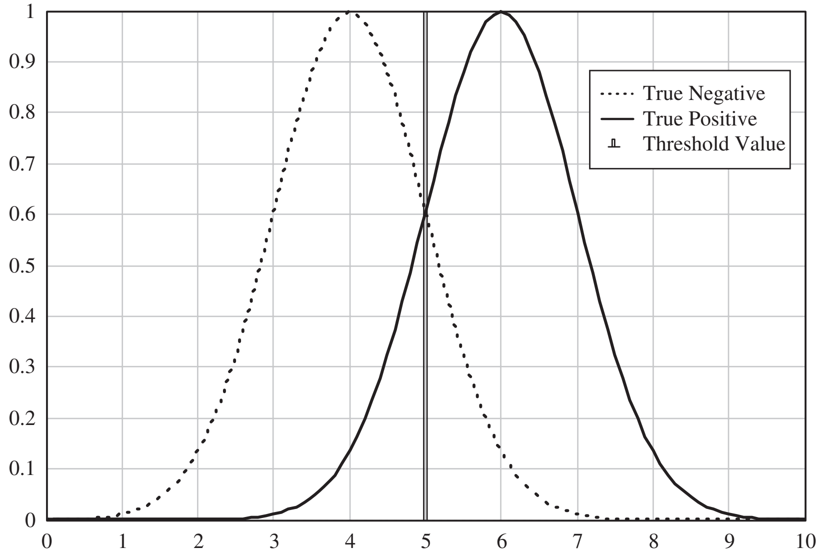

FIGURE 1.5 Distribution of true and false reports from a sample population.

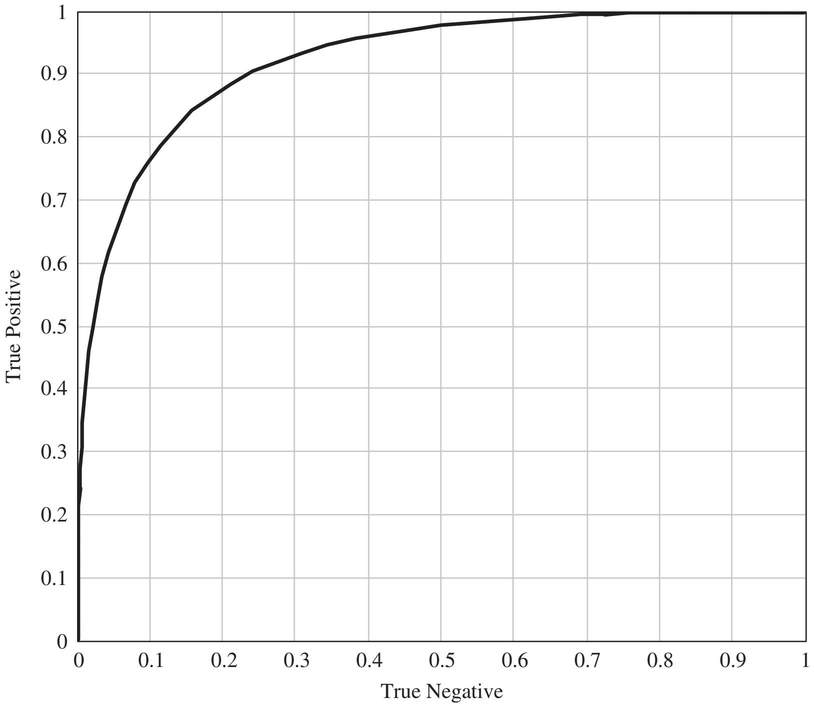

FIGURE 1.6 Receiver operating characteristic for distributions in Figure 1.5.

the higher the overall accuracy of the test. Examples of these are shown in Figure 1.7 for increasing separation of the mean values and hence less overlap, and Figure 1.8 shows decreasing separation of the mean values and hence more overlap.

The size of the sample must also be known in order to determine a confidence level in the result. Elementary statistical sampling theory can be used to show that the confidence that can be placed in a test of a limited sample set is fundamentally related to the size of the sample set. If 10 sensors are tested on a task and even if all provide a positive report (a probability of detection of 100%), the statistical confidence in the claim is limited by the number in the set. At the 95% limit, the upper and lower confidence bounds can be derived from the binomial distribution to show that with a sample set of 10, the bounds as shown in Figure 1.9 exist. The x axis shows the proportion of the sample set detected and the y axis shows the probability of detection.

In contrast, the limits for a sample set of 100 are much closer and are shown in Figure 1.10. These values are based on the small sample interval for calculating confidence intervals.

A fully detailed consideration of the issues is given by Simonson [32], who considers the difference between the small sample approach based on the

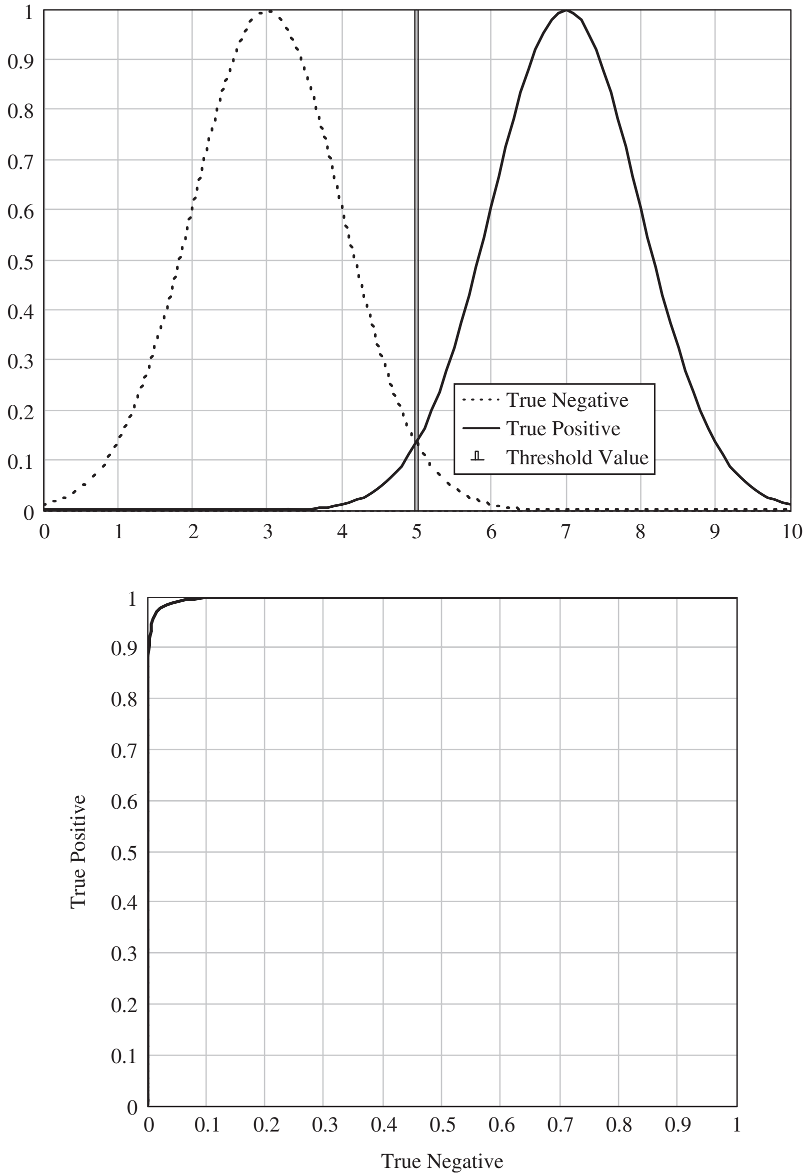

FIGURE 1.7 Effect of increased separation of information statistics on the ROC curve.

binomial distribution and a large sample approach using the normal distribution with respect to the detection of land mines. Note that the large sample distribution suggests a closer interval between the bounds. The detection of land mines is a useful example as a measure of the performance of a sensor as the consequences of a missed detection are significant for the operator.

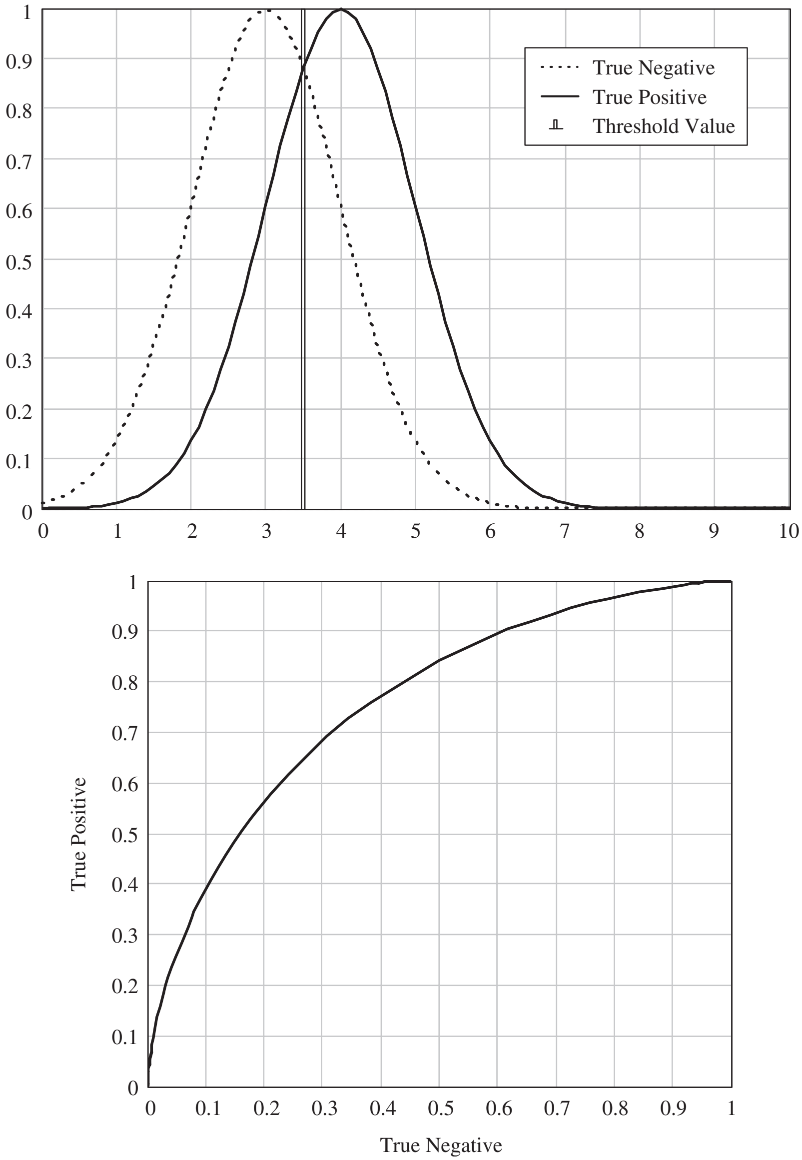

FIGURE 1.8 Effect of decreased separation of information statistics on the ROC curve.

Voles [33] considered this issue and showed that based on a Poisson distribution, even if no mines were missed by a sensor in a test of 100, then at the 95% confidence limit the highest value of probability of detection that can be claimed is 97%. Voles also showed that to achieve a 99.6% probability of detection at a confidence level of 95% would require a test of 750 mines and none should be missed.

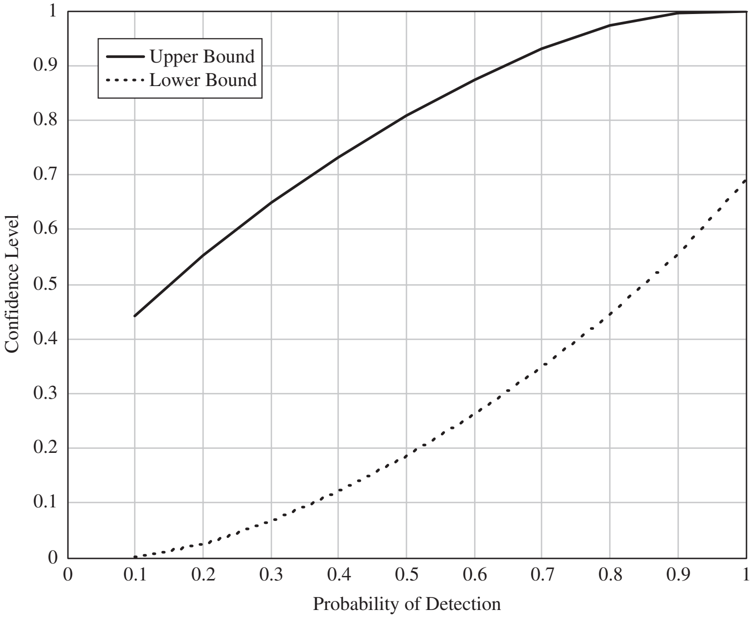

FIGURE 1.9 Upper and lower confidence bounds for a sample set of 10 (binomial distribution).

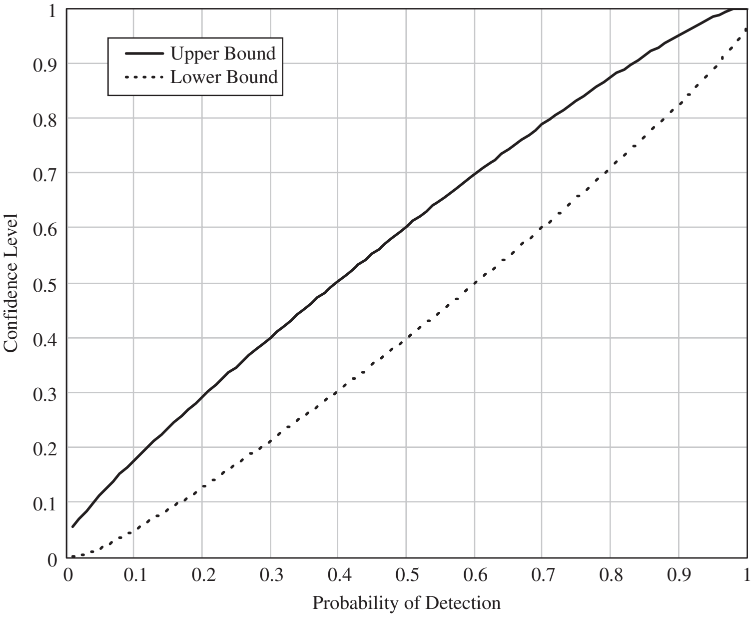

FIGURE 1.10 Upper and lower confidence bounds for a sample set of 100 (binomial distribution).

1.13 SUMMARY

The market for electromagnetic sensors for the detection of concealed targets has attracted considerable interest by potential end users from the military, security, and industrial bases. Considerable investment has been made in developing products for niche markets, and there is a growing interest in the various application areas. The threat from terrorist activities has galvanized research and development in this area, but the challenge of the basic physics in what is often an uncontrolled environment where high levels of clutter still remain. The most successful developments operate in a more controlled situation, and this may be one of the precursors to success. The opportunities are considerable, but issues of licensing, public acceptance of electromagnetic radiation, albeit at very low levels, as well as the reliability of detection and reduction of false alarms may be just as much a challenge to overcome as those related to the basic physics.