Wireless Networks and Mobile Communications Series

MILLIMETER WAVE TECHNOLOGY IN WIRELESS PAN, LAN, AND MAN

Edited by

Shao-Qiu Xiao

Ming-Tuo Zhou

Yan Zhang

CRC Press
Taylor & Francis Group
AN AUERBACH BOOK

MILLIMETER WAVE TECHNOLOGY IN WIRELESS PAN, LAN, AND MAN

Edited by
Shao-Qiu Xiao
Ming-Tuo Zhou
Yan Zhang

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business
AN AUERBACH BOOK

Auerbach Publications
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number-13: 978-0-8493-8227-7 (Hardcover)

Library of Congress Cataloging-in-Publication Data

Xiao, Shao-Qiu.
Millimeter wave technology in wireless Pan, Lan, and Man / Shao-Qiu Xiao, Ming-Tuo Zhou, and Yan Zhang.
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-0-8493-8227-7 (alk. paper) 1. Broadband communication systems. 2. Wireless communication systems. 3. Millimeter waves. I. Zhou, Ming-Tuo. II. Zhang, Yan, 1977- III. Title.

TK5103.4.X53 2007
004.6'8--dc22 2007011241

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the Auerbach Web site at
http://www.auerbach-publications.com

Contents

List of Contributors

Dan An
Millimeter-wave INnovation Technology Research Center
Department of Electronic Engineering
Dongguk University
Seoul, Korea

Pantel D. M. Arapoglou
National Technical University of Athens
Athens, Greece

T. Chen
CREATE-NET International Research Center
Trento, Italy

I. Chlamtac
CREATE-NET International Research Center
Trento, Italy

Panayotis G. Cottis
National Technical University of Athens
Athens, Greece

X. James Dong
University of California
Berkeley, California

James P. K. Gilb
SiBEAM
Fremont, California

Joerg Habetha
Philips Research Laboratories
Aachen, Germany

Sung-Chan Kim
Millimeter-wave INnovation Technology Research Center
Department of Electronic Engineering
Dongguk University
Seoul, Korea

Andrey Kobyakov
Corning Inc.
Corning, New York

J. Laskar
Georgia Institute of Technology
Atlanta, Georgia

Bok-Hyung Lee
Millimeter-wave INnovation Technology Research Center
Department of Electronic Engineering
Dongguk University
Seoul, Korea

J.-H. Lee
Georgia Institute of Technology
Atlanta, Georgia

Sheung L. Li
SiBEAM
Fremont, California

Huilai Liu
University of Electronics Science and Technology of China
Chengdu, China

Jim Misener
University of California
Berkeley, California

John Mitchell
University College London
London, U.K.

Athanasios D. Panagopoulos
National Technical University of Athens
Athens, Greece

Javier del Pardo
Philips Semiconductors
Sophia Antipolis, France

S. Pinel
Georgia Institute of Technology
Atlanta, Georgia

Emma Regentova
University of Nevada
Las Vegas, Nevada

Jin-Koo Rhee
Millimeter-wave INnovation Technology Research Center
Department of Electronic Engineering
Dongguk University
Seoul, Korea

Michael Sauer
Corning Inc.
Corning, New York

M. M. Tentzeris
Georgia Institute of Technology
Atlanta, Georgia

Pravin Varaiya
University of California
Berkeley, California

Bing-Zhong Wang
University of Electronics Science and Technology of China
Chengdu, China

Jianpeng Wang
University of Electronics, Science and Technology of China
Chengdu, China

H. Woesner
CREATE-NET International Research Center
Trento, Italy

Shao-Qiu Xiao
University of Electronics, Science and Technology of China
Chengdu, China

Felix Yanovsky
The National Aviation University
Kiev, Ukraine

Jijun Yao
National University of Singapore
Singapore

Wenbing Zhang
University of California
Berkeley, California

Yan Zhang
Simula Research Laboratory
Lysaker, Norway

Jun Zheng
Queens College
City University of New York
New York, New York

Ming-Tuo Zhou
National Institute of Information
and Communications Technology
Singapore

For references:
F. J. Yanovsky, "Millimeter Wave Radar: Principles and Applications," In Millimeter Wave Technology in Wireless PAN, LAN, and MAN, Editors: Shao-Qiu Xiao, Ming-Tuo Zhou, Yan Zhang, Chapter 10, pp.305-376, ISBN: 9780849382277, Auerbach Publications CRC Press, 2008, 464 pp.

Chapter 10

Millimeter-Wave Radar: Principles and Applications

Felix Yanovsky

Contents

This chapter provides a radar perspective for millimeter wave propagation and scattering. It considers radar principles and the features of subsystems and components of millimeter-wave radars. Rather complicated notions of radar theory are stated in a very simple manner as a kind of overview. Then, application of millimeter-wave radar for intelligent transportation systems

(ITS) is analyzed in detail as the main section of the chapter. The role of radar sensors in ITS is shown, and frequency allocation for ITS radars is analyzed. Traffic surveillance radar, which is an element of ITS infrastructure, is described. Then automotive radars are categorized into long range, medium range, and short range, and each category is considered. On this basis different functional applications of automotive radar are briefly described. Radar-based communications for both car-to-car and the entire ITS system are considered. The necessity and possibility of data exchange using WLAN (wireless local area network) is indicated. Millimeter-wave radars are employed in a wide range of commercial, military, and scientific applications for remote sensing, safety, and measurements. That is why other important millimeter-wave radar applications are considered. Finally, the conclusion is that millimeter-wave radar is a universal instrument for numerous promising applications and a device quite suitable for network use and data exchange via wireless networks.

10.1 Introduction

Millimeter waves were once considered unfit for practical use in radar. One of the main reasons was the absence of suitable means of generation, reception, channelization, and transmission of electromagnetic waves of millimeter range. Moreover, the laws of millimeter-wave propagation in the nonhomogeneous atmosphere were not studied enough.

Nowadays, creation of modern and prospective millimeter-wave radar systems is based on the research of propagation and scattering features in the millimeter-wave range as well as on the development of methods and means for millimeter-wave generation and reception.

Step by step both theory and practice discover new advantages of millimeter waves, and millimeter-wave radars become more and more applicable in different fields. Today millimeter waves are increasingly used in car radar, cloud radar, radar, and radiometry for concealed weapon detection (CWD), high-speed wireless access, ultra-high-speed wireless local area networks (WLAN), and other means of communications including radar-based communication systems.

High antenna gain at rather small aperture and the possibility to use wideband and very short waveforms facilitate improved resolution and accuracy of radar measurements, which is an obvious advantage of millimeter-wave radars, as well as huge information content and information rate with application of radar-based communication data systems. Moreover, as we now know, millimeter waves are characterized by stable propagation properties in unfavorable environments and improved noise immunity.

The millimeter-wave spectrum has become the focus of attention in recent years also because the lower frequency bands are filling up very quickly. New wideband applications, such as WLAN and radar, require large bandwidths, which are readily available at millimeter-wave frequencies.

However, significant attenuation, signal depolarization, amplitude, and phase changes are attached to millimeter-wave propagation, and atmospheric attenuation tends to be higher if the frequency increases, and it also depends on weather conditions. The selection of a particular frequency band for new radar systems depends therefore on a number of factors, including (1) the propagation environment, (2) the frequency bands available for a particular service, (3) backscattering properties of targets, and (4) the availability of appropriate technology.

Because of rather large absorption in the atmosphere, millimeter waves are used mainly in short-range radar systems.

Theory and applications of millimeter-wave radar are described elsewhere in books [1–3], book chapters [4–6], and survey papers [7]. Problems and advantages of millimeter-wave radar are discussed at various international conferences and symposia [8–12]. This is a field of rapid development and, from time to time, it is necessary to make a short stop to survey what has already been done in order to have a possibility to further advance and face the future with confidence. Thus, a consideration of the trends in development and application of millimeter-wave radar systems and their various functions, which have received significant development during recent years, is of doubtless interest.

In this chapter, the state of the art for millimeter-wave radar design and application is presented. First, a brief overview of millimeter-wave propagation and scattering is provided. This is followed by basic radar design principles. On the basis of millimeter-wave radar possibilities and real practical needs, different millimeter-wave radar systems can be created, particularly for intelligent transportation systems weather information systems, remote sensing, and other applications. These items are used as the core of the chapter.

10.2 Propagation and Scattering of Millimeter-Length Waves

Understanding millimeter-wave interaction with molecules of atmospheric gases, hydrometeors, turbulent inhomogeneity of air, and also the estimation of influence of vertical stratification of the atmosphere and reflections from underlying terrain on characteristics of received signals are rather important in radar applications.

Now the problem of millimeter-wave propagation is appreciably investigated. Results of research and theoretical calculations of scattering and molecular absorption in hydrometeors coincide quite well. The features of millimeter-wave behavior in the atmosphere that are the most significant for radar applications and the features of backscattering that underlie active radar will be considered in this section.

10.2.1 Molecular Absorption

The theoretical description of gaseous absorption is well established and a number of models have been developed to calculate the transmission and attenuation through the Earth's atmosphere. Millimeter-wave attenuation in atmospheric gases can be assessed, relying primarily on data on temperature, pressure, and humidity, all of which are normally available.

The theory of molecular absorption in the atmosphere is quite complicated. Therefore, normally researchers use numerous approximations when calculating molecular absorption spectra of gaseous components of the atmosphere. This influences the accuracy of the final result. Perhaps the most comprehensive theory of millimeter-wave gaseous absorption was developed by Kalmykov and Titov [13] and Zagorin et al. [14]. As a result of theoretic and experimental work, the method of the memory functions was developed for the description on the molecular level of the complex refractive index of polar gases for arbitrary symmetric molecules. According to Zagorin et al. [14], the developed model of molecular gaseous absorption describes sufficiently the phenomena under study in a broad range of pressures. In Figure 10.1, adapted from the work of Zagorin et al. [14], the absorption spectra of oxygen in dry atmosphere are shown at 29.7°C for a frequency band of 54–66 GHz. Solid curves represent the calculations in

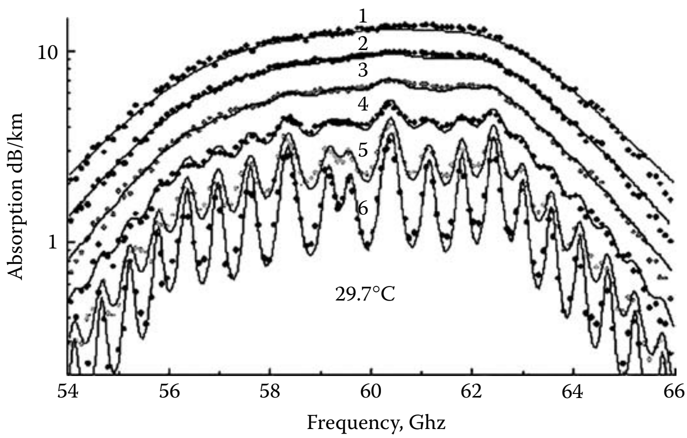

Figure 10.1 Absorption of oxygen at 54–66 GHz band in dry atmosphere as a function of frequency at 29.7°C and different pressure (height). The six curves correspond to six heights:(1) 0; (2) 3 km; (3) 6 km; (4) 9 km; (5) 12 km; (6) 15 km. Dots are experimental results. From Zagorin et al. [14].

the framework of the model [13]; dots are experimental data. Curves 1–6 correspond to different pressures (in kilopascals) and therefore to different heights (in kilometers): 1, 101.3 kPa (0 km); 2, 70.11 kPa (3 km); 3, 47.19 kPa (6 km); 4, 30.81 kPa (9 km); 5, 19.49 kPa (12 km); 6, 12.1 kPa (15 km).

Such calculations can be performed at different frequency bands for different gaseous components, particularly for water vapor, and also for the complex influence of both oxygen and vapor.

In the area of submillimeter wavelengths, the absorption is made by molecules of water vapor, carbonic gas, and oxygen. Air temperature decreases in the troposphere with increased height. That is why water content is also rather sharply reduced with height. Therefore, the infrared area of a spectrum is substantially accessible to monitoring from balloons and high-altitude planes. In this area of a spectrum, along with gaseous absorption, the self-radiation of the atmosphere is also essential, which is especially important for research of background radiation of the universe.

Summarizing, one can say that absorption of millimeter waves increases on average if frequency rises; however, there are pronounced resonance peaks of absorption in the atmosphere. They are caused by the presence of oxygen and water vapor. These phenomena are typical, for example, at the frequencies of 22.2 GHz (vapor), 60 GHz (oxygen), 118.8 GHz (oxygen), and 180 GHz (vapor). Under the condition of moderate air humidity (about 7.5 g/m^3 at the Earth's surface) the complete millimeter-wave attenuation at the separate parts of the spectrum runs up to 200 dB and even more. Between such stable absorption bands, the window regions exist. Average wavelengths and typical absorption factors of window regions are presented in Table 10.1.

The window regions are rather wide; therefore, frequencies around the mean values indicated in Table 10.1 normally may be chosen as standard values for different applications. Special practical interest is traditionally typical for window frequencies of about 35, 94, 140, and 220 GHz.

10.2.2 Attenuation in Hydrometeors

In addition to molecular absorption in air, attenuation during propagation is caused by particles in the atmosphere, especially condensed water vapor particles (hydrometeors) in the form of fog, cloud, rain, snow, and hail. The

Table 10.1 Absorption of Millimeter and Submillimeter Waves in Window Regions

Wavelength, mm	8.6	3.5	2.4	1.4	0.85	0.72	0.6	0.46	0.36	0.02
Frequency, GHz	35	86	125	214	353	417	500	652	833	1500
Absorption, dB/km	0.07	0.42	0.45	1.0	6	14	35	37	45	5

attenuation is specified by two mechanisms: (1) absorption of the incident radiation energy in a volume of a hydrometeor (e.g., a raindrop) and (2) diffraction scattering of the incident radiation by a hydrometeor into the ambient space.

When the radiation wavelength is much greater than the size of the hydrometeors, as in the case of microwave radar, the absorption cross-section is at least an order of magnitude greater than the scattering cross-section, and scattering can thus be neglected. However, this simplification is not valid in the millimeter region, because hydrometeors are comparable in size with the sounding wavelength. As a result, scattering occurs, leading to significant attenuation [15].

Rain, clouds, and fog are the most prevalent forms of hydrometeors encountered in the atmosphere, and rain, in particular, plays a dominant role in determining the availability and reliability of radar and communications systems operating at millimeter waves. Assuming spherical drops, in particular for clouds and light rains, the attenuation can be calculated using classical Mie scattering theory [16] using the known drop size distribution, terminal velocities of drops, and the complex refractive index of water. For nonspherical drops, particularly in the case of strong rain, more complex approaches are available that take into account polarimetric properties [17,18]. However, such approaches are nontrivial. At the same time very simple approximations have been developed in terms of power-law relationships between attenuation, γ, and rainfall rates, R, such as $\gamma = aR^b$ [19–20]. In this simple model, particular attention has been given to the data on the microstructure of rain used to calculate specific attenuation and to the applicability of such calculations to real rainfall situations.

As has been noted elsewhere [15], only a forward scattering brings the contribution to attenuation, and for rain, which is a very rare medium of randomly situated drops, especially in relation to millimeter-wave wavelength, this forward scattering is always coherent.

The contribution of scattering in the attenuation of millimeter waves is essentially different from centimeter waves. Attenuation of millimeter waves is substantially determined by scattering radiation, and the albedo of millimeter-wave single scattering practically does not depend on wavelength, rain rate, drop size distribution, and thermodynamic temperature of water in droplets. Note for comparison that in microwaves (centimeter waves) albedo is a decreasing power function of wavelength and also depends on rain rate, drop size distribution, and temperature of droplets.

The most important property of millimeter-wave propagation in all directions different from the direction of propagation (different from forward scattering) is the fact that for raindrops distributed randomly in space, the scattering on different droplets can be considered independent. This is because raindrops are distant enough from each other; that is, they are in the far-field region regarding the adjacent scatterers. Thus, each droplet

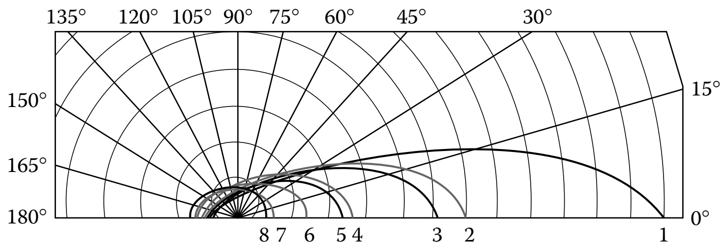

Figure 10.2 Normalized scattering indicatrices of the rain element. (1) λ = 1.4 mm, R = 12.5 mm/h; (2) λ = 1.4 mm, R = 1.56 mm/h; (3) λ = 2.2 mm, R = 12.5 mm/h; (4) λ = 2.2 mm, R = 1.56 mm/h; (5) λ = 3.3 mm, R = 12.5 mm/h; (6) λ = 3.3 mm, R = 1.56 mm/h; (7) λ = 8.6 mm, R = 12.5 mm/h; (8) λ = 8.6 mm, R = 1.56 mm/h. From Zagorin et al. [14]

interacts with electromagnetic waves in such a way as if other droplets do not exist. This allows the assumption that radiation scattered by the aggregate of different raindrops is incoherent scattering (but not forward scattering!).

Distribution of radiation scattered by rain in different directions is described by normalized scattering indicatrix. According to Zagorin et al. [14] in Figure 10.2, scattering indicatrices are shown for radio waves with wavelength λ = 1.4, 2.2, 3.3, and 8.6 mm in rains with rain rate R = 1.56 and 12.5 mm/h. Calculations were done on the basis of Mie theory [16]. Despite multilobed scattering indicatrix of separate particles (number of lobes $|m|\ x$, with $|m|$ as the modulus of complex refractive index particle material, and $x = 2\pi a/\lambda$, with a the particle radius), the shape of a scattering indicatrix of polydisperse medium, like rain, is very smoothed. Nevertheless, the effect connected with Mie scattering is very well expressed in the millimeter-wave band, in contrast to centimeter waves where indicatrix is close to the Rayleigh case.

This effect consists of two things: (1) the main lobe is considerably prolonged in the direction of wave propagation, and (2) the degree of oblongness depends on the wavelength, rain rate, and drop size distribution function. The intensity of scattered radiation in the direction of wave propagation increases with lessening wavelength and increasing rain rate. One can see from Figure 10.2 that the scattering indicatrix of a rain element at $\lambda = 8.6$ mm is almost symmetric and close to the Rayleigh case, whereas if λ decreases, the forelobe becomes elongated, and anisotropy of scattering is expressed brighter if rain is more intensive. The last fact is clear because increasing rain rate corresponds to an increase in the number of large drops.

Normalized scattering indicatrices of millimeter waves can be approximated by two-parameter expression [17] with sufficient accuracy to analytically estimate the level of mutual interferences between radio-electronic systems due to scattering radio waves in rain.

In the strict sense, falling raindrops are not spherical, orientation of their axes of symmetry has the preferable direction, and sizes are commensurable with wavelength. Therefore, polarization effects appear brightly at millimeter-wave propagation in rain. This phenomenon is useful for remote sensing.

Frozen precipitation, in the form of snow and hail, produces, on average, less influence on millimeter-wave propagation. In fact, snow, hail, and ice have much smaller dielectric constants than water, and frozen hydrometeors appreciably interact with electromagnetic radiation only when melting is taking place within the particles. Measurements of attenuation and backscatter by falling snow and rain at 96, 140, and 225 GHz can be found in Nemarich et al. [21].

10.2.3 Integrated Influence of Gaseous and Hydrometeor Attenuation

Perhaps the most comprehensive model for integrated attenuation calculations is the millimeter-wave Propagation Model (MPM) developed by Liebe [22]. This model was adopted by the International Telecommunication Union in recommendation [23]. It predicts propagation effects of loss and delay for the neutral atmosphere at frequencies up to 1000 GHz with contributions from dry air, water vapor, suspended water droplets (haze, fog, cloud), and rain. For clear air, the local line base (44 O_2 plus 30 H_2O lines) is complemented by an empirical water–vapor continuum. Input variables are barometric pressure, temperature, relative humidity, suspended water droplet concentration, and rainfall rate. The calculation example in Figure 10.3 is adapted from McMillan [7]. It shows the results of calculating the atmospheric attenuation over the range 40–1000 GHz for relative humidities of 50 and 100 percent and rainfall rates of 5 and 20 mm/h.

These calculations were done with a computer program [24] that calculates attenuation as a function of a variety of factors for a number of conditions such as rain and fog. This program has been shown to give results accurate to about 0.2 dB/km in the atmospheric window regions of interest in the range 0–1000 GHz.

The curve for 100 percent relative humidity includes attenuation due to 0.5 g/m^3 of condensed water vapor, corresponding to a fog that would give only 100 m visibility in the visible spectrum. Note that this thick fog has a considerably smaller effect on propagation than rainfall, especially at the lower frequencies, because attenuation due to fog results mainly from Rayleigh scattering in these bands. Rainfall is another matter, however. It does not limit optical visibility but produces strong attenuation in millimeter waves. Larger drops occur normally at higher rain rates. Since raindrops are

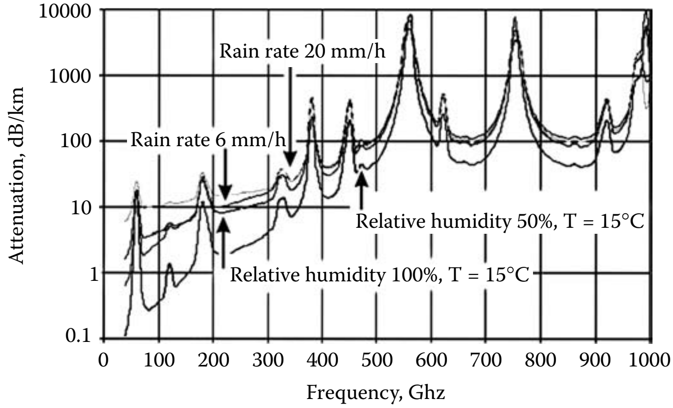

Figure 10.3 Atmospheric attenuation in the range 40–1000 GHz. From McMillan [7].

on the order of a few millimeters in diameter, strong attenuation due to Mie resonance scattering takes place.

10.2.4 Refraction

Refraction is a change in direction of propagating radio energy caused by a change in the refractive index or density of a medium.

The field of refraction coefficients undergoes strong variations in the surface layer of the atmosphere. Therefore, it is important to take into account the influence of weather conditions on the trajectory of millimeter waves propagating near the horizon.

Results of long-term measurements [14] have shown that the maximal value of an angular difference between apparent and true directions on a source of radiation is observed in autumn in anticyclonic weather at five angular minutes. From the same data it follows that maximal speed of change of this difference for the vertical component of angle of arrival is three angular minutes per hour. However, simulation under the worst conditions showed that essential trajectory curvature is possible on a surface radio path, which can result in errors and even loss of the target because of probable presence of air layers with super-refraction properties. The phenomenon of multipathing is also not incredible.

Simultaneous refraction measurements in vertical and horizontal planes have proved that horizontal refraction is at least two orders of magnitude less than vertical refraction. This result is in good coordination with known data on the structure of the troposphere. Note that the change of the angle of horizontal refraction was always less than the metering error (one angular second). Therefore, the results concerning vertical refraction are of interest.

On the biennial cycle of measurements in the middle latitudes [14], the distribution of vertical refraction angles appeared asymmetrical and has been precisely enough approximated by gamma distribution. The mean angle of refraction and root-mean-square angle made up accordingly 70 and 50 angular seconds. On average, the refraction at night is two to three times more than in the afternoon; in summer it is about two times more than in winter. The maximal magnitudes of refraction were observed at the moment of sunrise and sunset, which is associated with rising inversion layers of temperature and humidity at the surface layer in the morning and in the evening.

As a result of simultaneous measurements of refraction of millimeter waves and optical radiation, it was revealed that in summer, no steady correlation was observed between refraction angles at two frequency bands (correlation coefficient was 0.4), whereas in winter the correlation coefficient rose to 0.97. The explanation is rather simple: when air temperature is reduced, absolute air humidity also goes down and, hence, the distinction in parameters of refraction and beam trajectories of the millimeter-wave and optical radiation becomes less.

10.2.5 Underlying Terrain Irregularities

An interfacial area between air and earth is a weakly rough surface that provides, actually, a kind of mirror reflection in the microwave band. Such reflection is described by Fresnel's formulas [25]. In millimeter waves under the same conditions, wavelength and root-mean-square roughness are comparable, that is, surface irregularities play a significant role and the incoherent component of scattered reflection becomes dominant. Even in this case, however, an interference structure of the millimeter-wave field is apparent at a short distance and small grazing angle.

With increased distance, the zone of effective reflection, which is essential to formation of a fringe pattern, increases and includes both small-scale and large-scale irregularities, which can result in destruction of the interference structure. Besides, fluctuations of amplitude, phase, and a direction of propagation begin to appear that also deform the interference structure of a total field [26]. Complex phase of the fluctuating millimeter-wave field is defined by the superposition of three components: (1) direct waves; (2) the waves re-reflected by the underlying terrain irregularities; and (3) the waves scattered on turbulent inhomogeneities of the atmosphere, which will be described in the next section.

10.2.6 Turbulence

Atmospheric turbulence creates small-scale inhomogeneities in the refractive index, which are manifest in rapid fluctuations in the amplitude, phase, and angle of arrival of radio waves. This results in so-called scintillation phenomena, which can impact significantly on radar and communications systems and must be taken into account in system design. The scintillation effects are likely to be significant in the lower regions of the troposphere (the surface layer), where turbulent fluctuations produce mixing of air and are responsible for vertical transport processes, and in clouds, where turbulent eddies are the cause of mixing of air and hydrometeors.

The theory of wave propagation through a turbulent medium has been developed by Tatarskii [27]. Later, the further detailing to the microwave and millimeter-wave regions was done [14,28]. Using these theories, one can relate the general characteristics of a stationary scintillation event, such as the scintillation variance, Doppler spectrum width, and others, to the structure parameter, C_n^2, which is a measure of the turbulence-induced inhomogeneities in the refractive index, and also to other parameters such as the eddy dissipation rate. Such theories can be useful not only to estimate the turbulence effects to millimeter-wave propagation but also for deriving information about atmospheric turbulence from radar signals [29]. However, there is currently a paucity of reliable statistical data on atmospheric turbulence parameters, and empirical models have accordingly been developed that are based generally on surface parameters such as temperature and humidity, and which can hence be applied to the design of radar and communications systems.

10.2.7 Scattering and RCS

In Section 10.2.2, the phenomenon of scattering was considered as a source of wave attenuation. However, in the case of radar, the wave scattering should be additionally considered as a source of useful signal and also clutter. Features of this useful aspect of millimeter-wave scattering will be outlined now.

Considering a rain element as a radar target (for cloud radar, as an example), all directions of scattering, as shown in Figure 10.2, except of the wave line along the abscissa, represent this aspect of scattering (if bistatic radar is taken into account). The direction of 180° (back lobe) represents the backscattering, the only component of scattering that is important for monostatic radar. Hereinafter, the term radar means monostatic radar, when both transmitter and receiver are located in the same position.

Thus, the energy scattered back to the source of the wave (called backscattering) constitutes the radar echo of the object. The intensity of the echo is described explicitly by the radar cross-section (RCS) of the object (target). The units of the RCS are the equivalent area, usually expressed in square meters.

Millimeter-wave radar targets and clutter have been considered by Kulemin [3], who described reflections from land, sea, and precipitation, including land and sea backscattering for the small and extremely small grazing angles that are necessary for clutter rejection in radar systems. A summary of the interactions between radiated waveform and different targets and clutter affecting operation of radar in the millimeter-wave band is also presented.

General principles of target RCS description and measuring in the millimeter-wave band are the same as in other radar frequency bands [30]; however, small wavelengths require (1) more accurate theoretic considerations, such as calculations using the Mie approach instead of the Rayleigh approximation for raindrops, and (2) more difficult measurements because of the application of complicated millimeter-wave technology.

Comprehensive consideration of backscattering phenomena and the RCS for a wide variety of targets is beyond the scope of this book. Taking into account that millimeter-wave radar is actually a short-range sensor and some of its important applications concern the intelligent transportation systems (ITS) and automotive safety systems such as the forward collision avoidance assistance system (FCAAS), which has to be capable of detecting not only other vehicles but many other objects including pedestrians, let us consider the RCS of a pedestrian as an example of a millimeter-wave radar target. This is perhaps one of the most complicated targets because the RCS is difficult to measure. This consideration is completely based on the results of work by Yamada [31], who has researched the RCS of pedestrians for 76-GHz radar. The measurements were done with an FMCW (continuous-wave frequency-modulated) radar system from a distance of 5 m. Experimental data were obtained by rotating the pedestrian on the turntable and measuring the radio wave reflection intensity from all directions. The obtained scattering pattern is shown in Figure 10.4a. Figure 10.4b shows the results obtained for the moving average of the same data about an angle of 2.6 degrees (10 samples). The RCS is measured in decibels relative to a square meter, dBsm.

The average value of the RCS was found to be −8.1 dBsm. This is about 15–20 dB less than the reflection intensity of the rear of a vehicle. A spread of the RCS was more than 20 dB. Moreover, the results showed that the reflection intensity of the pedestrian's front and back is about 5 dB higher than the pedestrian's side. The radio wave reflection intensity depends on the pedestrian's aspect. The reflection intensity of a naked human body is almost the same as that of clothes that have a comparatively high radio wave reflection intensity, such as a cotton shirt.

In the case of the unwrinkled shirt, there is very little change in the reflection intensity, even when the shirt is swung to the right and left. For the wrinkled shirt, however, the reflection intensity changes considerably with the swing. Two or more scatter points (where the radio waves are reflected strongly) normally are created by wrinkling the clothes. This is why the RCS changes when the shirt moves. Perhaps this change in the

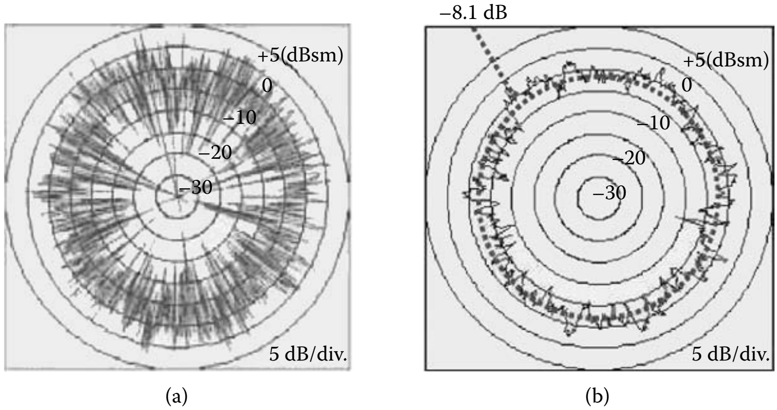

Figure 10.4 (a) Pedestrian scattering pattern raw data (left); (b) Averaged scattering pattern (right) [31].

RCS and the reflection intensity occurs because the waves reflected from these scattering points produce phase interference.

This example shows that millimeter-wave backscattering contains a lot of information about the target; it can be measured and used in many different applications. Even an insect may provide a measurable RCS in the millimeter-wave band.

Significant attenuation of millimeter wave can be considered a disadvantage of this frequency band; however, the same property can also be used for deriving information about the environment in remote sensing systems as well as for improving interference protection and electromagnetic compatibility. These aspects, radar principles, and applications will be considered later in this chapter.

10.3 Radar Design Principles

The basic principles of millimeter-wave radar are similar to those of microwave radar. The stronger wave attenuation discussed above can even be advantageous in certain radar and communications applications. For example, the transmission frequency can be selected such that the atmosphere imposes additional attenuation, thus minimizing unwanted interference from other cofrequency systems and improving the efficiency of spectrum usage. In fact, millimeter-wave radar systems have intermediate properties between microwave and infrared systems. They should be designed in such a way to take the best features from each. In this section we consider common principles of radar in relation to the features of millimeter-wave systems.

10.3.1 Radar Tasks

Assume that an observer is situated at a point O, and his task is to learn what object is located at another point, A. The observer (a radar) can radiate electromagnetic energy (waves) and concentrate it (with the help of an antenna) in a given direction. It is important to note the following. The main energy flow is spatially concentrated by the shape of the main beam; in spite of this, some energy (more or less) is, nevertheless, radiated in all directions without exception. The same, of course, concerns the direction of receiving reflected signals. The observer can have some a priori information about the object (radar target) and the environment. Under these conditions, the main tasks of radar are

- *Detection*: decision making regarding the presence or absence of a target with minimum allowable probabilities of erroneous decisions
- *Measurement*: a process to estimate the coordinates and parameters of motion of a target with minimum allowable errors
- *Resolution*: separate surveillance (detection and measurement) of an individual target in the presence of other targets
- *Recognition*: ascertainment that a resolved target belongs to the given class of targets
- *Target tracking*: the use of radar measurements for continued tracking of a given target

The numerous applications of radar can be reduced to this limited number of tasks.

10.3.2 Physical Processes

Let us assume a radar radiates a sounding signal (waveform), which after a time reaches a point where an object A (a target) is located. As a result of interaction with target A, the incident wave induces both electric and magnetic currents in the target, and they, in turn, generate electromagnetic waves propagating over all directions, including backscattering signal directed to point O. Reflected signal reaches point O and causes a corresponding signal in the form of a current or voltage. The delay time of the reflected signal contains range information. If the target is moving relative to the radar, the reflected signal gets a Doppler shift of frequency proportional to the radial velocity and inversely proportional to the radar wavelength, that is essentially higher in the millimeter-wave band than in longer wavelength bands. If the target has a nonspherical shape, the polarization of the reflected signal is different from the polarization of the radiated signal and also depends on the mutual orientation (in space) of a target and antenna beam.

It is clear that all information on the target can be obtained only by comparison of radiated and received signals. This information can be in the form of electric signals, and further interpretation and transformation into physical or geometrical parameters is an additional independent problem.

10.3.3 Sounding Waveforms

Various kinds of sounding waveforms can be used in millimeter-wave radar. The most obvious is division of all possible waveforms on continuous-wave (CW) and pulse sounding signals. A modulation of the sounding radiation is necessary at least to measure target range. Frequency (FM), phase code (PCM), amplitude (AM), and polarization modulations are possible. Different modulating functions can be used, including noise (random) function, but in the majority of cases the waveform is deterministic. Depending on the spectrum width, sounding signals are divided into narrow band (NB), wideband (WB), and ultrawideband (UWB).

Now we consider only a classical type of radar. In this case the sounding waveform is rather simple. It can be a CW FM wave normally with linear FM or a train of short pulses with pulse repetition time, which is much more than pulse duration. The spectrum width of such signals, B, most often is many times less than the carrier frequency of radiation, f_o, especially in millimeter-wave radar; that is, for the radar sounding signal, $B/f_o << 1$, excluding some special cases that will be considered in Sections 10.3.6 and 10.3.10. This inequation is a condition of the NB signal. Any NB signal $U(t)$ can be expressed as [32]

$$U(t) = A(t) \cos [2\pi f_0 t + \varphi(t)], \tag{10.1}$$

where $A(t)$ and $\varphi(t)$ are functions of time that are very slowly changing during the time $T = 2\pi/f_o$.

The theory of radar that was initially developed reasoning from such simple models as expression (10.1) now is very much advanced and is valid for a wide variety of waveforms (sounding signals), both NB and WB. Along with a law of time modulation being fulfilled in the transmitter, variations with time of orientation and parameters of antenna affect essentially the aggregate space–time modulation of radar signals. Selection of the sounding signal during radar design normally defines key features of the radar system, namely: resolution and measurement accuracy of range, radial velocity and angular data of targets; possibility to provide required energetic parameters at limited peak power of millimeter-wave generators; and interference immunity of the system.

Important properties of sounding signals are described with the help of ambiguous functions [32,33]. The most recent and advanced radar theory [33,34] uses the term “mismatch function” instead of ambiguous function.

This theory notes a difference between (1) matched and (2) optimal cases of signal resolution. Matched resolution takes place as a result of signal processing that is optimized for the background of uncorrelated stationary interference with known parameters; that is, without taking into account any other possible signals except predicted signal. In this case, improvement of resolution is provided only by the selection of the signal structure. Optimal (mismatched) processing is used for better reduction of strong unwanted signals, taking into account their features. Optimal (mismatched) processing can be nonadaptive, oriented on a predetermined typical situation, or adaptive, which means it can adjust to the unknown in advance of a specific situation.

10.3.4 Radar Signals and Information

It is natural to expect that a reflected signal looks like the sounding waveform. In the case of NB radar, it corresponds to model (10.1). If target A is a stationary target, only the amplitude and phase are changed while the moving target could change the frequency of the reflected signal relative to the radiated one. Note that other targets will be illuminated as well, specifically those that are located on the same distance as target A; reflected signals from such targets will simultaneously reach the point O where the radar is situated. Thus the reflected signal in point O is defined as a sum of all signals returned simultaneously and can be described also by expression (10.1).

In Section 10.2.6 we considered the RCS of a target without taking into account polarization properties. Now let us clarify in more detail what information can be obtained from radar returns. Suppose that neither interferences nor any effect of propagation medium exist, and confine our consideration to linear polarization. Under this condition, suppose at first that an electric field vector of incident wave E_i is horizontally oriented: horizontal component $(E_H)_i \neq 0$ and vertical component $(E_V)_i = 0$. For many targets the scattered waves have different polarization than the incident waves. This phenomenon is known as cross-polarization. So, in the general case, the electric field vector of a backscattered signal, E_b, has another spatial orientation. That means it has both $(E_H)_b \neq 0$ and $(E_V)_b \neq 0$ orthogonal components. Naturally, vector E_b is proportional to vector E_i, hence both $(E_H)_b$ and $(E_V)_b$ components of a backscattered vector are proportional to $(E_H)_i$:

$$(E_H)_b = S_{HH}(E_H)_i; \tag{10.2}$$

$$(E_V)_b = S_{VH}(E_H)_i, \tag{10.3}$$

where S_{HH} and S_{VH} are coefficients, which generally are modulus constituents of the scattering matrix $[S]$ composed of four numbers, S_{xy}, $(x = H; V, y = H; V)$.

Having recollected expression (10.1), one can see that each component of backscattered wave, in the general case, gets a phase shift relative to the incident (or radiated) wave. In the considered case, the orthogonal components of the electric field vector can be expressed by the following time representation:

$$(E_H)_b = S_{HH}A(t)\ \cos\,[2\pi f_o t + \varphi(t) + \psi_{HH}], \tag{10.4}$$

$$(E_V)_b = S_{HV}A(t)\ \cos\,[2\pi f_0 t + \varphi(t) + \psi_{HV}]. \tag{10.5}$$

In addition to modules S_{HH} and S_{HV}, phase shifts ψ_{HH} and ψ_{HV} are argument of complex constituents of the scattering matrix, [S]. It is seen from formulas (10.3) and (10.5) that in the case of a horizontally polarized incident wave, the backscattered wave is defined by four parameters, S_{HH}, S_{HV}, ψ_{HH}, and ψ_{HV}. Consideration of a vertically polarized incident wave will result in another four parameters, S_{VV}, S_{VH}, ψ_{VV}, and ψ_{VH}.

In general, an incident wave, radiated by radar, may have an arbitrary or any given polarization, which is characterized by two orthogonal polarization components, $(E_H)_i$ and $(E_V)_i$ in the case of a linear polarization basis. Thus complete description of the radar target can be done with the help of the indicated eight numbers, which constitute the scattering matrix mentioned above:

$$[S] = \begin{bmatrix} S_{HH} & S_{HV} \\ S_{VH} & S_{VV} \end{bmatrix}, \tag{10.6}$$

where s_{xy}, $x = H; V$, $y = H; V$, and quantities s_{xy} are in general complex with modulus S_{xy} and argument ψ_{xy}. The scattering matrix is individual for each object or a class of objects and provides target signature.

In reality it is difficult to measure absolute values of amplitudes and phases. That is why relative measurables are often used; for example, such values as S_{HH}/S_{VV}; S_{HY}/S_{VV}; ψ_{HH}-ψ_{YY}, and some others.

The backscattered RCS is related to the scattering matrix components by the following relation:

$$\begin{bmatrix} \sigma_{HH} & \sigma_{HV} \\ \sigma_{VH} & \sigma_{VV} \end{bmatrix} = 4\pi R^2 \begin{bmatrix} |S_{HH}|^2 |S_{HV}|^2 \\ |S_{VH}|^2 |S_{VV}|^2 \end{bmatrix}, \tag{10.7}$$

where σ_{xy}, $x = H; V$, $y = H; V$ is the RCS at given polarization properties on transmitting and receiving. Similar and equivalent equations can be obtained through circular polarization [35].

Polarization is mostly sensitive to the shape and orientation of a target or its components. Velocity of a target is reflected in corresponding Doppler frequency that gives additional information.

10.3.5 Spatial Resolution

Reflected signals are received by the radar antenna mainly within some solid angle, $\Delta\Omega$. Quantitative estimation of this solid angle can be done separately for two plane angles, $\Delta\theta$ and $\Delta\phi$, normally in the horizontal and vertical plane, correspondingly, and each of these two angles is defined by the ratio λ/d of wavelength, λ, to the linear size of the antenna, d, in the appropriate section. Thus, a reflected wave and finally a signal at the input of a radar is formed by the currents that are induced by the incident wave on the elementary area with linear sizes $R\Delta\theta$ and $R\Delta\phi$ within distance R. Obviously, for millimeter-wave radar it is easy to reach the λ/d ratio at least an order of magnitude better than for microwave radar.

Suppose we have a pulse radar that radiates a pulse with a rectangular envelope, and pulse duration is τ. In this case, all objects located along the same direction within distance $\Delta R = c\tau/d$ (c is speed of light) will be perceived as a single object. A typical pulse duration of microwave radar is of 1 μs, which gives $\Delta R = 150$ m. In order to improve range resolution, radar designers work to decrease τ. However, a decrease of pulse length leads to decreasing radiated energy and, finally, radar barrier in accordance with the radar equation [30,36], and this is one of the problems.

On the other hand, the shorter τ, the broader spectrum width B, and the theory of radar proves that, in general, a better range resolution can be achieved by broadening the spectrum of radiated waveform, which may be not only pulsed radiation but CW as well (see Section 10.3.3). Range (and also velocity) resolution potential of a waveform can be estimated with the help of the ambiguous function that was also considered in Section 10.3.3. Generally speaking, millimeter-wave radar has very high potentials to generate short (nanosecond) pulses and WB waveforms.

Finalizing the notion of spatial resolution, note that all objects within a parallelepiped of the size $\Delta R \times R\Delta\theta \times R\Delta\phi$, named resolution volume, will be perceived as a united single object. Actually, decreasing resolution volume is one of the core problems of radar design.

10.3.6 Pulse Compression and Synthetic Aperture

Now we know that a way to lessen the range size of a resolution volume consists in decreasing pulse duration or, more exactly, spectrum spreading. Special kinds of modulation are used within a pulse to generate WB signals ($\tau B >> 1$) without lessening pulse duration. Thus, radar designers may choose a pulse duration, τ, such that it provides the necessary radiating energy (and radar barrier) and then achieve the necessary range resolution by broadening the spectrum with the help of within-pulse modulation (mostly FM and PSM). Special processing of WB signals provides pulse compression at the output of the matched filter [32]. The compression ratio equals the time–bandwidth product, τB, and may be rather high (up to thousands). The theoretical limit of range resolution is defined by the wavelength.

Whereas lessening pulse duration and broadening spectrum width are related to engineering constraints, the problem of lessening tangential sizes of resolution volume ($R\Delta\theta$ and $R\Delta\phi$) is confronted with physical constraints because angles $\Delta\theta$ and $\Delta\phi$ are proportional to λ/d. Obviously, the first way to improve angle resolution is to decrease operational wavelength. Use of millimeter-wave band allows one to make the linear sizes of the resolution cell up to ten times smaller than in the case of microwave radar. The second way, an increase of antenna sizes, however, leads to the appearance of very large antenna construction, which causes technological difficulties apart from the fact that a large antenna is inconvenient, expensive, heavy, impossible to be applied on board, and so forth. Accuracy of antenna beamforming depends on relations between the phases of electric current in different points of the antenna, and in the millimeter-wave band, even very small distances, like a fraction of a millimeter, correspond to extremely big phase changes. Accuracy of adjustment is very critical in such antennas. That is why protection against thermal broadening, wind, and rain and avoidance of earth wave influence and other exposures are independent problems of high importance. Very big ground-based antennas are mostly unique and extremely expensive at both development and maintenance. In the case of airborne and spaceborne applications, antenna size is limited by the linear size of a platform, and to get a really high λ/d ratio is impossible. The tendency of azimuth resolution improvement (lessening angle $\Delta\theta$) resulted in the creation of a long-fuselage aircraft antenna. However, nowadays the much more productive idea of synthetic antenna aperture is implemented. Actually, any antenna produces the composition of signals obtained from different elements of the antenna surface by taking into account the correspondent phase incursion, caused by the features of antenna configuration. Synthetic aperture is created artificially by the following steps: (1) measurement of sequential values of amplitudes and phases of field strength in different points of the space as antenna elements; (2) memorization of these values; and (3) special composition of them. These sequential measurements are done in flight, which provides a brilliant possibility to create artificially an antenna, the size of which is defined by the distance between the first and the last inflight measurement. This means that such an antenna can be practically unlimited in length.

All theoretical and engineering difficulties, which accompanied the implementation of synthetic aperture, were successfully got over, and a kind of radar that uses such antenna is called synthetic aperture radar (SAR) [30].

As is easy to see, a special signal processing in the synthetic aperture antenna provides antenna beam compression that is similar to the pulse compression considered above. These two compression technologies improve spatial resolution dramatically.

Modern SAR can provide a λ/d ratio of up to thousands. Use of SAR has reduced the radar resolution cell so significantly that in some cases radar images become similar to photography.

10.3.7 Target Selection

Clutters created as a result of reflections from unwanted objects or background returns have a considerable influence on the quality of radar operations. There are different possibilities for selecting wanted targets on the background of clutter. Among the most efficient are polarization methods. Some targets do not transform polarization of incident waves; in matrix (10.6), they have $\sigma_{HH} = \sigma_{VV}$ and $\sigma_{HV} = \sigma_{VH} = 0$. Normally, they are smooth, convex, conducting bodies that have sizes and radii of curvature much more than wavelength. However, the majority of targets are polarization dependent. It is possible to find such polarization for radiated waves, which provides maximal ratio of returns from target and clutter within a single resolution volume. Radar contrast may reach up to 20 dB at polarization selection. A significant increase of the contrast opens the possibility to correlate scattering matrix with a target to solve the inverse problem and implement target recognition [37].

In the case of target movement, a reflected signal has a Doppler shift in the frequency relative to the radiated signal. Doppler shift is proportional to the ratio of the radial component of the target velocity to the wavelength. If among the scatterers inside the resolution volume only a wanted target is moving, it can be selected on the background of other scatterers, which are clutters, with the help of frequency (velocity) selection. Moving-target indication (MTI) is used in many modern types of radar [30].

10.3.8 Radar Detection

Radars often deal with very weak signals. Their intensity can be comparable with receiver noise, which is described by the same model as useful signal (10.1), where both amplitude and phase are random time functions. Noise acts all the time whereas signal may be either present or absent (a binary problem) [36]. A voltage at the input of a radar receiver can be represented as two summands:

$$U_{in}(t) = aU_S(t) + U_N(t), \tag{10.8}$$

where $U_S(t)$ corresponds to the wanted signal described by model (10.1), and $U_N(t)$ corresponds to all other sources including noise voltage and also is described by the same model (10.1) with different randomly changing values of amplitude and phase. Note that parameter $a = 1$ in the presence of a target or $a = 0$ when a target is absent.

A problem definition of radar detection can be formulated as follows way: determine a value of parameter a in Equation (10.8); if $a = 1$, a target is detected.

However a rigorous solution of Equation (10.8) is impossible. Thus it is fundamentally impossible to reply accurately to the question of whether a target is present in the resolution volume or it is absent. Such a reply can be only of a conjectural nature. Quantitative estimates of the appropriate conjectures are probabilities of their reliability. The reliability of a conclusion about a value for parameter a can be improved by increasing the observation period; that is, the interval of the function, $U_{in}(t)$, which is analyzed. A key distinction between functions $U_{in}(t)$ in two situations (a target is present and a target is absent) consists in the difference of statistical laws to which the stochastic functions $U_{in}(t)$ submit.

Let us try to understand those types of errors that inevitably arise during decision making on the presence or absence of a target. Assume a radar receiver produces some processing of input signal, $U_{in}(t)$ that resulted in a signal, $U_{out}(t)$, which is a function of an additive mixture of the wanted signal and the receiver noise:

$$U_{out}(t) = f[aU_S(t) + U_N(t)]. \tag{10.9}$$

Receiver noise, $U_N(t)$ is always present and acts as the input of a receiver while a signal, reflected from the target, $U_S(t)$, acts as a component of the mixture only if $a = 1$ (presence of the target in the resolution volume). A function, $f[*]$, symbolizes some procedure of signal processing. It should be chosen in such a way as to maximize the signal-to-noise ratio (SNR) at the output of the receiver. However, in any type of function, $f[*]$, in all cases the only suitable decision rule is a threshold rule: if $U_{out}(t)$ is more than some threshold value, U_0, the decision "target is present" should be made. Otherwise, the decision "target is absent" should be made.

This consideration clearly demonstrates that a threshold decision-making procedure is accompanied by two kinds of errors: (1) false alarm, when at the absence of a target in the resolution volume, the decision of detection is made; and (2) target skip, when at the presence of a target in the resolution volume, the decision of absence of a target is made. Corresponding probabilities of erroneous decisions are false alarm probability, F, and target skip probability, $(1 - D)$, respectively. Correct detection is a contrary event relative to a skip of the target. That is why probability of true detection is D.

Radars can be designed for different applications. However, in all cases, it is desirable to make erroneous decisions as rarely as possible. The use of a threshold decision rule limits influence to only one possibility: to change the value of the threshold, U_0.

An increase in the threshold naturally results in lessening the false alarm probability, F, but entails a decrease in the detection probability, D. On the contrary, lessening the threshold results in a reduction of the target skip probability (growth in D) but entails growth of the false alarm probability, F.

How might a radar designer determine the appropriate threshold level? Normally the level of false decision probabilities is defined by the user of the radar information on the basis of required radar functions. In turn, probabilities of false decisions constitute the basis for determination of the threshold. However, the fact that two independent probabilities define the reliability of radar detection leads to an unlimited number of possible criteria of detection quality. In radar theory and practice, the Neumann–Pearson criterion is generally accepted. According to this criterion, the false alarm probability is fixed at the acceptable level, F, and under this condition the detection probability, D, is estimated. Of course, we seek to have D as high as possible; it might be close to 1. However, how high can it be in reality? To answer this question, let us revert to formula (10.8), where signal processing is defined by the function $f[*]$. The value of D depends not only on the threshold value but also on the efficiency of the signal processing algorithm. Function $f[*]$ should be designed in such a way as to maximize the SNR at the input of a threshold device. For a given level, $F = F_o$, the maximum possible level of D will be reached. The problem of signal processing consists in the choice or synthesis of such a function, $f[*]$, at which in the framework of a given criterion the detection probability becomes maximum. Thus the Neumann–Pearson criterion of radar detection can be written as

$$F = F_o; D = D_{max}. \tag{10.10}$$

It is obvious that at a threshold rule of decision making, an algorithm $f[*]$ cannot be linear. In many cases, a function $f[*]$ is implemented in the matched filter, which is appropriated to the expected signal (radiated waveform). It gives at its output a value proportional to the energy of the reflected signal by the processing of input signal during its duration.

Development of signal processing algorithms is associated with knowledge of statistical information on wanted signals, background reflections, and receiver noise. This knowledge is used as a priori information for the synthesis of optimal detection algorithms [36,38]. The more complete a priori information, the more effective algorithm can be developed; that is, value D_{max} can be closer to the limiting value equals to unit.

However, in many cases real statistics of signals may differ from the models accepted during the synthesis. This may explain the essential decrease in algorithm efficiency though it was synthesized as optimal in accordance with a priori information. That is why special attention is focused on the development of robust nonparametric [30,33,39] and adaptive [33,40] algorithms for radar detection and recognition.

10.3.9 Radar Measurement

Measurement is a separate radar task. It is important to provide the required accuracy when measuring basic parameters and characteristics of reflected signals to allow determination of spatial target coordinates (range and angular position), velocity of target, and other target parameters. Whereas potential reliability of radar detection depends exclusively on signal energy, the accuracy of measurement depends not only on energy but also on the waveform.

The accuracy of direction finding depends on the antenna pattern when it is directed to the target. The best accuracy can be achieved using the monopulse technique. Monopulse radar splits the antenna beam into parts and compares the signal strength of the various parts. That means the comparison always takes place based on the reflection of a single pulse. This radically helps to avoid the problem that appears when radar signals change in amplitude for reasons that have nothing to do with beam alignment.

Classical radar theory rigorously proves that to provide high-accuracy measurements of both target range and target velocity, the waveform should be long-continued (accurate measurement of Doppler shift) and as wideband as possible (accurate measurement of time delay). This means the requirement of using WB waveforms with the time–bandwidth product $\tau B >> 1$ like that was in respect to radar resolution (Section 10.3.5). A sounding signal that satisfies this inequation can be called a complex signal in the sense that such a waveform is very different from the simplest radar waveform, which is a harmonic curve.

A complex signal is compressed as a result of processing in the radar receiver (Section 10.3.6), and the properties of complex signals, particularly FM and PCM pulses, noise-like waveforms, and others, can be estimated and compared among themselves with the help of the ambiguity function (Section 10.3.3).

Whereas radar detection was implemented by a threshold rule that was applied to voltage (10.8), the range measuring procedure consists of searching for a maximum of the same function, $U_{out}(t)$. Note that the best waveform with respect to a criterion of simultaneously measuring target range and velocity is the ideal noise signal because it has an ambiguity function, $U(t, f)$, that is akin to the delta function located in a point of the searched maximum. Coordinates of this maximum, $U(t_m, f_m)$, correspond to the target range, $R_m \sim t_m$, and target velocity, $v_m \sim f_m$.

Another condition of accurate measurements is a high enough SNR, which represents the energetic aspect of any radar measurement.

10.3.10 Nonclassical Types of Radar

Let us now consider some nonclassical kinds of radar that are especially important with respect to millimeter-wave applications.

UWB radar. In accordance with the FCC (the U.S. Federal Communications Commission) definition, a system is referred to as UWB if its fractional bandwidth, $B_F = (f_h - f_l)/f_c$, is more than 0.2 or total bandwidth $B > 0.5$ GHz; here f_h and f_l are the upper and lower spectrum components measured at −10 dB points, and f_c is the central frequency. Based on the second part of this definition, UWB radar systems with bandwidth $B > 0.5$ GHz but less than 20 percent of the center operating frequency, $B < 0.2f_c$, in the millimeter-wave band can be designed using classical radar theory and the traditional technology of millimeter-wave components, whereas UWB systems designed at $B < 0.2f_c$ have some specific differences and require a more novel approach. A comprehensive theory of UWB radar has still not been developed. However, significant features of UWB radar are known [41]. One of them is a change of the waveform during radiation by the antenna and also during propagation, at the time of scattering, and when receiving the backscattered signal. Therefore, traditional correlation processing or matched filter application can be senseless in the case of UWB radar. Some special approaches have been developed. Moreover, signal shape and some other parameters depend on the direction of radiating or receiving. These and many other peculiarities differ UWB radar theory from classical radar. Nevertheless, UWB radar offers a number of attractive advantages that make it promising and useful in many practical applications as a radar and sensing tool. UWB systems are particularly applicable as vehicular radar ground-penetrating radar (GPR), through-wall imaging sensors, medical imaging devices, and so forth.

Noise radar can be used in both NB and UWB versions [42,43]. This direction is quickly developing nowadays, provides nice resolution, solves the problem of ambiguous measurements, and is quite applicable for the millimeter-wave band.

Bistatic and multistatic radar, in which target radiation is performed from one position and scattered signals are received in other positions, is of great interest. Our vision—when the sun serves as the source of illumination and we perceive the light, which is scattered by entourage objects—is a good illustration of bistatic (multistatic) radar. The phenomenology of bistatic radar offers a significant benefit for different military and civilian systems, enabling separation of emitters and collectors, greatly increasing survivability. The theory of bistatic radar can be found in work by Mahafza [35]. Numerical simulations of the bistatic millimeter-wave radar return from a rocket-shaped object were performed by the Advanced Sensors Collaborative Technology Alliances [44] to identify the best bistatic configurations for detection of low-flying missile-looking objects. Polarimetric measurements of the bistatic scattered fields from a rough, dry soil surface were performed by Nashashibi and Ulaby [45] at 35 GHz over the entire upper hemisphere.

Secondary radar uses one radar station as interrogator, which illuminates an object, usually a vehicle, and stimulates another radar station, called a transponder, installed on the vehicle to reply. The transponder-reply contains special information, for example, about the parameters of the flight and the state of some on-board systems. Secondary radar of the L-band is widely used in civil and military aviation [46]. Millimeter-wave secondary radar systems are of interest for automotive ITS, which will be considered later.

Passive radar uses the electromagnetic radiation that is naturally produced by a target. As is well known, any lukewarm body emits radiation to a greater or lesser extent. At a body temperature of 300 to 350 K, the maximum intensity of this radiation falls in the infrared (IR) band. Passive radar that is based on detection of this radiation is called radiometry [47] and has been used successfully. The advantages of such IR radar consist of emission security and difficulties of jamming and target camouflage. Drawbacks are associated with the impossibility of straightforward selection of targets on range and with the strong influence of atmospheric conditions. The same principle is applied to millimeter-wave passive radar systems, which are almost free from these disadvantages in comparison with IR systems. Useful signal is essentially less in the millimeter-wave than in the IR band; nevertheless, this is not a problem for use of such millimeter-wave radiometric systems [48].

10.4 Radar Subsystems and Components

Millimeter-wave radars are designed for very different applications with different functionalities. That is why radar configuration can also be quite different. Nevertheless, any radar system has several major subsystems that perform standard functions. For example, a typical pulse radar system always contains a synchronizer, a transmitter, a duplexer, a receiver, and an indicator. The main features of millimeter-wave radar are related to radio frequency (RF) subsystems and components.

The intermediate position of the millimeter-wave band between microwaves with corresponding waveguide technology and infrared waves with typical optical methods allows application of both approaches for the calculation and development of RF components at millimeter waves.

Theoretical, physical, and engineering fundamentals of millimeter-wave components have been described [49]. Here we just briefly indicate the main possibilities for building RF components of different functions.

10.4.1 Transmitters

The choice of a reliable, high-powered millimeter-wave-transmitting device usually is a serious problem. This is due to the necessity to use transmitters that should provide both the rather high transmitting power needed to achieve a high radar sensitivity and spatial resolution simultaneously (see Section 10.3). Transmitters for millimeter-wave radars can be designed on the basis of both electrovacuum and semiconductor generators. A series of efficient millimeter-wave magnetrons were designed in the mid-1960s [50]. Among them, magnetrons were designed with champion power (e.g., pulse power of 100 kW at a wavelength of 4 mm).

The transmitter problem has been solved using spatial-harmonic magnetrons with cold secondary-emission cathodes [51]. In comparison with classical magnetrons, such magnetrons can operate effectively in almost an entire millimeter-wave band. Moreover, they have smaller dimensions and weight, higher peak and averaged output power, and larger lifetimes while maintaining other well-known advantages of magnetron tubes. A disadvantage of magnetrons is noncoherence of the train of pulses, which may be very important in some applications.

Some other vacuum tubes, such as klystrons, backward-wave tubes, and gyrotrons, are also suitable for coherent radar. Modern gyrotrons can be designed for power outputs of 22 kW CW at 2 mm and 210 kW pulsed at 2.4 mm [7]. An array of gyrotrons was developed to build a megawatt radar operating in the Ka band [52]. However, in many important applications such a huge power is not necessary, fortunately. For many experimental radars, more common power is about 1–2 kW. Such tubes, like the extended interaction amplifier klystron [53], can be used in real coherent radars as amplifiers in the output stage of a transmitter. These millimeter-wave devices are positioned between the very-high-power tubes and solid-state devices.

A good alternative to vacuum tubes is the solid-state generator. Mostly Gunn oscillators [54] and impact avalanche transit-time (IMPATT) diodes [55] are used. The high electron mobility transistor (HEMT) amplifier is an important new development for fully solid-state millimeter-wave radars. Such devices are suitable for high-bandwidth, medium-power amplifiers; experimental UWB radars can nowadays be designed with their help, as described elsewhere [56,57].

A set of power amplifier modules containing InP (indium phosphide substrates) HEMT monolithic millimeter-wave integrated circuit (MMIC) chips were designed for oscillator sources in the 90–130 GHz band [58]. The modules feature 20–45 mW of output power, to date the highest power from solid-state HEMT MMIC modules above 110 GHz.

Solid-state devices suffer from the same decrease in size of the frequency-determining elements as do vacuum tubes; thus, solid-state device operation mostly is limited to about 230 GHz [7]. Nevertheless, solid-state oscillators of higher frequencies can be definitely designed [59].

Kasatkin and Chayka [60] describe methods of analysis and design of millimeter-wave transmitters with semiconductor diodes and transistors. Physical principles of different millimeter-wave diodes and transistors, optimization methods of frequency-stabilized and wideband self-oscillating systems, as well as synchronized and frequency-multiplying systems are considered in this book. The power of generated oscillations of different active devices can be summarized in branched and hybrid electrodynamic systems, summation resonators and waveguides, and quasi-optical spatial-developed systems [60].

Millimeter- and submillimeter-wave lasers can be selected as a separate class of millimeter-wave generators. Methods of millimeter-wave femtosecond waveforms generation based on two-stream free electron lasers [61] are very promising.

10.4.2 Antennas

A wide variety of antennas can be effectively used in millimeter-wave radar, including lens antennas, Cassegrain antennas, patch antennas, microstrip antennas, and slot antennas.

Different configurations of planar antennas and antenna arrays have been developed. As an example, a millimeter-wave planar antenna array of 64 elements is described elsewhere [62].

The state-of-the-art performances of the single-layer waveguide arrays have been considered [63]. Various types of antenna input ports are being designed for the compact interface to millimeter-wave RF circuits. Low side-lobe design as well as a beam scan/switch capability have also been developed. The latest millimeter-wave wireless systems with these antennas are directed toward applications such as fixed wireless access (FWA), LAN, automotive radars and road monitors in ITS, and so on.

New developments of modeling techniques and technologies for multi-frequency antennas, conformal arrays, and smart beamforming are reported [64]. Some new applications require multifunction antennas with multiband capability even beyond millimeter waves.

As indicated in McMillan [7], at frequencies above about 100 GHz, and at lower frequencies for many applications, metal waveguides become unacceptably lossy because of skin effect losses and our inability to make these waveguides with the precision required for low-loss operation. In many cases, these problems can be solved using techniques developed for the visible and IR portions of the spectrum. This approach to the propagation and handling of millimeter-wave and tetrahertz radiation has been called quasi-optics.

Quasi-optic components of the bidirectional amplification array for transmit/receive front ends have been surveyed [65]; advantages of their application in wireless communications and radar are discussed and a millimeter-wave 22-element multilayer lens array using solid-state integrated circuits is presented. Finally, a review of antenna technology for millimeter-wave automotive sensor applications has also been presented [66].

10.4.3 Receivers

Both direct-detection receivers and heterodyne detectors are used in millimeter-wave radar. The earliest detectors of millimeter-wave and terahertz radiation were simple point–contact diodes. This technique is still used for the higher frequencies today. It has been refined in recent years by the use of Schottky barrier structures. These diodes have operating frequencies extending well into the terahertz range. Another detector suitable for the submillimeter-wave range can be built on the metal oxide–metal (MOM) diode. An interesting variant of the point–contact mixer is the back-to-back diode configuration in which the fundamental frequency and all odd harmonics are canceled, resulting in a mixer that operates at twice the fundamental, and in some cases at four times the fundamental [67]. This configuration extends the frequency range to 320 GHz and higher. In beam-led Schottky barrier diode detectors and mixers, the diodes are fabricated by the same techniques used to make integrated circuits, and for this reason, they can be included in these circuits. More details can be found in McMillan's overview [7].

10.4.4 Integrated Circuits Technology

Monolithic integrated millimeter-wave circuits have emerged as an attractive option in the field of millimeter-wave communications and millimeter-wave sensorics and radar. The combination of active devices with passive planar structures, including antenna elements, allows single-chip realizations of complete millimeter-wave front ends. The state-of-the-art silicon- and SiGe-based MMICs have been reviewed [68]. Compact heterojunction field-effect transistor (HJFET) monolithic integrated-circuit switches will contribute to the low-cost and high-performance millimeter-wave radar and communications systems [69]. The millimeter-wave radar possibilities have been greatly aided by recent large-scale government and industry investment in millimeter-wave integrated circuit development in such programs as MMIC and others.

10.4.5 Other Components

Among advanced radar component technologies, micro-electro-mechanical system (MEMS) devices [70] are of particular interest. They will be important for many applications, including millimeter-wave phased arrays for terahertz radiometric systems and millimeter-wave SAR.

The MMIC program has developed monolithic chips, such as voltage-controlled oscillators, driver amplifiers, power amplifiers, doublers, mixers, switches, and monolithic transceivers. This chapter does not focus on some important components, such as the low-noise amplifiers, power amplifiers, frequency multipliers, feed horns, power dividers, slot couplers, matched hybrid tees, directional couplers, PIN switches, and other integral parts of a radar system. Nevertheless, all of them have been developed, are produced by many firms, and are suitable for different millimeter-wave radar applications, a part of which will be considered in the next three sections.

10.5 Intelligent Transportation System Applications

10.5.1 Role of Radar Sensors in ITS Structure

The ITS programs (Intelligent Transportation Systems in the United States and Intelligent Transport Systems in European Union countries) were started in the beginning of the 1990s. The U.S. Department of Transportation's ITS program [71] is based on the fundamental principle of *intelligent vehicles* and *intelligent infrastructure* and the creation of an intelligent transportation system through integration within and between these two components (Figure 10.5). This principle is shared in other parts of the world. In the European Union, ERTICO (Intelligent Transport Systems Europe) [72] is a public/private partnership working to facilitate the safe, secure, clean, efficient, and comfortable mobility of people and goods in Europe through the widespread deployment of ITS. Other countries all over the world, particularly Canada, China, India, South Africa, Brazil, East European countries, and Russia are also interested and participate in ITS research, development, and deployment.

The **intelligent infrastructure** segment consists of several major components. Among them are those using radar systems as sensors: arterial

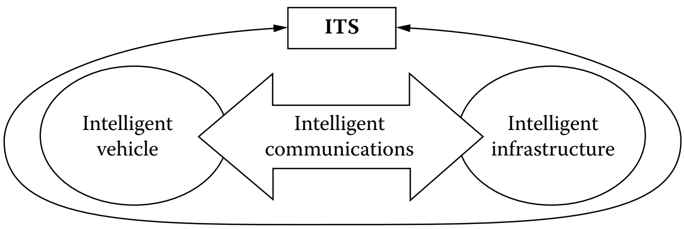

Figure 10.5 General structure of ITS.

management, including surveillance, traffic control, lane management, and enforcement, particularly speed and stop/yield enforcement based also on radar; freeway management with traffic surveillance systems using detectors and video equipment to support the most advanced freeway management applications; incident management, including surveillance and detection; emergency management with early warning systems; and **road weather management** based on surveillance, monitoring, and prediction.

Even more radar-based components are associated with the **intelligent vehicles** segment, which consists of collision avoidance systems, collision notification systems, and driver assistance systems. Let us consider them in more detail.

Collision avoidance systems can implement at least seven functions with the help of radar:

1. Intersection collision warning systems, designed to detect and warn drivers of approaching traffic at high-speed intersections.
2. Obstacle detection systems, which use vehicle-mounted sensors to detect obstructions, such as other vehicles, road debris, or animals, in a vehicle's path and alert the driver.
3. Lane change warning systems, deployed to alert bus and truck drivers of vehicles, or obstructions, in adjacent lanes when the driver prepares to change lanes.
4. Lane departure warning systems, which warn drivers that their vehicle is drifting out of the lane.
5. Road departure warning systems, designed to detect and alert drivers to potentially unsafe lane-keeping practices and to keep drowsy drivers from running off the road.
6. Forward collision warning systems, which use radar detection to avert vehicle collisions. These systems typically use in-vehicle displays or audible alerts to warn drivers of unsafe following distances. If a driver does not properly apply the brakes in a critical situation, some systems automatically assume control and apply the brakes in an attempt to avoid a collision.
7. Rear-impact warning systems, which use radar detection to prevent accidents. A warning sign is activated on the rear of the vehicle to warn tailgating drivers of impending danger.

Collision notification systems supply public/private call centers with crash location information; they use in-vehicle crash sensors, satellite (GPS, GLONASS, GALILEO) technology, and wireless communication systems.

Driver assistance systems (DAS) include navigation/route guidance and driver communication systems, which use GNSS (global navigation satellite system) and wireless communication technologies, drowsy driver warning alert, precision docking, roll stability control, and other systems that do not directly use radar information. However, some important components are actually based on radar sensorics. Among them:

1. Object detection systems that warn the driver of an object (front, side, or back) that is in the path or adjacent to the path of the vehicle.
2. Cruise control and adaptive cruise control (ACC), which is intelligent cruise control, speed control, and distance control to adjust speed in order to maintain a proper distance between vehicles in the same lane.
3. Vision enhancement, which improves visibility for driving conditions involving reduced sight distance due to night driving, inadequate lighting, fog, drifting snow, or other inclement weather conditions [73].
4. Lane-keeping assistance systems, which are related to ACC and radar sensors [74].

Thus radar technology and sensorics play an important role in the development and deployment of ITS and automotive advanced electronics. Because of the requirements to provide high accuracy, nice resolution, and small equipment size, the overwhelming majority of automotive radar sensors are designed at the millimeter-wave band. Millimeter-wave radar sensors today are the heart of ITS. Sensing moving targets and complex obstacles using active millimeter-wave radars is the most important component in automotive collision avoidance and intelligent cruise control systems.

An overview of the application of automotive radars was provided by Mende and Rohling [75]. They noted that in the last few years numerous new DAS applications have been under evaluation or development. First automotive radar sensors were introduced in passenger cars as a comfort feature. Now they are designed also or even first of all to improve safety. New functions of millimeter-wave radar appear very quickly, and no list can be complete because different manufacturers sometimes use different names as well as a slightly different understanding for desired functions of the equipment. Each manufacturer has its own predicted sequence for the introduction of those functions. It depends on what the customer research and marketing studies have identified so far as functions a customer is willing to pay for.

In accordance with the findings of Mende and Rohling [75], both current and promising applications of automotive radar fall into four categories, as follows:

1. Applications related to sensor and display to improve comfort:

   - Parking aid: Invisibly mounted distributed sensors behind the bumpers.

- Blind spot surveillance: The zones beside a vehicle are covered by radar sensors; a warning is displayed when the driver is about to change lanes when the (radar) field of view (FOV) is occupied.

2. Vehicle control applications to improve both **comfort and control:**

- ACC: Longitudinal vehicle control at a constant speed with additional distance control loop.
- ACC plus: Improves the handling of cut-in situations with a wider FOV at medium range.
- ACC plus stop and go: Improves/allows the vehicle control function in an urban environment, with complete coverage of the full vehicle width.

3. Restraint systems applications to improve safety:

- Closing velocity sensing: The main technical challenge in this application is to decide whether a crash will happen and to measure the impact position and speed before it happens to adaptively adjust thresholds/performance of restraint systems (which are not fired by the radar system).
- Precrash firing for nonreversible restraints: See above. Nonreversible restraint systems (like airbags) are directly fired by the sensor system. This can be done even before the crash happens, with crash position and severity selective. This function is of most importance for side crashes, to gain a few life-saving milliseconds to fire before the crash happens.

4. Collision-related applications to improve both safety and control:

- Collision mitigation: See restraint systems–related functions. The sensor system detects unavoidable collisions and applies full brake power (by overruling the driver).
- Collision avoidance: In future function, the vehicle would automatically take maneuvers to avoid a collision and calculate an alternative path, overruling the driver's steering commands.

Key problems with each function implementation have also been discussed [75]. The typical key questions are cost, number of sensors, frequency approval problems, mounting position, sensor fusion, low false alarm rate, liability issues, and so forth. Regarding the sequence of new functions introduction, the authors [75] mentioned that official organizations are already evaluating the feasibility of certain functions and a forced introduction is under discussion.

10.5.2 Frequency Allocation

Intelligent infrastructure's surveillance function can be implemented with radar sensors. Such radars designed for roadside traffic data collection and monitoring are limited by FCC regulations to operating frequency bands near 10.5, 24.0, and 34.0 GHz. Advanced imaging techniques for traffic surveillance and hazard detection may use also 94-GHz mid-millimeter-wave radar and 35-GHz long-millimeter-wave radar [74].

With regard to automotive radars, the feasibility of millimeter-wave radar technology has already been demonstrated in the neighboring 76–77 GHz band for long-range radar (LRR) ACC systems [76]. Typically, short-range radar (SRR) requires high-range resolution. As was shown in Section 10.3, a wideband signal provides high resolution. That is why UWB waveforms are frequently used in these applications. If cost-effective 24-GHz band operation is desired, legal restrictions varying from country to country have to be taken into account. On a worldwide basis, only a few parts of bandwidth are free to use. In the United States, the FCC has allowed the use of UWB radar sensors since 2002 [77]. In Europe, the European Commission approved the decision on allocation of the 24-GHz frequency band (from 21.625 to 26.625 GHz) for automotive SRR temporarily, until 30 June 2013. Included is the task to work toward an early introduction of equipment operating in the 79-GHz band by means of a research and development program. From mid-2013, new cars have to be equipped with SRR sensors operating in the 79-GHz frequency range. This frequency band was designated for the use of automotive SRR starting 19 March 2004 [78], and the following regulations are fixed:

- The 79-GHz frequency range (77–81 GHz) is designated for SRR equipment on a noninterference and nonprotected basis, with a maximum mean power density of −3 dBm/MHz EIRP (effective isotropic radiated power) associated with a peak limit of 55 dBm EIRP.
- The maximum mean power density outside a vehicle resulting from the operation of one SRR equipment shall not exceed −9 dBm/MHz EIRP.
- The 79-GHz frequency range (77–81 GHz) should be made available as soon as possible and not later than January 2005.

The European approach of a temporary use of 24 GHz with a transition to 79 GHz is called a packaged solution, to make an early contribution to the enhancement of road safety possible and to allow time for the development of the 79-GHz technology, which is not yet mature for SRR sensors. The current state and prospect of frequency band usage in automotive radar can be generalized, as presented in Table 10.2.

Table 10.2 Automotive Radar Frequency Bands

Frequency Band(s)	*Country, Organization*	*Functions*	*Note*
76–77 GHz	European Telecommunications Standards Institute (ETSI)	Automotive LRR, also road surveillance radar	From 1998 and 1992
21.625–26.625 GHz	European Commission	Automotive SRR	Until 2013
46.7–46.9 GHz, 76–77 GHz	United States, FCC	Vehicle-mounted field disturbance sensors, including vehicle radar systems	
76–77 GHz	European Conference of Postal and Telecommunications Administrations	Vehicular radar systems	
60–61 GHz, 76–77 GHz	International Telecommunication Union	Transport information and control systems	From 2000
60–61 GHz, 76–77 GHz	Japan, Ministry of Post and Telecommunication (MPT)	Transport information and control systems	
60–61 GHz, 76–77 GHz	Asia-Pacific Telecommunications Standardization Program (ASTAP)	Low-power short-range vehicle radar equipment	
76–77 GHz	Australian Communications Authority	ITS automotive radar component	From 2001
77–81 GHz	European Commission	Automotive SRR	From 2004

Hence, currently operating bands are 76-GHz NB, 77–81-GHz UWB, 47-GHz NB (U.S.), 24-GHz NB (200-MHz bandwidth), and 24-GHz UWB (3-GHz bandwidth). Additionally, baseband impulse UWB radars with bandwidth $B < 10$ GHz can be used, and 152 GHz is suggested for future research [79].

10.5.3 Traffic Surveillance Radar

Road transport and traffic telematics (RTTT) radars are used as sensors in surveillance systems. Traffic surveillance technologies play an essential role in incident detection, traffic management, and travel time collection. There are two basic types of traffic surveillance systems: road based and vehicle based [80]. Road-based detection systems can be intrusive or nonintrusive. Traditional intrusive sensors include inductive loops, magnetometers, and other devices that are installed directly on the pavement surface or in the road surface.

Comparatively new, nonintrusive aboveground sensors can be mounted above the lane of traffic they are monitoring or on the side of a roadway where they can view multiple lanes of traffic at angles perpendicular to or at an oblique angle to the flow direction. The technologies currently used in aboveground sensors are video image processing, millimeter-wave radar, laser radar, passive infrared, ultrasonic, passive acoustic array, and combinations of sensor technologies. Like the subsurface sensors, the aboveground sensors measure vehicle count, presence, and passage. However, they can additionally provide vehicle speed, vehicle classification, and multiple-lane, multiple-detection zone coverage [81].

Roadside-mounted millimeter-wave radar transmits energy toward an area of the roadway from an overhead antenna. The beamwidth of millimeter-wave radar can be rather narrow (Section 10.3.5); that is, an area in which the millimeter-wave radar energy is transmitted in short distance can be designed in accordance with the lane width. When a vehicle passes through the antenna beam, a portion of the transmitted energy is reflected back toward the antenna. The energy then enters a receiver where the detection is made, and vehicle data, such as volume, speed, occupancy, and length, are calculated by signal processing. Two types of radar sensors are used in roadside applications: continuous-wave (CW) nonmodulated Doppler radar and CW frequency modulated (FMCW) radar. The traffic data they receive is dependent on the shape of the transmitted waveform. A generalized diagram of a CW radar sensor is shown in Figure 10.6.

The CW nonmodulated sensor transmits a signal that is constant in frequency with respect to time. According to the Doppler principle, the motion of a vehicle in the detection zone causes a Doppler shift, which is extracted from the beat frequency at the output of the mixer and can be used to detect moving vehicles and determine their speed. Such CW Doppler radar is

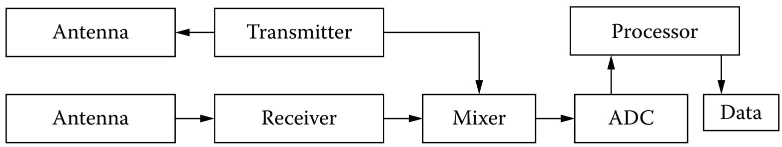

Figure 10.6 A CW radar generalized diagram.

also used to implement the speed enforcement function. CW systems measure the instantaneous range rate and maintain continuous contact with the target. That is why they can be used in tracking by speed systems. However, CW Doppler sensors that do not incorporate an auxiliary range measuring capability cannot detect motionless vehicles. Range measuring capability can be implemented in FMCW radar. The principle of FMCW radar has been described in many books [30]. The simplest way to modulate the wave is to linearly increase the frequency during one half period of modulation, T_M, and then decrease it back during the second half period. It is illustrated in Figure 10.7 (upper graph), where the solid line is the frequency of the transmitted waveform and the dashed line is the frequency of the received signal reflected from an immovable object. The lower graph in Figure 10.7 shows beat frequency, which depends on delay time and, thus, on the range of the object. When a moving car is the target, the beat frequency depends also on car speed, as illustrated in Figure 10.8, where beat frequency during the positive (up) and negative (down) portions of the slope, are denoted, respectively, as f_u (Doppler shift is added) and f_d (Doppler shift is subtracted) [35].

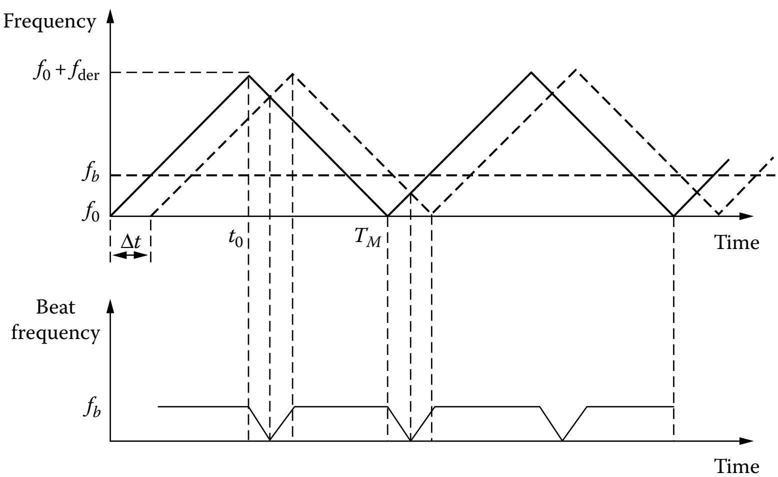

Figure 10.7 Frequency–time dependence and beat signal for a motionless target.

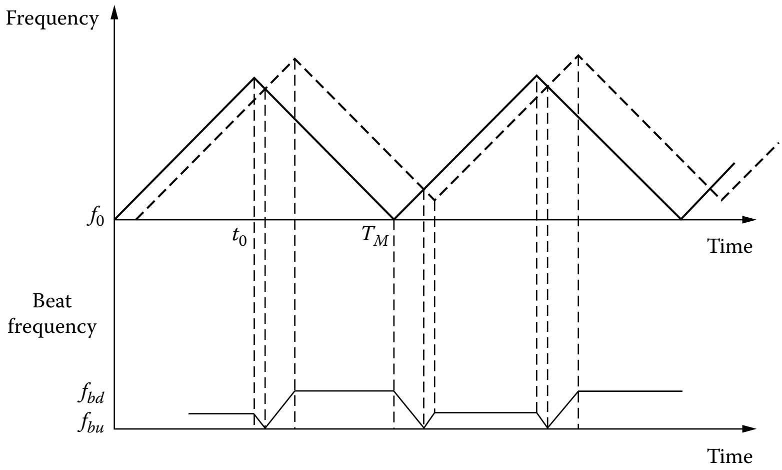

Figure 10.8 Frequency–time dependence and beat signal for a moving target.

Both range information and velocity information may be extracted from such a beat signal by signal processing in each range. As was shown in Sections 10.3.5 and 10.3.6, radar range resolution is defined by the spectrum width of the radiated waveform. In the case of FMCW radar, the spectrum width, B, directly depends on the frequency deviation, f_{dev}, and the potential range resolution is approximately $\Delta R = c/2f_{dev}$.

One can easily calculate that, for NB 24-GHz radar with $B = 200$ MHz, the potential range resolution, ΔR, is about 75 cm. It can be much higher in the case of, say, 76-GHz millimeter-wave radar. A range bin size is normally close to ΔR and less than the antenna beam footprint. Thus the forward-looking surveillance FMCW radar can measure vehicle speed in a single lane using a range-binning technique that divides the FOV in the direction of vehicle travel into range bins, as shown in Figure 10.9.

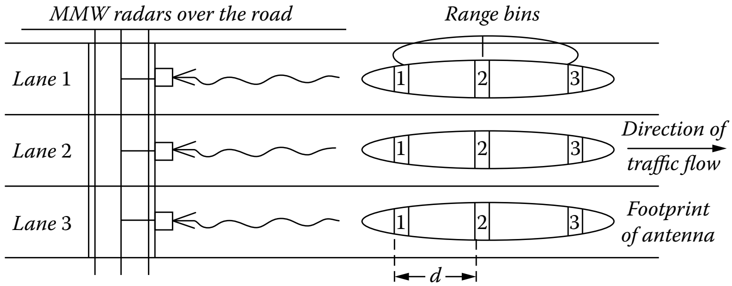

Figure 10.9 Range-binned footprints of radar sensors in traffic lanes [81].

A range bin technique allows the reflected signal to be partitioned and identified from smaller regions on the roadway. Vehicle speed, V, is calculated as $V = d/\Delta t$, where d is the known distance between leading edges of two range bins and Δt is the difference between points of time when a vehicle passes through these range bins.

Another promising development of millimeter-wave radar for intelligent infrastructure has been reported [82] where a radar sensor for an advanced cruise-assist highway system is proposed. This radar uses WB pseudo-noise–modulated signal in millimeter-wave radar. The radar prototype is built at the central frequency of 76.5 GHz. As was shown in Section 10.3, WB and noise signal provide better potential performances in comparison with traditional NB, in particular, an FMCW signal.

Along with road-based surveillance, recent advances in vehicle sensors and detection algorithms open the opportunity to implement or enhance vehicle-based surveillance systems. Vehicle-based traffic surveillance systems [80] involve probe vehicles equipped with tracking devices, such as transponders, that allow the vehicles to be tracked by a central computer facility. Such systems are rather promising. They can be used to detect incidents, provide rich data on travel times, and estimate flows and origin–destination patterns. These vehicle-based technologies are built on secondary radar principles close to those used in air traffic control radar beacon systems.

Another purpose of vehicle transponders is for automatic vehicle identification (AVI) or radio frequency identification (RFID). Such transponders [83] are essential to any electronic toll collection function; AVI tags have become increasingly sophisticated and intelligent.

10.5.4 Automotive Radar

A simple but suitable parameter to technically distinguish radars is the maximum range. Along with traditional distinguishing SRR and LRR, the medium-range automotive radar (MRR) has been introduced [75,84]. Therefore, we distinguish the following radar categories: LRR, with a maximum range of 150 m; MRR, with a maximum range of 40 m; and SRR, with a maximum range of 15 m. Their applications for the automotive functions listed in Section 10.5.1 are given in Table 10.3, where FSK means frequency shift keying. The content of this table is completely taken from Mende and Rohling [75], however, it is supplemented in the last and the next-to-last columns by additional suitable frequency bands and radar principles. It should be mentioned that possible functions are not limited by those listed here. For example, pedestrian detection, overtake support, rear collision warning, lane keeping, and other functions are quite expedient and possible technically to be implemented.

Table 10.3 Automotive Applications of Millimeter-Wave Radar

	Requirements			*Suitable Sensors*	*Suitable Radar*	*Suitable Carrier*
Function	*Range*	*Velocity*	*FOV*	*Category*	*Principle*	*Frequency*
1. Parking aid	0.2–5 m,	0 to ±30 km/h	Full vehicle width	2–4xSRR per bumper	UWB, pulsed	24 GHz (21.625–26.625), 77–81 GHz
2. Blind spot surveillance	0.5–10 m/ 0.5–40m	Reasonable velocity interval	Two lanes beside vehicle	1–2xSRR or 1–2xMRR per side	FMCW/FSK/pulsed, UWB	24 GHz, 77–81 GHz
3. ACC	1–150 m	Reasonable velocity interval	Three lanes in front of vehicle in 65 m	1xLRR	FMCW/FSK/pulsed	76–77 GHz
4. ACC plus	1–150 m/ 0.5–40 m	Reasonable velocity interval	Three lanes in front of vehicle in 20 m	1xLRR/1xMRR	FMCW/FSK/pulsed	76–77 GHz, 24 GHz, 77–81 GHz
5. ACC plus stop & go	0.5–150 m/0.5–40 m	Reasonable velocity interval	Three lanes in front of vehicle in 10 m Full vehicle width in 0.5 m	1xLRR/1xMRR	FMCW/FSK/pulsed	76–77 GHz, 24 GHz, 77–81 GHz
6. Closing velocity sensing	0.5–10 m/0.5–30m	Any velocity	About 45°	1xSRR/1xMRR	FMCW/FSK, UWB	24 GHz, 77–81 GHz
7. Precrash reversible restraints	0.5–10 m/ 0.5–30 m	Any velocity	Full vehicle width in 0.5 m	2xSRR/2xMRR	FMCW/FSK, UWB	24 GHz, 77–81 GHz
8. Precrash nonreversible restraints	0.5–10 m/ 0.5–30 m	Any velocity	Full vehicle width in 0.5 m	2xSRR/2xMRR	FMCW/FSK, UWB	24 GHz, 77–81 GHz
9. Collision mitigation	0.5–150 m/ 0.5–40 m	Any velocity	Three lanes in front of vehicle in 10 m Full vehicle width in 0.5 m	1xLRR/2xMRR	FMCW/FSK	76–77 GHz, 24 GHz, 77–81 GHz
10. Collision avoidance	0.5–150 m/ 0.5–40 m	Any velocity	Three lanes in front of vehicle in 10 m Full vehicle width in 0.5 m	1xLRR/2xMRR	FMCW/FSK	77 GHz, 24 GHz, 77–81 GHz

[a]An ultrasonic may be considered as an alternative to the first function. Functions 2 to 5 can also be implemented by laser radar; however, MMW radar is preferable because it is practically an all-weather automotive sensor. Functions 6 to 10 do not have any suitable alternatives.

[b]Adapted from Mende and Rohling [75].

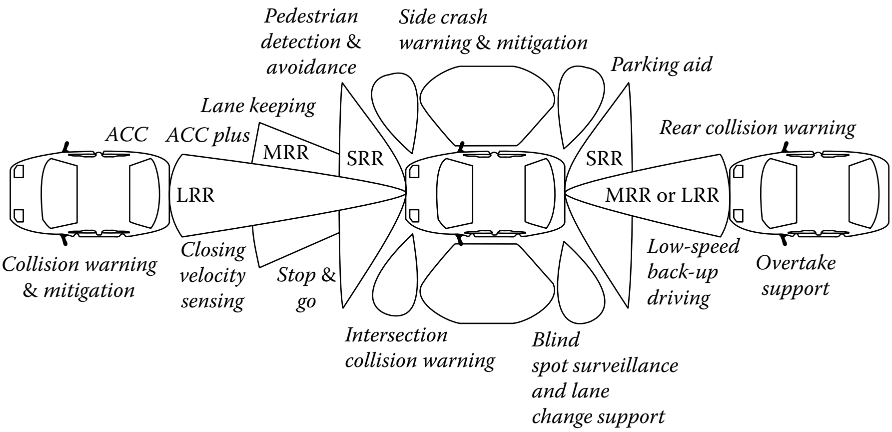

Figure 10.10 Layout of antenna patterns along the perimeter of the car to implement different functions.

Certainly, each radar sensor may be used as a multifunctional device, which can reasonably reduce the cost. An example of layout of schematic antenna patterns to realize a number of automotive radar functions is given in Figure 10.10.

10.5.5 Long-Range Radar

Conventionally, LRR delivers a target list with distance, angular position, relative speed, and reflectivity of significant objects within typical cycle times of 50 ms.

The size of a target can be smaller or bigger than the spatial resolution of the radar. Naturally, high-resolution radar is preferable because vehicles appear as laterally and longitudinally extended objects, which opens an additional possibility of target recognition. Normally, LRR maximum range is 150 m (ACC application) and MRR can be 1–1.5 m. LRR is typically implemented at 76.5 GHz center frequency (1 GHz bandwidth available), which generally corresponds to ETSI and FCC specifications. LRRs of 24 GHz have also been developed [85] and are in use. LRR has a limited FOV. Coverage in azimuth is typically 12° (up to 20°) and 6° in elevation. Range resolution is 1–5 m in different models, with a speed interval of 250–500 km/h. In some cases the maximum range can be increased to 200 m, but the higher the range, the bigger the problem of target-lane association. LRR can be applied as a single unit.

LRR can be built on different radar principles, such as FMCW radar, CW radar with FSK, or pulse Doppler radar. Noise modulation can also be considered.

An FSK CW LLR is described by Takezaki et al. [86]. This radar unit employs an MMIC for the high-frequency module that transmits and receives 76-GHz band radio waves. The MMIC chipset consists of four chips: a voltage-controlled oscillator, a power amplifier, and two receivers. These chips are integrated in a monolithic RF module combined with an integrated flat antenna. The RF module and signal processing board are integrated in the same housing to achieve a small, lightweight radar unit. This radar unit employs two-frequency CW radar modulation, in which an FSK signal is transmitted and the relative speed of objects is measured from the Doppler frequency and the distance to the objects is measured from the phase of the reflected signals. For azimuth angle measurement, the monopulse technique (Section 10.3.9) is used, in which the signals reflected from the vehicle are received by two antennas and the direction of the vehicle is determined from the amplitude ratio of those two received signals.

A pulse Doppler LRR is discussed in Schneider and Wenger [87]. This radar is designed to provide imaging of vehicle underbodies and detection of hidden objects via reflections from the road surface. That requires higher sensitivity with respect to a conventional ACC radar sensor. An increased target dynamic of 50 dB was assumed. Together with the dynamic due to propagation attenuation in the 5–150 m range of 60 dB, an overall requirement for the system dynamic results, which is difficult to be handled by a CW system. Hence pulsed waveform was chosen for this imaging radar system design because of its robustness against saturation.

At a center frequency of 76.5 GHz, the FOV in azimuth is $\pm 10^\circ$, the azimuth beam width is 1.0°, the elevation beam width is 5.0°, the real range resolution is 1 m, and the velocity resolution is 1 km/h.

The central component of the system is an embedded PC performing system control and radar image composition. Its main periphery is formed by timing and control electronics, an IF processor module for converting the IF signal from the receiver module into baseband I/Q (inphase and quadrature) signals and digitization, a digital signal processor performing the Doppler FFTs (Fast Fourier Transforms) and other preprocessing, and a number of common devices.

A ferrite circulator for the transmit and receive duplex is mounted together with a receive low-noise amplifier directly at the antenna and connects to the transmit and receive modules. The transmit signal is generated in a phase-locked dielectric resonator oscillator (DRO) at 19.125 GHz, pulse gated in a two-stage PIN modulator, and multiplied to 76.5 GHz in an active quadrupler with an output power of about 16 dBm. The minimum pulse length is 3.5 ns. The key component in the transmit module is a biased, balanced fundamental mixer. It converts to an IF signal of 3 GHz, which is led to the base system on a high power level in order to minimize interference in the long transmission line. The system is connected to the radar control PC via Ethernet LAN.

A 76–77 GHz pulse Doppler radar module for LRR with a three-beam antenna is described by Gresham et al. [88].

An FMCW LRR is the most typical in automotive applications. The FMCW principle was considered in Section 10.5.3. As a way to keep the hardware and architecture relatively simple, the peak power down, and at the same time achieve robust performance, an FMCW approach is frequently used as opposed to a more sophisticated pulse Doppler implementation [54]. A radar of this type has a relatively low peak power output and can meet the range and velocity resolution requirements if a sufficiently large frequency deviation is used. Such radar sensors are often developed as multibeam antenna systems with sequential lobing technique [75] or with monopulse technique [85].

10.5.6 Medium-Range Radar

This category of radar introduced by Mende and Rohling [75] can fill the gap between SRR and LRR regarding maximum range. They cover a range from 0.5 m to 70 m and a speed interval of –500 km/h (closing) to +250 km/h (opening) [84]. The minimum range is usually less than 0.6–1 m. They can be implemented as a radar network of distributed MRRs and a central processing unit. But single-sensor operation is also possible and is preferred in many cases for cost reasons. Measuring range, angle, and relative radial velocity in multitarget scenarios at one time, they are capable of handling highly dynamic situations. For direct angular measurement, either sequential lobing or monopulse techniques may be applied.

As an example, the universal medium-range radar (UMRR) [84] can be considered. The UMRR frequency band is 24 GHz. The UMRR has multimode capability and may be switched between UWB pulse operational mode and FMCW NB mode within one measurement cycle. In NB FMCW mode, UMRR performances correspond to typical MRR requirements: min. range, 0.75 m; max. range, 60 m; velocity interval, -69.4 ± 69.4 m/s. UMRR uses a combination of FSK and LFM (linear frequency modulation) waveform design principles [89]. It also has a flexible bandwidth by operating in modes of NB operation and a 1–500 MHz maximum modulation bandwidth. Such a universal and flexible device can be used in different configurations, improving the functionality of automotive radar.

10.5.7 Short-Range Radar

The requirements of SRR are short range but wide FOV and high accuracy. Typically, such radar should detect targets in the range 0.2–30 m, with an azimuth FOV of about 100°, and a maximum velocity of more than 240 kmh. SRR sensors were first developed in the 24-GHz band. More recent development in Europe has been fulfilled in the 79-GHz band. In many cases, SSRs are designed as UWB pulse radars ($B = 3$ GHz). In this case, target velocity is estimated from the range rate. However, FMCW technique is also applicable.

It is difficult and expensive to design quick scanning in the FOV to measure azimuth position of targets. Another way could be in principle using very narrow antenna beams per sensor and multiple sensors around the car. However, the cost of such a system grows by the number of sensors and by the number of antenna beams per sensor.

That is why the multistatic principle for automotive radar networks was developed [90]. That was a brilliant idea to provide accurate angle measurements with a number of cheap radar sensors, which have no angle resolution at all but can measure target range and target velocity with high accuracy. The simplest technique consists in using a linear array of several sensors, spaced along the bumper, each having up to 60° beamwidth. Each sensor measures the range to the target with high accuracy, and the ranges are different for each sensor in the general case. From these measured results it is possible to estimate an angular position of the target. The real situation may be complicated because of multiple and extended targets in the FOV. Position reconstruction of a large target based on triangulation is not accurate enough because the different sensors detect different parts of the same target. Moreover, the range-velocity estimation should be provided. The multilateration procedure, which is used to solve this problem, has been described in detail [91,92]. It is a real technical challenge to handle the large number of detections in the data association and tracking as well as in the range, velocity, and angle parameter estimation.

Let us consider the signal processing procedure of four FMCW radar sensors as described by Rohling and Fölster [91]. For data acquisition, a waveform is used that consists of four individual chirp signals (Figure 10.11). The waveform parameters are center frequency, 77 GHz; number of chirps, 4; single chirp duration, 2 ms; first sweep bandwidth, 1 GHz; second sweep bandwidth, 500 MHz.

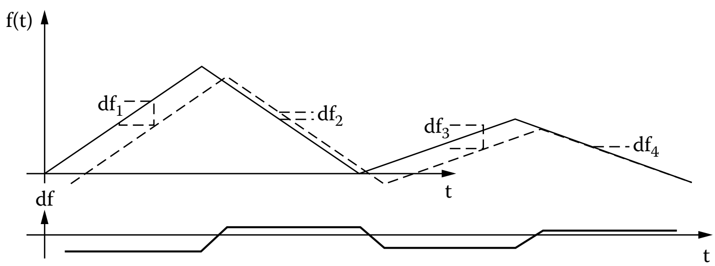

Figure 10.11 Four-chirp FMCW waveform and the receive signal for a single-target situation.

Four individual chirps provide a sufficient redundancy in multitarget or extended target situations to suppress ghost targets in the range–velocity processing. For each individual chirp signal, the beat frequencies, $df_1, \ldots df_{41}$, shown in Figure 10.11, will be estimated at each individual radar sensor by applying an FFT, respectively. A single-target detection with range r_s and velocity v_S leads to a deterministic beat frequency for each chirp signal of the waveform. This beat frequency is related to target range and velocity by the linear equation $f_{CS} = a_C r_S + b_C v_S$, where parameters a_C and b_C depend on chirp duration, bandwidth, and carrier frequency. Based on the four beat frequencies measured by a single sensor, the point target range and velocity can be derived simultaneously by an intersection process. In this case and in a single-point target situation, the four measured frequencies are transformed into target range and velocity, unambiguously. But in multiple or even extended target situations, this range velocity calculation could lead to some ghost targets.

Each sensor of the radar network has an individual position behind the front bumper. Therefore, each sensor will calculate individual values for target range and velocity based on the four measured beat frequencies inside the FMCW waveform. Thus, a set of linear equations can be derived that describes the relationship between 16 measured beat frequencies and sensor-specific target range and velocity parameter (two physical quantities, r and v, multiplied by four chirps and four sensors).

In multi-target situations the association of the detected beat frequencies at the FFT output to different targets is not trivial. Therefore, a data association process has to be performed using the redundancy given by the four chirp signals inside a single waveform. The radar network signal processing described by Rohling and Fölster [91] calculates the azimuth angle (or target position in Cartesian coordinates) of each target in multiple or even extended target situations based on the precise range measurement of each radar sensor. Furthermore, the tracking procedure is part of the network processing. In different configurations of the system, two to six SRRs may be used in such a network. The features of sensor design and its application to automotive problems are considered in Rickett and Manor [93].

10.5.8 Adaptive Cruise Control System

Unlike conventional cruise control, ACC can automatically adjust speed to maintain a proper distance between vehicles in the same lane. This is achieved through a forward-looking millimeter-wave LRR sensor, digital signal processor, and longitudinal controller. Jaguar and Mercedes first introduced 76-GHz automotive radar to provide ACC in 1999, operating throttle and brakes to maintain headway. Jaguar used FMCW LRR with a mechanical scanned antenna, and Mercedes applied pulse Doppler LRR with a quasi-optic antenna [79].

The latest innovations in automotive radar systems are based on the positive experiences with the LRR-based ACC function.

10.5.9 Road Departure Warning System

In 2001 the project of the road departure warning system was tested in field operational research. The project defines and evaluates a system that warns drivers when they are about to drift off the road and crash into an obstacle, as well as when they are traveling too fast for an upcoming curve. Technologies include a vision- and radar-based lateral drift warning system and a map-based curve speed warning system [83]. The system is based on the information about the current situation obtained by two forward-looking LRR and two side-looking SRRs. The technology also includes a camera-based lane detection and map-based curve speed warning system using GPS data. More details see UMTRI [94]. Forward- and side-looking radar systems detect the presence of any obstacles on the shoulder (such as parked cars) or the roadside (such as poles or guardrails).

Another approach [95] is based on lane position sensing using a special selective stripe detected by radar. The radar sensor measures lateral position by sensing backscattered energy from a frequency-selective surface constructed as lane striping and mounted in the center of the lane.

10.5.10 Blind Spot Monitoring and Lane Change Control System

A lane change assistant should help to increase safety when drivers change lanes. Such a system needs two SRRs looking at the blind spots; that is, laterad and a little back to the adjacent lanes. An example of a lane change assistance system is described by Valco Raytheon [96]. It consists of two 24-GHz radar sensors joined to a control box and two LED warning indicators mounted in the side rear-view mirrors. The sensors continuously monitor the presence, direction, and velocity of vehicles in the roadway lanes adjacent to the protected vehicle. The radar image sensors create a digital picture of the traveling environment. The digital information is processed by a central control module. When vehicles, motorcyclists, or bicyclists move into a blind spot of the protected automobile, the central control box alerts the driver by lighting the warning indicators in the side rear-view mirrors. The system range extends to 40 m, with a 150° broad FOV. The radar is a multibeam system operating in a narrow bandwidth. Using several beams to recognize objects in the blind spot allows for high accuracy in determining the position and distance of the object as well as its relative speed.

The second example [83] is the Visteon system, which is a close-in blind spot monitor, covering a detection range of 6 m.

Another example of a blind spot detection sensor is a UMRR [89] optimized for short-range detection, which implements detection algorithms, tracking, object-to-lane mapping, and a warning algorithm (illuminating warning LEDs). This blind spot monitoring system's range is 0.3–8 m. A sensor operates in a speed interval from 7 to 250 km/h. For the sensor fusion case, it is reasonable to combine the two blind spot sensors with a third medium-range (70 m) or long-range (120 m) sensor. Additional applications of a blind spot detector may be (1) warn to open door when object approaches, and (2) side/rear precrash or presafe applications.

10.5.11 Obstacle Detection

LRR, MRR, and SRR can be used as sensors for obstacle detection. Object classification can also be performed on the basis of radar data. Probabilities of true and erroneous classification using a millimeter-wave radar system are presented in Kruse et al. [97].

10.5.12 Radar-Based Communications

Air traffic control surveillance systems widely use secondary radar technology to get more precise and comprehensive information and data exchange. A similar technology adapted for motor transport needs may be established in the framework of ITS. It can be considered as radar-based communications. This kind of data exchange can be used for both the vehicle–vehicle and vehicle–infrastructure communications arena.

Two aspects of radar-based communications in millimeter waves related to intelligent infrastructure were considered in Section 10.5.3. Now we add some other possibilities that may be important for an intelligent vehicle system.

One concept is communication using a read–write RF tag. This idea is similar to the radio frequency ID that has become more and more important nowadays. An RF tag can be activated when illuminated by standard vehicle 77-GHz radar. The return signal carries additional coded information. In this case the automotive millimeter-wave radar receives not only reflections but digital data. After signal detection, useful information is extracted and used to improve safety. For example, an RF tag placed on a bridge footing in a complex highway environment can provide key data as to the size of this potential obstacle, thus enabling the vehicle system to better interpret the situation. Every vehicle may also be provided with an individual RF tag, creating a very robust and cost-effective secondary radar system. For example, stationary and moving targets can be distinctly identified by the data encrypted into the tag, which actually is a kind of transponder.

Such an interrogator–transponder system can be applied to establish car-to-car communications based on the secondary radar principle.

Another possibility relates to direct-use millimeter-wave radar for communications. A car-to-car communications operation together with millimeter-wave radar systems can combine the data from different vehicles, allowing observation of the complete car environment. An improvement can be achieved if one car has access to the sensor information of the preceding and following cars. The potential use of the millimeter-wave radar spectrum for communication needs is analyzed by Winkler et al. [98]. The developed system consists of a pulse radar and a communication transceiver with 4 Mb/s. The main lobe of the pulse radar waveform spectrum occupies a bandwidth of 250 MHz. The frequency band of the transceiver, which is small compared to the pulse spectrum, is placed at the first side-lobe of the pulse spectrum. The pulse radar is designed to allow simultaneous sensing over a range of nearly 40 m, and the communication link has a maximum range of 200 m. The feasibility of the concept and its superior dynamic range has been shown [98] in case PN-code is used for ranging and data transmission. A configurable RISC processor, consisting of FPGA (field-programmable gate array) logic resources, is connected to the radar and the transceiver. It sets operation parameters and addresses a LAN chip for data exchange between the system and a PC over Ethernet.

More details on wireless LAN application to car-to-car communications are provided by Zlocki and Zambou [99].

10.5.13 Radar-Based Automatic Road Transportation System

The availability of high-resolution millimeter-wave radar sensors, secondary radar systems, and radar-based communications along with modern technologies creates more possibilities to improve ITS. Kramer [100] presents an idea of a fully automatic road transportation system and proposes the system's architecture. The concept of this hypothetical system includes a network of short-range, high-resolution millimeter-wave radar sensors that monitors traffic space; a network of sensors, some in the vehicles, that registers road conditions and traction parameters; and a computer network that receives information from the two sensor systems and the road users and generates guidance commands.

The system could use special navigation signals in addition to the radar signals, similarly to GPS. The in-vehicle precision navigation system may transmit the vehicle's position, velocities, turn rates, and so on to the central guidance system. This would substantially reduce the tasks for the fixed installation radars, which would then only detect and observe noncooperative road users and random obstacles. Noncooperative road users and pedestrians might also carry responders that communicate with the central guidance system. Because of the low signal powers involved, the responders could even be integrated in wristwatches.

During the conversion to an exclusively automatic road transportation system, vehicles might have transceivers that communicate with the central guidance system. The reception of guidance information would allow for participation in optimum traffic management. The realization of the automatic transportation system should start with a small prototype to successively refine the definition of sensor requirements and the algorithms for the central guidance system.

10.5.14 Automatic Driving

Future vehicles will fuse data from the millimeter-wave radar sensors (up to 12 per vehicle) with vision, navigation, communications, and vehicle dynamics to provide safety and convenience. The dataware level of such a vehicle approaches to what is enough to dramatically unload the driver.

Automatic driving systems are actually under development; for example, AutoDrive [101]. AutoDrive is a system for automatic driving of cars and commercial vehicles on highways. It uses GPS positioning, radars, intervehicle signaling, and wireless Internet to aid driving, which is mainly those electronic facilities considered above. AutoDrive is a completely automated highway driving system. By 2030, all major interstates in the United States are expected to support AutoDrive lanes [101] with completely automated car and commercial vehicle driving. Any car updated for AutoDrive will be able to enter these lanes and enjoy speed limits of around 130 mph.

Such a system will use GPS to accurately locate the vehicle's position on the map and then steer the car according to the path specified by the map. Intervehicle signaling (IVS) will be used to keep track of neighboring vehicles, detecting speed changes and responding to lane change requests from other vehicles. The radar feed will be used to identify objects in the vicinity of the car. The main objective of the radar in AutoDrive will be to detect nonvehicle objects that might be present on the highway. The precision radar will detect objects that are more than 3 cm in height.

Map updates can be obtained over a wireless Internet connection. Most map updates are obtained at the time of trip start. The maps are extremely detailed and store information about the different lanes with an accuracy of ±1 cm.

Weather feed is used to adjust driving parameters according to the current weather conditions. Construction and road closure detection is implemented using IVS. An IVS transmitter is placed in a closed lane. Vehicles receive the IVS signal from the transmitter and decide to change lanes. Fully automated driving can be considered as an ultimate level of ITS development.

10.6 Remote Sensing Applications

10.6.1 Cloud Radar

10.6.1.1 Introductory Notes

Applications of millimeter-wave radar to study clouds and precipitation are known from the 1950s, but early in the development of millimeter-wave meteorological observations they were limited to backscatter power measurements mainly because of hardware problems. As early as 1966 weather radar MRL-1 (Oblako) was produced and then widely used for weather observations in the Soviet Union. It was two-channel incoherent radar with wavelength $\lambda = 32$ mm in one of the channels and $\lambda = 8$ mm in the second one. However, the weather forecasters underestimated the millimeter-wave channel at that time. It did not seem to be a highly effective instrument for practical needs due to little range in comparison with the 3-cm channel and lack of developed observation techniques and data interpretation. This situation changed completely during the last two decades. Millimeter-wave Doppler radars are considered now as an actual instrument for permanent monitoring of the atmosphere and investigation of clouds and precipitation.

As distinct from ITS applications, weather radars are comparatively long-range sensors. That is why a majority of millimeter-wave weather radars are designed to operate in the relatively transparent window regions, mainly about 34–36 and 93–95 GHz. Nevertheless, water vapor substantially attenuates millimeter waves in the troposphere, which is a disadvantage, of course, but can also be used to derive some useful information about clouds and precipitation. Scatterers include nonprecipitating cloud water and ice-phase precipitation, insects, and seeds.

Weather objects are volume distributed targets. High spatial resolution of millimeter-wave radar turns it into a rather fine instrument for cloud structure investigation.

Nowadays a number of scientific and industrial institutions all over the world perform research in the field of remote sensing of troposphere with millimeter-wave radars, design and produce new radars, and develop new techniques for cloud observation and algorithms for signal and data processing.

This is a separate, important, and very wide area of knowledge. Here we will just touch on some features of millimeter-wave radar applications in the field of meteorology.

10.6.1.2 Features, Methods, and Advantages

The phenomenon of electromagnetic wave scattering on hydrometeors forms the basis for weather observations and measurements with the help of millimeter-wave radar. As was considered in Section 10.2, in case size *r* of the hydrometeor is small comparatively to wavelength λ (Rayleigh case), an RCS (and reflected power) is proportional to r^6/λ^4. This is valid in the millimeter-wave band for cloud droplets but, in the case of larger raindrops, especially in the short-wave part of the millimeter-wave band (95 GHz), resonance phenomena can play an essential role. A high sensitivity of millimeter-wave weather radar results from this RCS proportionality to $1/\lambda^4$.

Dual-wavelength radar (microwaves plus millimeter waves) allows measuring attenuation of radar signal and improving estimation of rain rate or cloud water content. Inasmuch as in the millimeter waves band λ may be comparable with r, the scattering law appreciably differs from the Rayleigh case, and by knowing frequency-dependent wave attenuation (see Section 10.2) one can estimate raindrop size distribution from measured data at different wavelengths. An example of retrieving cloud and rain parameters from dual-wavelength measurements at the Ka-band and W-band is provided by Bezvesilniy and Vavriv [102].

Real hydrometeors in many cases are not spherical. For example, raindrops are normally oblate, and they are more oblate if they are larger; cloud droplets are mostly spherical; and ice particles are complicated in shape. The polarization properties of a radar signal at scattering on nonspherical hydrometeors depend on the shapes of the scatterers and the mutual orientation of scatterers and radar beam. That is why application of polarimetric measurements opens up possibilities to recognize hydrometeor shapes and hence their aggregative state.

Hydrometeor movement cases Doppler shift. This results in change of Doppler spectrum of the returns from a radar resolution volume. Measurements of spectrum parameters give possibility to study microstructure and dynamic processes in the atmosphere.

The physical basis for detecting different weather phenomena and measuring meteorological variables is a relationship of echo-signal parameters with the peculiarities of microstructure and the dynamics of scatterers (droplets, ice crystals, snowflakes, etc.) within a resolution volume or an aggregate of resolution volumes. In operational observations and research works, the following types of radars are used:

- Incoherent: conventional pulse radar
- Coherent: pulse-Doppler radar, FMCW radar, or CW with other modulation formats
- Polarimetric: application of polarization diversity on the basis of a conventional pulse radar
- Doppler-polarimetric: coherent radar with application of polarization diversity for measurements

Incoherent radar measures just the power parameters of reflected signals that are related with weather object reflectivity.

Coherent radar measures parameters of Doppler spectra. Theory fundamentals describing relations between detected signal and features of scatterer movement as well as the sounding techniques by ground-based weather radar were developed already in the 1960s. At that time it was important that Doppler spectrum width could be estimated by means of special signal processing with incoherent radar for the narrower Doppler frequency dynamic range.

The instruments for remote sensing of the atmosphere that were developed on the basis of incoherent radar and pulse Doppler radar are widely used in radar meteorology and operational weather observation for detection and measuring of winds, storms, turbulence, and related phenomena [103].

Polarimetric radars measure relative polarimetric parameters of reflected signal, such as differential reflectivity (a ratio of reflectivity values at the alternatively polarized radar signals; for example, at horizontally and vertically polarized electromagnetic waves), linear depolarization ratio (a ratio of a cross-polarized component of reflected signal by a copolarized one), correlation between reflections at orthogonal polarizations, and specific differential phase (a difference between propagation constants for horizontally and vertically polarized electromagnetic waves per unit of range).

Doppler-polarimetric radars simultaneously use spectral and polarimetric characteristics [104]. It can be not only a simple combination of Doppler and polarimetric parameters but also new integrated characteristics, such as a curve of the spectral differential reflectivity and its slope parameter, differential Doppler velocity, and others [105]. Fully polarimetric Doppler radars are able to enhance dramatically information possibilities of the remote sensing of the atmosphere.

Application of sophisticated Doppler-polarimetric techniques in high-resolution millimeter-wave radars is made possible by the great advances in digital signal processing technology and the significant increase in the role of software in modern radar system design, which has resulted in single-chip processors and special-purpose IC that can simultaneously execute algorithms to compute all necessary quantities in real time. The development of solid-state millimeter-wave componentry, high-power oscillators and amplifiers (Section 10.4) hastened the evolution of reliable and stable radars, which have become extremely useful instruments for ground-based, airborne, and even spaceborne remote sensing of clouds and precipitation. The 35-GHz frequency band is considered now as the most suitable band for performing observation with the help of ground-based millimeter-wave radar, whereas the 95-GHz band has obvious advantages for developing airborne and spaceborne tools for meteorological observations though it is not a rule. The usefulness of millimeter-wave radar does not mean that weather radars of other frequency bands (S, C, and X bands) are not important anymore. They have their own advantages. However, millimeter-wave radar systems with high sensitivity and resolution are required to research even rather weak and thin cloud layers.

10.6.1.3 Examples of Systems and Applications

Built using modern reliable technology, millimeter-wave radar systems are capable for long-term, unattainable operation and real-time, accurate measurements of various cloud and precipitation characteristics. Such radars should include a reliable system of permanent calibration, a possibility of remote control, diagnostics, and access to radar data via a network. The millimeter-wave cloud radars developed and produced at the Institute of Radio Astronomy in the Ukraine satisfy these requirements to a great extent [51]. They use the spatial-harmonic magnetron with the cold secondary-emission cathodes described in Section 10.4. The application of the magnetron in weather radar has predetermined the development of a coherent on-receive technique for the implementation of Doppler spectrum measurements. This technique proposes memorizing in some way the values of the phase of the RF pulses emitted by a transmitter and comparing these values with those measured by a receiver. The recent advances in microprocessor technique and digital signal processing have enabled [51] the memorization and comparison procedures in digital form. This has resulted in accurate measurements of Doppler spectrum and its moments with performance similar to those offered by truly coherent radar systems.

Pulsed Doppler radar from the University of Massachusetts, Amherst, is described by Bluestein and Pazmany [106]. It is a 3-mm-wavelength mobile Doppler radar system mounted in a Ford 350 Crewcab pickup truck. A 1.2-m Cassegrain dish antenna has a half-power beamwidth of 0.18° and provides azimuthal resolution of just under 10 m in the 3-km range. The radial resolution is 15 m at all ranges. The radar transmitter is designed with a multiplier chain. It has an operating frequency of 95.04 GHz. It was successfully used for tornado observations [106] and for fine-scale observations of dynamic phenomena via a pseudo-multiple-Doppler radar processing technique to decompose radial velocity vectors into the individual components of motion [107].

A low-power solid-state W-band FMCW radar system for airborne measurements of clouds and precipitation is presented by Mead et al. [108]. A millimeter-wave I/Q homodyne detector is used in this radar instead of a simple mixer.

Different compact millimeter-wave radar for airborne studies of clouds and precipitation, this time a pulsed solid-state radar with fully coherent transmitter and receiver is described by Bambha et al. [109]. Another example is the Wyoming cloud radar (WCR), which is an observational system of 95 GHz for the study of cloud structure and composition. It is installed on the Wyoming KingAir airplane. WCR provides high-resolution measurements of reflectivity, velocity, and polarization fields. Depending on the antenna configuration used, the scanned plane from the KingAir can be vertical or horizontal, and with two antennas, dual-Doppler analysis is possible [110].

Spaceborne applications of millimeter-wave radar were discussed previously in some papers, especially the use of satellite-based 95-GHz radars for measuring the vertical distribution of clouds [104]. Now millimeter-wave weather radar has been used already for cloud observation from space. CloudSat was launched April 28, 2006. The main CloudSat instrument is a 94-GHz cloud profiling radar (CPR) [111]. CloudSat uses this advanced radar to slice through clouds to see their vertical structure, providing a completely new observational capability from space. Earlier satellites could image only the uppermost layers of clouds. Thanks to millimeter-wave CPR, CloudSat is among the first satellites to study clouds on a global basis. It looks at their structure, composition, and effects. CloudSat measurements have applications in air quality, weather models, water management, aviation safety, and disaster management. However, low-power solid-state scanning millimeter-wave radar systems cannot provide the necessary sensitivity to detect low-reflectivity cloud particles, especially at longer ranges from space. That is why new high-power electronic scanning millimeter-wave radar is proposed by Remote Sensing Solutions, Inc. [112] on NASA demand. It is expected that this system will lead to future generations of large-aperture spaceborne electronic scanning radars.

Another millimeter-wave application to atmospheric remote sensing is a kind of passive radar—millimeter-wave radiometry. This can be realized from both a ground-based platform and spaceborne apparatus.

Taking into account different scattering mechanisms, various combinations of instruments may give promising results at tropospheric observations. An example is the 4-D-Cloud Project, which makes intensive use of dual-wavelength (35/95 GHz) radar together with radiometry, namely the 22-frequency radiometer MICCY [113].

Another good example of different observation tools with joint application is the international CloudNet project, which aims to provide a systematic evaluation of clouds in forecast and climate models by comparing the model output with continuous ground-based observations of the vertical profiles of cloud properties. CloudNET is a research project supported by the European Commission [114]. Three experimental sites called cloud observing stations (COSs) have been arranged in Chilbolton (UK), Sirta (France), and Cabauw (The Netherlands) where different instruments from a number of institutions of European countries were collected. Every COS is equipped with millimeter-wave radars and radiometers (94-GHz Doppler cloud radar, 35-GHz cloud radar, 24/37-GHz radiometer, 22-channel MICCY radiometer) and also microwave radars of different frequency bands, lidars, and other tools including standard meteorological instruments, rain gauges, and disdrometers. This project brings significant results in different aspects of the remote sensing of troposphere and its applications [115].

In this chapter it is impossible even to list all known projects or the corresponding institutions that are doing research in the field of millimeter-wave weather radar in different countries. This overview of millimeter-wave meteorological radar does not provide comprehensive and deep knowledge on the topic, but it is quite sufficient in order to understand that this is one of the promising applications of millimeter-wave technology that are nowadays under quick development.

It is worthy also to note that millimeter-wave weather radars may be useful for observations of other objects in the atmosphere besides meteorological objects and phenomena [116]. Among them, blowing dust, birds, and insect echoes [117].

The only thing that should be added is the importance of weather radar networking. Millimeter-wave radar is really a modern instrument that is quite suitable for network application, data transmission, and data exchange. The radars must have network capabilities enabled for remote radar control and data receiving via any network supporting the TCP/IP protocol, including the Internet. Remote control and diagnostics of the radar operation from any network computer are needed as well. Any authorized user should have access to radar data and images via local Ethernet in real time. The Internet access should provide viewing of both current information and previously stored data. Wireless PAN, LAN, and MAN are applicable in appropriate cases.

10.6.2 Remote Sensing of the Terrain

Radar sensors operating in millimeter waves can be installed on board aircraft or spacecraft. They play an important role for both aircraft navigation (altimeters) and surface investigation (SAR, radiometer, scatterometer, etc.). An overview of spaceborne remote sensing instruments was provided by Glackin [118]. Millimeter-wave radar for remote sensing of the Earth falls into the general classes of passive and active sensors. Passive sensors, called radiometers, collect and detect natural radiation, whereas active sensors emit radiation and measure the returning signals.

Passive millimeter-wave sensors include imaging radiometers, synthetic-aperture radiometers, and submillimeter-wave radiometers. Active millimeter-wave sensors include classical radars, SAR, altimeters, and scatterometers.

Passive imagers and sounders generally operate at frequencies ranging from 6 to 200 GHz. Submillimeter-wave radiometers have recently been used for measuring cloud ice content.

The problem of high spatial resolution in radiometry can be overcome through a technique of aperture synthesis, as was explained in Section 10.3

for active radars. In the passive version this concept was previously used in radio astronomy, where the operation of a large solid dish antenna is simulated by using only a sparse aperture or thinned-array antenna. In such an antenna, only part of the aperture physically exists and the remainder is synthesized by correlating the individual antenna elements. This kind of aperture synthesis differs a little from a similar technique that has a long and successful history in airborne and spaceborne SAR.

Active sensors can be broadly divided into real-aperture radars and SARs. Some are interferometric, meaning that they exploit the signals that are seen from two somewhat different locations, which is a powerful means of elevation measurement. This can be done using two antennas separated by a rigid boom, or using a single antenna on a moving spacecraft that acquires data at two slightly different times, or using similar antennas on two separate spacecraft. Modern SARs frequently also use the radar polarimetric principle, taking into account the polarization properties of the surface. The most powerful SARs apply both principles: polarimetry and interferometry.

Real-aperture radars can be further categorized as scanning (imaging) radars, altimeters, and scatterometers. (Atmospheric radars were considered above.) A prototype of new high-power electronic scanning millimeter-wave radar was recently designed [112]. A scanning millimeter-wave radar is a critical tool for improving the remote sensing of the Earth and other bodies in our solar system.

Altimeters measure surface topography, and radar altimeters are typically used to measure the surface topography of the ocean (which is not as uniform as one might think). They operate using time-of-flight measurements and typically use two or more frequencies to compensate for ionospheric and atmospheric delays. Altimeters have been flying since the days of Skylab in 1973. Aperture synthesis and interferometric techniques can also be employed in altimeters, depending on the application. A millimeter-wave altimeter using an FMCW system in the radio navigation frequency band can be installed on a helicopter.

Scatterometers are a form of instrument that uses radar backscattering from the Earth's surface. The most prevalent application is for the measurement of sea surface wind speed and direction. This type of instrument first flew on Seasat in 1978. A special class of scatterometer called delta-k radar can measure ocean surface currents and the ocean wave spectrum using two or more closely spaced frequencies.

SAR also flew for the first time on Seasat. These radars sometimes transmit in one polarization (horizontal or vertical) and receive in one or the other. A fully polarimetric SAR employs all four possible send/receive combinations. SARs are powerful and flexible instruments that have a wide range of applications, such as monitoring sea ice, oil spills, soil moisture, snow, vegetation, and forest cover.

The specific aspects of millimeter-wave SAR application are related at least to three advantages in comparison with longer wavelength SAR systems:

1) Compactness of the instrument
2) Potential not only to reach extremely high angular (lateral) resolution due to the SAR principle but also really high-range resolution because of a possible broader spectrum width
3) Ease of signal processing due to short aperture length necessary for good lateral resolution and consequently low importance of imaging errors because of high robustness against the instabilities of the airborne carrier platform

All these potential advantages of millimeter-wave SAR are characteristic for experimental radar MEMPHIS [119], which has two front ends: one at 35 GHz and the other at 94 GHz. The radar waveform is a combination of a stepped frequency waveform and an FM chirp. For the high-resolution mode, the frequency is stepped up from pulse to pulse over a bandwidth of 800 MHz in steps of 100 MHz to gain a range resolution of about 19 cm. Hägelen [120] studied the detection of moving vehicles and the determination of their ground speed with the application of experimental radar MEMPHIS in monopulse mode (Section 10.3.9). The results show that monopulse processing is an adequate technique to process millimeter-wave SAR data in the case of a ground MTI.

The indicated features of millimeter-wave SAR open a lot of interesting and useful applications of such radars. SAR systems operated from small airborne platforms like motor gliders or even remotely piloted air vehicles have to take advantage of millimeter-wave systems because only this frequency region offers short aperture times, which guarantee ease of processing and a less stringed demand on platform stability [120].

10.7 Imaging Systems for Security and Safety Applications

The capability of millimeter waves to pass through fog, clouds, drizzle, dry snow, smoke, and other substances makes the millimeter-wave imaging systems the most efficient instrument to resolve a number of problems that cannot be solved with the help of infrared and visible imaging systems. In particular, object detection and recognition for provision of security and safety is a very important and promising field of millimeter-wave radar applications. In this brief review we consider two groups of such applications: (1) the devices for concealed weapon detection (CWD) and (2) aviation safety applications, including foreign object detection (FOD) of airfield.

10.7.1 Miniature Radar and Radiometric Systems for CWD Applications

CWD at a safe distance is a new field of great importance in which millimeter-wave radar can be effectively applied. Normally, CWD systems include instruments, devices, equipment, and technologies to detect the weapons most commonly concealed on human bodies, but also in containers or vehicles. Millimeter-wave passive systems, which are also called radiometers, can be applied for imaging different scenes, objects, and structures.

All bodies emit, absorb, reflect, and transmit millimeter-wave energy, and the quantity of energy that is emitted, absorbed, reflected, and penetrated depends on the material, shape, temperature, and surface condition of the body and also on the frequency. This actually is the basis for passive detection of a concealed weapon and other objects. Millimeter waves penetrate well through clothing; the human body basically absorbs millimeter waves (which is equivalent to thermal self-radiation); and weapon material reflects ambient radiation. For example, indoor radiometric sensors will see the contrast between radiation of a human body of 309 K and room temperature of 297 K. At the same time, metal components reflect almost all radiation.

A tutorial overview of development in imaging sensors and CWD processing is done by Chen et al. [121]. In the first passive millimeter-wave imaging sensors the millimeter-wave data were obtained by means of scans using a single detector that took up to 90 min to generate one image [121].

The single-channel radiometric CWD imaging system was designed in the Kiev Research Center "Iceberg" [122]. It had a heterodyne detector of 90–94 GHz and a parabolic antenna of 300 mm diameter, which formed the beamwidth of 0.6°. The beam could scan mechanically in the horizontal plane with a shift in the vertical plane after each scan. The computer control allows a change in the scan rate, the size, and the number of angular pixels. As shown by Denisov et al. [122], a human body passive image of 100×150 pixels, obtained indoors, was formed at the screen of the display during 1 min. It demonstrated that the system could quite clearly detect a plastic handgun hidden in the clothing. In order to provide system operation in realtime, the authors proposed a multichannel imaging system with a reception sensor array providing simultaneous reception of signals from different parts of an object under investigation. In particular, the 16-channel system [122] provides an image during 1 s.

Recent advances in millimeter-wave sensor technology have led to video-rate (30 frames/s) millimeter-wave cameras [121]. One such camera is a 94-GHz radiometric pupil-plane imaging system that employs frequency scanning to achieve vertical resolution and uses an array of 32 individual waveguide antennas for horizontal resolution [123,124].

Another approach was considered by Essen et al. [125]. They emphasized the development of a demonstrator for CWD applications and an imaging system for medium-range applications, up to 200 m. The short-range demonstrator is a scanning system operating alternatively at 35 GHz or 94 GHz to detect hidden materials such as explosives, guns, or knives beneath the clothing. The demonstrator uses a focal plane array approach using four channels in azimuth, while mechanical scanning is used for the elevation. The medium-range demonstrator employs a single-channel radiometer on a pedestal for elevation over azimuth scanning. To improve the image quality, methods have been implemented using a Lorentzian algorithm with Wiener filtering.

Millimeter-wave passive sensors can be combined with other devices to increase the quality of imaging and the reliability of weapon detection. Currie et al. [126] considered the application of infrared and millimeter-wave sensors to solve CWD, through-the-wall surveillance, and wide-area surveillance under poor lighting conditions. The operation of different sensors, in particular, infrared cameras, millimeter-wave passive and active cameras, and millimeter-wave real-aperture and holographic radars, have been described. All of these sensors form images, but the images are of varying quality. That is why methods using multiple sensors to improve performance [126] are expedient.

An example of active millimeter-wave radar for CWD is described by Chang and Johnson [127]. FMCW radar is designed for unobtrusive detection of concealed weapons on persons or in abandoned bags. The developed 94-GHz radar system provides image scanning and is suitable for portable operation and remote viewing of radar data. This system includes a fast image-scanning antenna that allows for the acquisition of medium-resolution 3D millimeter-wave images of stationary targets with frame times on the order of 1 s. It allows CWD on the background of the body and environmental clutter such as nearby furniture or other people. The 94-GHz radar-emitted power of approximately 1 mW is considered low and poses no health concerns for the operator or the targets [127]. The low-power operation is still sufficient to penetrate heavy clothing or material. In contrast to passive imaging systems, which depend on emission and reflection contrast between the weapon and the body and clothing, this active radar system operates the same way both indoors and outdoors.

Information about small radar units designed for using a robotic remote-controlled machine to inspect roadway objects and debris for concealed bombs has been published [128]. Such devices could be used to detect explosives at checkpoints for buildings and transportation hubs. Government officials are particularly interested in being able to spot suicide bombers and to monitor large areas for the introduction of explosives, without terrorists being aware that they are under surveillance [128]. This publication indicates that the goal achievement relies on a technology of active millimeter-wave radar, already used today in automotive collision-avoidance systems. Combined with a video camera and software, such a system is designed to detect explosives from afar [128].

A comparison of passive and active millimeter-wave radar sensors for CWD applications shows the following advantages and disadvantages of both technologies. The benefits of a passive radar sensor are (1) it is undetectable if one doesn't take into account a leakage of local oscillator, which can be used in some devices for heterodyne detection; (2) it is absolutely safe for people; (3) the image is similar to a photograph and easy to understand; and (4) the SNR depends less on range. On the other hand, the shortcomings of a passive method are (1) stringent requirements on receiver sensitivity; (2) greater dependence on external conditions, first of all, on ambient temperature; and (3) acquisition of fast, high-quality images requires application of quite expensive sensors such as the focal plane array.

In contrast, the positive properties of an active sensor are formed by its reduced requirements on receiver sensitivity, less dependence on external factors, and acceptability of scanning architectures that makes it cheaper. However, the active radar sensor has a number of disadvantages: (1) it is obviously detectable; (2) it causes problems with irradiating noncooperative targets (difficulty of covert surveillance); (3) sometimes it can be unsafe for both operators and objects; (4) harder image interpretation; and (5) the SNR is hardly dependent on range; that is, active radar has a limited range of detection.

A combination of different nature sensors, such as millimeter waves, infrared, and normal camera [129] with image fusion [130] gives the most promising results. Different works on CWD are supported by the U.S. Office of Justice Programs [131].

10.7.2 Safety Navigation Applications Including FOD of Airfield

As was shown above, the better sensitivity allows for increased scanning velocity due to the reduction of adequate integration time to provide good image quality. The diffraction-limited spatial resolution of a passive millimeter-wave imaging system is inversely proportional to the diameter of the quasi-optical antenna. Certain improvement of image quality can be achieved by the digital processing of the obtained image with help from mathematic methods. Thus the development of the practical millimeter-wave imaging system requires an increase in the number of receiving sensors in the focal plane array and use of the quasi-optical antenna with sufficiently big diameter. Gorishyake et al. [132] present a 32-channel 33–38-GHz imaging system that provides fast image with rather high image quality in a full angle of view of 90° in the horizontal plane in 3 s. Such an imaging system can be used to provide navigation on the ground or at sea, especially at short distances where surface radar clutter is high, for remote sensing in space and air investigations, for all-weather surveillance, and in many other commercial and special applications.

One of the important directions of millimeter-wave imaging system development is application for improvement of airport operations under the condition of increasing flight intensity. In accordance with Qinetiq [133], the Qinetiq Tarsier T1100 is the first radar designed for detection of debris on runways. It gives a real-time airfield picture. The system scans the runway for debris approximately every 60 s, typically giving an inspection between every aircraft movement. It is FMCW radar with a central frequency of 94.5 GHz, 600 MHz bandwidth, 100 mW transmit power, sawtooth modulation type, and a 2.56-ms sweep repetition interval. The system provides a 2-km detection range at location accuracy of 0.5 m in the range and 0.2° in azimuth. It fulfills a 180° scan during 72 s and supports simultaneous targets. When a piece of FOD is detected, a visual and audible alarm is raised and the FOD location is shown on the display. Until the FOD is removed, Tarsier will continue to highlight the FOD location on the runway. The system records all events in a log for future reference, as well as for process analysis and improvement [134].

Another new field for millimeter-wave radar applications is helicopter collision avoidance and piloting radar. Traditional radar instruments cannot be applied as an airborne system for autonomous flight guidance purposes due to lack of resolution. On the other hand, optical sensors such as infrared systems provide excellent resolution but are nearly blind in adverse weather conditions such as fog and rain. A new radar technology called ROSAR (synthetic aperture radar based on rotating antennas) promises to overcome the deficiencies of the traditional radar systems. In 1992 Eurocopter Deutschland and Daimler-Benz Aerospace started a research program to investigate the feasibility of a piloting radar based on ROSAR technology: HELIRADAR [135]. HELIRADAR has been designed to provide a video-like image with a resolution good enough to safely guide a helicopter pilot under poor visibility conditions to the target destination. To yield very high resolution a similar effect as for synthetic aperture radar systems can be achieved by means of a rotating antenna. This principle is especially well suited for helicopters, because it allows for a stationary carrier platform.

A multisensor autonomous approach landing capability (AALC) for air mobility platforms that increases aircrew situational awareness in low- and no-visibility conditions has been developed by BAE Systems [136]. The AALC system fuses millimeter-wave radar and an optical sensor—either infrared or low-light television—processing those inputs to render the best available image on a head-up, head-down, or helmet-mounted display. The system, drawing on this technology in the weather-penetrating capabilities of the 94-GHz imaging radar technology, is designed to permit aircraft landings in zero-ceiling/zero-visibility (0/0) conditions such as fog, dust, smoke, snow, and rain. It provides visual situational awareness of the runway environment, enhances obstacle avoidance, and minimizes pilot spatial disorientation caused by lack of visual perspective. AALC is fully autonomous, placing all sensors aboard the aircraft with no need for ground-based landing aids, significantly improving flexibility in mission planning and execution.

10.8 Conclusion

We have considered millimeter-wave radar principles in this chapter. We saw features and advantages of millimeter-wave radars, as well as some of their important applications. Numerous other possible applications of millimeter-wave radar cannot be considered even briefly in the framework of a chapter such as this. An example is a millimeter-wave tomograph [137], which allows retrieval of both images of slices in a 3D isosurface for objects buried under the plane surface of a medium. The instrument can find application in medicine, biophysics, nondestructive test analysis, and many other areas utilizing a novel detection technology that can provide plan and elevation views of probing spaces. Numerous millimeter-wave radar applications follow from the consideration of millimeter-wave properties, radar principles, and some examples considered brief. Some of the applications are briefly reviewed here:

- *Industrial applications*: Speed and range measurement for industrial uses; industrial depth measurement in hostile environments
- *Meteorological applications*: Severe weather studies and measurement, clear air turbulence detection, and wind field measurements
- *Aviation applications*: Aircraft collision warning and obstacle detection system for helicopters, airport airfield surveillance, runway visualization, and wind shear detection
- *Artificial vision*: Robotic vision, unmanned aerial vehicle, unmanned surface vehicle.
- *Vision and sensing* in adverse weather or environment
- *Harbor monitoring* and navigation guidance
- *Safety and security devices*: Passive imaging for security applications, radio-wave imaging, presence and motion sensors for automated systems, intrusion detection
- *Military applications*: Surveillance, air defense, sniper and artillery location-tracking, missile guidance and tracking, seekers, and finally passive detection of targets in millimeter waves

The tendency of millimeter-wave–band applications to solve various tasks has a steady character now. The opportunity for wide application of millimeter waves in the radar systems of different functions has opened.

This resulted from advances in the developing componentry and creating perfect engineering devices on this basis, as well as from the necessity of quality improvement of radar measurements and the transfer of large information content.

Millimeter-wave radars are employed in a wide range of commercial, military, and scientific applications for remote sensing, safety, and measurements. Millimeter-wave sensors are superior to microwave- and infrared-based sensors in most applications. Millimeter-wave radars offer better range resolution than lower frequency microwave radars and can penetrate fog, smoke, and other obscurants much better than infrared sensors. Millimeter-wave radars are applicable for integrated use and data fusion with other sensors.

Millimeter-wave radar is a universal instrument that can serve as an additional communication channel, for example, in car-to-car communications; it is quite suitable for network application, data transmission, and data exchange. Millimeter-wave radars have good network capabilities and enable remote control and data receiving via any network including the Internet and wireless PAN, LAN, and MAN.

References

[1] N. C. Currie and C. E. Brown, *Principles and Applications of Millimeter-Wave Radar*, Artech House, Inc., Norwood, MA, 1987.

[2] N. C. Currie, R. D. Hayes, and R. N. Trebits, *Millimeter-Wave Radar Clutter*, Artech House, Inc., Norwood, MA, 1992.

[3] G. P. Kulemin, *Millimeter-Wave Radar Targets and Clutter*, Artech House, Norwood, MA, 2003.

[4] E. K. Reedy and J. C. Wiltse, "Fundamentals of millimeter-wave (MMW) radar systems," in *Aspects of Modern Radar*, by E Brookner, Ed., Artech House, Norwood, MA, 1998.

[5] E. K. Reedy and W. L. Cassaday, "Millimeter radar: Current assessment, future directions," in *Millimeter and Microwave Engineering for Communications and Radar*, SPIE Press, Bellingham, WA, 1994.

[6] E. K. Reedy and G. W. Ewell, "Millimeter radar," in *Infrared and Millimeter Waves*, K. Button and J. Wiltse, Eds. Academic Press, New York, 1981.

[7] R. W. McMillan, Terahertz imaging, millimeter-wave radar, NATO Advanced Study Institute: Advances in sensing with security applications, 17–30 July 2005, Il Ciocco, Italy, www.nato-asi.org/sensors2005/papers/mcmillan.pdf

[8] 3rd ESA Workshop on Millimeter Wave Technology and Applications, Espoo, Finland, 21–23 May 2003.

[9] "Physics and engineering of millimeter and submillimeter waves, 1998," MSMW '98. Third International Kharkov Symposium, 15–17 Sept. 1998.

[10] "Physics and engineering of millimeter and submillimeter waves, 2001," MSMW 2001. Fourth International Kharkov Symposium, 4–9 June 2001.

[11] "Physics and engineering of microwaves, millimeter and submillimeter waves, 2004," MSMW 2004. Fifth International Kharkov Symposium, 21–26 June 2004.

[12] "25th International Conference on Infrared and Millimeter Waves," Beijing, China, 12–15 Sep. 2000.

[13] Yu. P. Kalmykov and S. V. Titov, "A semiclassical theory of dielectric relaxation and absorption in polar fluids: Memory function approach to the extended rotational diffusion models. Relaxation phenomena in condensed matter," W. T. Coffey, *in Advances in Chemical Physics*, Ed., Series Editors I. Prigogine and S. A. Rice, Wiley, New York, 1994, vol. 87, pp. 31–122.

[14] G. K. Zagorin, A. Yu. Zrazshevsky, Ye. V. Konkov, A. V. Sokolov, S. V. Titov, G. I. Khokhlov, and L. F. Chernaya, "Factors having an influence to millimeter wave propagation in the surface layer of atmosphere" [in Russian], *Journal of Radio-Electronics*, no. 8, 2001.

[15] H. C. van de Hulst, *Light Scattering by Small Particles*, J. Wiley, New York, 1957.

[16] D. Deirmendjian, *Electromagnetic Scattering on Spherical Polydispersions*, Elsevier, New York, 1969.

[17] F. J. Yanovsky, "Phenomenological models of Doppler-polarimetric microwave remote sensing of clouds and precipitation," *IEEE International Geoscience and Remote Sensing Symposium IGARSS-02*, Toronto, Canada, vol. 3, 2002, pp. 1905–1907.

[18] F. J. Yanovsky, C. M. H. Unal, H. W. J. Russchenberg, and L. P. Ligthart. "Doppler-polarimetric weather radar: Returns from wide spread precipitation," *Proceedings International Workshop on Microwaves, Radar and Remote Sensing MRRS 2005*, September 19–21, Kiev, Ukraine, pp. 139–146.

[19] D. Maggiori, "Computed transmission through rain in the 1–400 GHz frequency range for spherical and elliptical drops and any polarization," *Alta Frequenza*, vol. L.5, 1981, pp. 262–273.

[20] ITU-R Recommendation P.838-1, "Specific attenuation model for rain for use in prediction methods," *Radiocommunication Bureau, ITU*, Geneva, Volume 2000 P Series, 2001.

[21] J. Nemarich, R. J. Wellman, and J. Lacombe, "Backscatter and attenuation by falling snow and rain at 96, 140 and 225 GHz," *IEEE Trans. Geosci. and Remote Sens.*, 26, 1988, pp. 319–329.

[22] H. J. Liebe, "MPM—an Atmospheric millimeter-wave propagation model," *International Journal of Infrared and Millimeter Waves*, vol. 10, 1989, pp. 631–650.

[23] ITU-R Recommendation P.676-4, "Attenuation by atmospheric gases," *Radiocommunication Bureau, ITU*, Geneva, Volume 2000 P Series, 2001.

[24] H. J. Liebe and D. H. Layton, NTIA Report 87-224 National Telecommunications and Information Administration, Boulder, CO, 1987. www.its.bldrdoc.gov/pub/ntia-rpt/87-224/

[25] F. G. Bass and I. M. Fuks, *Wave Scattering from Statistically Rough Surfaces*, Pergamon Press, 1979.

[26] G. A. Andreev, "Millimeter-wave beams in ground-based telecommunication systems," *Journal of Communications Technology and Electronics*, vol. 46, no. 9, 2001, pp. 1022–1031.

[27] V. I. Tatarskii, "The effects of the turbulent atmosphere on wave propagation," Israel Program for Scientific Translations Ltd., Jerusalem, 1971. IPST Cat. No. 5319. (Available from U.S. Dept. of Commerce, UDC 551.510, ISBN 07065 0680 4, NTIS, Springfield, VA, USA.)

[28] A. Ishimaru, *Wave Propagation and Scattering in Random Media*, vol. 2, Academic Press, New York, 1978.

[29] R. J. Doviak and D. S. Zrnich, *Doppler Radar and Weather Observations*, Academic Press, New York, 1993.

[30] *Radar Handbook*, 2nd ed., M. I. Skolnik, Ed., McGraw-Hill, New York, 1990.

[31] N. Yamada, "Radar cross section for pedestrian in 76GHz band," *R&D Review of Toyota CRDL*, vol. 39 no. 4, pp. 46–51.

[32] C. E. Cook and M. Bernfeld, "Radar signals, in *An Introduction to Theory and Application*, Academic Press, New York, 1967.

[33] Ya. D. Shirman, *Computer Simulation of Aerial Target Radar Scattering, Recognition, Detection, and Tracking*, Artech House, Norwood, MA, 2002.

[34] Ya. D. Shirman and V. N. Manzhos, "Theory and technique of processing radar information in noise background" [in Russian], Radio i Svyaz', Moscow, 1981.

[35] B. R. Mahafza, *Radar Systems Analysis and Design Using Matlab*, CRC Press, Boca Raton, FL, 2000.

[36] D. K. Barton, *Radar System Analysis and Modeling*, Artech House, Norwood, MA, 2005.

[37] W. M. Boerner, "Polarization dependence in electromagnetic inverse problems," *IEEE Trans. AP*-29, March 1981, pp. 262–274.

[38] F. Le Chevalier, *Principles of Radar and Sonar Signal Processing*, Artech House, Norwood, MA, 2002.

[39] F. J. Yanovsky, R. B. Sinitsyn, and I. M. Braun, "Reliability of detection of radar signals from hailstones by using parametric and non-parametric algorithms," *Proc. 2nd European Radar Conference, EuMA, IEEE*, 2005, Paris, pp. 121–124.

[40] L. P. Ligthart, F. J. Yanovsky, and I. G. Prokopenko, "Adaptive algorithms for radar detection of turbulent zones in clouds and precipitation," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 39, no. 1, Jan. 2003, pp. 357–367.

[41] *Introduction to Ultra-Wide Band Radar Systems*, J. D. Taylor, Ed., CRC Press, Boca Raton, FL, 1995.

[42] K. A. Lukin, "Millimeter wave noise radar applications: Theory and experiment," *Proc. 4th International Kharkov Symposium Physics and Engineering of Millimeter and Sub-Millimeter Waves*, Kharkov, Ukraine, 2001, pp. 68–73.

[43] X. Xu and R. M. Narayanan, "FOPEN SAR Imaging UWB Step-frequency and Random Noise Waveform," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 37, no. 4, Oct. 2001, pp. 1287–1300.

[44] "2001 Annual Report of the Advanced Sensors Collaborative Technology Alliance." www.arl.army.mil/main/ResearchOpportunities/alliances/supporting_files/annual_reports/2001/as01ar.doc

[45] A. Y. Nashashibi and F. T. Ulaby, "Millimeter-wave bistatic radar: Clutter characterization and SAR imaging," *The IASTED Conference on Antennas, Radar, and Wave Propagation*, Banff, Alberta, Canada, 3–5, July 2006. www.astapress.com.Content_Of_Proceeding.aspx?ProceedingID=385

[46] M. Kayton and W. R. Fried, *Avionics Navigation Systems*, John Wiley & Sons, New York, 1997.

[47] R. McCluney, *Introduction to Radiometry and Photometry*, Artech House, Norwood, MA, 1994.

[48] "Microwave and millimeter wave radiometry." www.millitech.com/pdfs/Radiometer.pdf

[49] V. E. Lyubchenko, Ed., *Physics and Technology of Millimetre Wave Devices and Components*, Taylor & Francis, London, 2002.

[50] A. I. Nosich, Y. M. Poplavko, D. M. Vavriv, and F. J. Yanovsky, "Microwaves in Ukraine," *IEEE Microwave Magazine*, Dec. 2002, pp. 82–90.

[51] D. M. Vavriv, "Ukrainian Institute of Radio Astronomy High-Resolution Radars," *IEEE Aerospace and Electronic Systems Magazine*, vol. 20, no. 10, Oct. 2005, pp. 19–24.

[52] A. A. Tolkachev, B. A. Levitan, G. K. Solovjev, V. V. Veytsel, and V. E. Farber, "A megawatt power millimeter-wave phased-array radar," *IEEE AES Systems Magazine*, pp. 25–31, July 2000.

[53] Communications & Power Industries.

[54] M. E. Russell, A. Crain, A. Curran, R. A. Campbell, C. A. Drubin, and W. F. Miccioli, "Millimeter-wave radar sensor for automotive intelligent cruise control (ICC)," *IEEE Transactions on Microwave Theory and Techniques*, vol. 45, no. 12, Dec. 1997, pp. 2444–2453.

[55] G. M. Brooker, S. Scheding, M. V. Bishop, and R. C. Hennessy, "Development and application of millimeter wave radar sensors for underground mining," *IEEE Sensors Journal*, vol. 5, no. 6, Dec. 2005, pp. 1270–1280.

[56] M. Schlechtweg and A. Tessmann, "COBRA 94 ultra broadband experimental radar for ISAR applications," *International Conference on Signal Processing Applications and Technology (ICSPAT 2000) Proceedings*, pp. 1515–1519. www.icspat.com/papers/630mfi.pdf

[57] H. Essen, A. Wahlen, R. Sommer, G. Konrad, M. Schlechtweg, and A. Tessmann, "A very high bandwidth millimetre wave radar," *Electronic Letters*, vol. 41, no. 22, 2005, pp. 1247–1248.

[58] L. Samoska, E. Bryerton, M. Morgan, D. Thacker, K. Saini, T. Boyd, D. Pukala, A. Peralta, M. Hu, and A. Schmitz, "Medium power amplifiers covering 90–130 GHz for the ALMA telescope local oscillators," *IEEE MTT-S International Microwave Symposium Digest*, vol. 3, 2005, pp. 1583–1586.

[59] HiTeC colloquium by Mark Rodwell, UCA, Santa Barbara on "30–700 GHz transistor and diode integrated circuits," 12 Sept. 2005, DIMES, TU-Delft. http://www.dimes.tudelft.nl/live/pagina.jsp?id=677bb180-c90b-4b89-96a5-bdfcc552805d&lang=en

[60] L. V. Kasatkin and V. E. Chayka, *Semiconductor Devices of Millimeter Range* [in Russian], Veber Publishing House, Sevastopol, Ukraine, 2006, 319 pp.
[61] V. V. Kulish, O. V. Lysenko, V. I. Savchenko, and I. G. Majornikov, "Source of femto-second wave packages on the basis of two-stream free electron lasers," *Proceedings International Workshop on Microwaves, Radar and Remote Sensing MRRS 2005*, Sept. 19–21, Kiev, Ukraine, pp. 304–309.
[62] T. Sehm, A. Lento, and A. V. Raisanen, "Planar 64 element millimetre wave antenna," *Electron. Lett.*, vol. 35, no. 4, 1999, pp. 253–255.
[63] M. Ando and J. Hirokawa, "High gain and high efficiency planar antennas for various wireless systems in millimeter wave bands," *XXVIIth General Assembly of the International Union of Radio Science* (URSI), CAF.O.2 (Oral), pp. 716–719 (Maastricht, the Netherlands, 17–24 Aug. 2002).
[64] A. Roederer and J. Mosig, "COST: Co-Operation Scientifique & Technique on antennas—Results and perspectives, *"International Symposium on Antennas*, 12–14 Nov. 2002, Nice, France.
[65] Z. Popovic and A. Mortazawi, "Quasi-optical transmit/receive front ends," *IEEE Transactions on Microwave Theory and Techniques*, vol. 46, no. 11, Nov. 1998, pp. 1964–1975.
[66] K. Solbach and R. Schneider, "Review of antenna technology for millimeter wave automotive sensors." http://hft.uni-duisburg-essen.de/forschung/paper/MF-TuB3_Neue_Version.pdf
[67] R. W. McMillan, C. W. Trussell, Jr., R. A. Bohlander, J. C. Butterworth, and R. E. Forsythe. "An experimental 225 GHz pulsed coherent radar," *IEEE Transactions on Microwave Theory and Techniques*, vol. 39, no. 3, March 1991, pp. 555–562.
[68] P. Russer, "Si and SiGe millimeter-wave integrated circuits," *IEEE Transactions on Microwave Theory and Techniques*, vol. 46, no. 5, May 1998, pp. 590–603.
[69] H. Mizutani, M. Funabashi, M. Kuzuhara, and Y. Takayama, "Compact DC-60-GHz HJFET MMIC switches using ohmic electrode-sharing technology," *IEEE Transactions on Microwave Theory and Techniques*, vol. 46, no. 11, pt. 1, Nov. 1998, pp. 1597–1603.
[70] G. M. Rebeiz, *RF MEMS Theory, Design and Technology*, John Wiley, New York, 2003.
[71] Federal Intelligent Transportation Systems (ITS) program. www.itsoverview.its.dot.gov/
[72] ERTICO—Intelligent Transport Systems Europe. www.ertico.com
[73] N. A. Stanton and M. Pinto, "Will radar-based vision enhancement make driving safer? An experimental study of a hypothetical system on a driving simulator," *Proceedings of the I MECH E Part D Journal of Automobile Engineering*, vol. 215, no. 9, 20 Sept. 2001, pp. 959–967.
[74] C. A. MacCarley, "Advanced imaging techniques for traffic surveillance and hazard detection," *Intellimotion*, vol. 6, no. 2, 1997, pp. 6–8.
[75] R. Mende and H. Rohling, "New automotive applications for smart radar systems," http://www.smartmicro.de/New_Automotive_Applications_for_Smart_Radar_Systems_V5.pdf

[76] “A review of automotive radar systems devices and regulatory frameworks,” Document: SP 4/01, April 2001, Australian Communications Authority, 9 pp. http://www.acma.gov.au/acmainterwr/radcomm/frequency_planning/spps/0104spp.pdf

[77] R. H. Rasshofer and K. Gresser, “Automotive radar and lidar systems for next generation driver assistance functions,” *Advances in Radio Science*, vol. 3, 2005, pp. 205–209.

[78] K. M. Strohm, H.-L. Bloecher, R. Schneider, and J. Wenger, “Development of future short range radar technology,” *European Microwave Week 2005, Conference Proceedings*, 3–7 Oct. 2005, Paris, pp. 165–168.

[79] E. G. Hoare, “Automotive millimetre-wave radar. Current applications and future developments.” www.iee.org/Events/Hoare.pdf

[80] Intelligent Transportation Systems—Traffic Surveillance. www.calccit.org/itsdecision/serv_and_tech/Traffic_Surveillance/survoverview.htm

[81] “A summary of vehicle detection and surveillance technologies used in intelligent transportation systems,” Prepared by L. E. Y. Mimbela and L. A. Klein, 30 Nov. 2000. www.nmsu.edu/ traffic/

[82] S. Nishikawa and H. Endo, “Applications of millimeter-wave sensors in ITS,” *Furukawa Review*, no. 18, 1999, pp. 1–5. www.furukawa.co.jp/review/fr018/fr18_01.pdf

[83] R. Bishop, *Intelligent Vehicle Technology and Trends*, Artech House, Norwood, MA, 2005.

[84] Smart Microwave Sensors GmbH. www.smartmicro.de/home.html

[85] R. Mende, M. Behrens, and S. Milch, “A 24 GHz ACC radar sensor,” Proc. International Radar Symposium IRS 2005, Berlin, 2005, pp. 91–95.

[86] J. Takezaki, N. Ueki, T. Minowa, and H. Kondoh, “Support system for safe driving. A step toward ITS autonomous driving,” *Hitachi Review*, vol. 49, no. 3, 2000, pp. 107–114.

[87] R. Schneider and J. Wenger, “High resolution radar for automobile applications,” *Advances in Radio Science*, vol. 1, 2003, pp. 105–111.

[88] I. Gresham, N. Jain, T. Budka, A. Alexanian, N. Kinayman, B. Ziegner, S. Brown, and P. Staecker, “A 76–77GHz pulsed-doppler radar module for autonomous cruise control applications,” 2000, IEEE. www.anokiwave.com/pdffiles/radarpaper.pdf

[89] R. Mende, “The UMRR 24GHz radar sensor family for short and medium range applications,” 8 April 2004.

[90] H. Rohling, A. Höβ, U. Lübbert, and M. Schiementz, “Multistatic radar principles for automotive RadarNet applications,” *IRS 2002 International Radar Symposium*, Bonn, Germany, 2002, pp. 405–410.

[91] H. Rohling, and F. Fölster, “Radar network based on 77GHz FMCW sensors,” *Proceedings 2nd International Workshop on Intelligent Transportation (WIT 2005)*, Hamburg, Germany, 2005, pp. 113–118.

[92] H. Rohling, “FMCW sensors for an automotive radar network,” *Proceedings International Workshop on Microwaves, Radar and Remote Sensing MRRS 2005*, Sept. 19–21, Kiev, Ukraine, pp. 24–32.

[93] B. Rickett and R. Manor, “A vision of future applications for an automotive radar network,” *WIT 2004 International Workshop on Intelligent*

Transportation, Hamburg, Germany, 2004. www.radarnet.org/publications/zip/wit_paper_2004.pdf

[94] University of Michigan Transportation Research Institute, "Road departure crash warning field operational test system architecture," May 2004. www.umtri.umich.edu/erd/RDCWWebsitesummary.ppt

[95] "The OSU autonomous vehicle." www.ece.osu.edu/citr/Demo97/osu-av.html

[96] Valeo Raytheon, "Valeo Raytheon's lane change assistance system." www.valeoraytheon.com

[97] F. Kruse, F. Fölster, M. Ahrholdt, M.-M. Meinecke, and H. Rohling, "Object classification with automotive radar," *Proc. International Radar Symposium IRS 2003*, Dresden, Germany, 2003, pp. 137–142.

[98] V. Winkler, J. Detlefsen, U. Siart, K. Böhm, and M. Wagner, "Automotive radar sensor extended by a communication capability," *Proc. International Radar Symposium IRS 2005*, Berlin, 2005, pp. 607–612.

[99] A. Zlocki and N. Zambou, "Application of WLAN vehicle-to-vehicle communication for automatic guidance of a vehicle driven in platoon," *Proceedings 2nd International Workshop on Intelligent Transportation (WIT 2005)*, Hamburg, Germany, 2005, pp. 125–129.

[100] G. Kramer, "Envisioning a radar-based automatic road transportation system," *IEEE Intelligent Systems*, May–June 2001, pp. 75–77 (also in *IEEE Intelligent Transportation Systems Council Newsletter*, vol. 3, no. 3, July 2001, pp. 3–6).

[101] AutoDrive System. www.eventhelix.com/ThoughtProjects/AutoDrive/

[102] O. O. Bezvesilniy and D. M. Vavriv, "Novel possibilities of Ka- and W-band dual-wavelength Doppler measurements for retrieving cloud and rain parameters," *Proceedings of the International Workshop on Microwaves, Radar and Remote Sensing MRRS-2005*, Kiev, Ukraine, 2005, pp. 71–75.

[103] R. J. Doviak and D. S. Zrnich, *Doppler Radar and Weather Observations*, Academic Press, New York, 1984. (2nd ed., 1993).

[104] J. B. Mead, A. L. Pazmany, S. M. Sekelsky, and R. E. McIntosh, "Millimeter-wave radars for remotely sensing clouds and precipitation," *Proceedings of the IEEE*, vol. 82, no. 12, Dec. 1994, pp. 1891–1906.

[105] F. J. Yanovsky, H. W. J. Russchenberg, and C. M. H. Unal, "Retrieval of information about turbulence in rain by using doppler-polarimetric radar," *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 2, 2005, pp. 444–450.

[106] H. B. Bluestein and A. L. Pazmany, "Observations of Tornadoes and other convective phenomena with a mobile, 3-mm wavelength, Doppler radar: The spring 1999 field experiment," *Bulletin of the American Meteorological Society*, vol. 81, no. 12, 2000, pp. 2939–2951.

[107] C. Weiss, H. B. Bluestein, A. L. Pazmany, and B. Geerts, "Fine-scale radar observations of a dryline during the International H2O Project (IHOP)," *The 84th AMS Annual Meeting*, Seattle, WA, 2004. Submitted to the *Sanders Symposium Monograph*, 25 Feb. 2005, 53 pp. http://ams.confex.com/ams/84Annual/techprogram/program_194.htm

[108] J. B. Mead, I. PopStefanija, P. Kollias, B. Albrecht, and R. Bluth, "Compact airborne solid-state 95 GHz FMCW radar system." http://artemis.rsmas.miami.edu/pubs/ppt/ams03_cfmcw_extended_abstract.pdf

[109] R. P. Bambha, J. R. Carswell, J. B. Mead, and R. E. McIntosh, "A compact millimeter wave radar for airborne studies of clouds and precipitation," *IEEE IGARSS Symposium*, 1998. http://abyss.ecs.umass.edu/uav-web/igarss98.pdf

[110] Wyoming Cloud Radar (also data communicated privately by Bart Geerts). http://www-das.uwyo.edu/wcr/

[111] NASA: The Science Mission Directorate. http://science.hq.nasa.gov/missions/satellite_24.htm

[112] S. M. Sekelsky and J. Carswell, "High power electronic scanning millimeter-wave radar system design," *IEEE Aerospace Conference*, 4–11 March 2006, pp. 1–6.

[113] 4D-Clouds Project, http://www.meteo.uni-bonn.de/Deutsch/4d-clouds/tools/miccyrad/

[114] CloudNet Project. http://cree.rdg.ac.uk/radar/cloudnet/

[115] CloudNet Publications. http://www.cloud-net.org/publications/publications.html

[116] D. S. Zrnic and A. V. Ryzhkov, "Recognition of nonmeteorological echoes with a dual-polarization radar," *Preprints 28th International Conference on Radar Meteorology*, 7–12 Sept. 1997, Austin, Texas, Amer. Meteor. Soc., pp. 5–6.

[117] A. Khandwalla, S. M. Sekelsky, and M. Quante, "Algorithms for filtering insect echoes from cloud radar measurements," *13th ARM Science Team Meeting Proceedings*, Broomfield, CO, March 31–April 4, 2003. www.arm.gov/publications/proceedings/conf13/extended_abs/khandwalla-a.pdf

[118] D. L. Glackin, "Earth remote sensing: An overview," http://www.aero.org/publications/crosslink/summer2004/01.html

[119] H. Schimpf, H. Essen, S. Boehmsdorff, and T. Brehm, "MEMPHIS—a fully polarimetric experimental radar," *Proc. IEEE IGARSS 2002*, vol. III, Toronto, 2002, pp. 1714–1716.

[120] M. Hägelen, H. Essen, T. Brehm, M. Ruegg, and E. Meier, "Traffic monitoring with millimeterwave monopulse SAR." Unpublished paper. Corresponding author: Dr. Helmut Essen, FGAN-Research Institute for High Frequency Physics and Radar.

[121] H. M. Chen, S. Lee, R. M. Rao, M. A. Slamani, and P. K. Varshney, "Imaging for concealed weapon detection," *IEEE Signal Processing Magazine*, March 2005, pp. 52–61.

[122] A. G. Denisov, V. N. Radzikhovsky, V. P. Gorishniak, S. E. Kuzmin, and B. M. Shevchuk, "Radiometric imaging system for concealed weapon detection," *12th International Crimean Conference Microwave & Telecommunication Technology*, Sept. 9–13, 2002, Sevastopol, Ukraine, pp. 106–107.

[123] A. Pergande and L. Anderson, "Video rate millimeter-wave camera for concealed weapons detection," *Proc. SPIE*, vol. 4373, 2001, pp. 35–39.

[124] C. A. Martin, S. E. Clark, J. A. Lovberg, and J. A. Galliano, "Real-time wide-field-of-view passive millimeter-wave imaging," *Proc. SPIE*, vol. 4719, 2002, pp. 341–349.
[125] H. Essen, H.-H. Fuchs, D. Nötel, F. Klöppel, P. Pergande, and S. Stanko, "Passive millimeter-wave imaging at short and medium range," Technologies for Optical Countermeasures II; Femtosecond Phenomena II and Passive Millimetre-Wave and Terahertz Imaging II, Proc. SPIE, vol. 5989, 2005, pp. 347–353.
[126] N. C. Currie, F. J. Demma, D. D. Ferris Jr., B. R. Kwasowsky, R. W. McMillan, and M. C. Wicks, "Infrared and millimeter-wave sensors for military special operations and law enforcement applications," *International Journal of Infrared and Millimeter Waves*, Springer, Netherlands, vol.17, no. 7, July 1996, pp. 1117–1138.
[127] Y.-W. Chang and M. Johnson, "Portable concealed weapon detection using millimeter wave FMCW radar imaging," Final report 189918 / Dr. NCJRS, 2001. www.ncjrs.gov/pdffiles1/nij/grants/189918.pdf
[128] A. Soule, "Norden veterans back on the radar with explosives detector," *Fairfield County Business Journal.* http://www.fairfieldcbj.com/archive/080706/0807060024.php
[129] The University of Texas at Arlington, IRIS—Concealed weapon detection. http://www.iris.uta.edu/projects2.html
[130] R. S. Blum, "Image fusion," Lehigh University. www.lehigh.edu/optics/Documents/2004OpenHouse/2004ARLWorkshop/13-5-blumImageFusion.pdf
[131] U.S. Department of Justice, Office of Justice Programs, National Institute of Justice. http://www.ojp.usdoj.gov/nij
[132] V. Gorishnyak, A. Denisov, S. Kuzmin, V. Radzikhovsky, and B. Shevchuk, "8 mm passive imaging system with 32 sensors," *European Radar Conference*, Amsterdam, 2004, pp. 333–336.
[133] QinetiQ Tarsier T1100 airport debris detection. www.QinetiQ.com/Tarsier
[134] P. D. L. Beasley, G. Binns, R. D. Hodges, and R. J. Badley, "Tarsier: A millimetre wave radar for airport runway debris detection," *1st European Radar Conference, Amsterdam*, Oct. 2004, pp. 261–264.
[135] W. Kreitmair-Steck, A. P. Wolframm, and A. Schuster, "Heliradar: The pilot's eye for flights in adverse weather conditions," Proc. SPIE, vol. 2736, Enhanced and Synthetic Vision 1996, J. G. Verly, Ed., May 1996, pp. 35–41.
[136] Bae Systems. "Autonomous approach landing capability improves situational awareness for air mobility platforms. http://www.na.baessystems.com/releasesDetail.cfm?a=316
[137] A. A. Vertiy and S. P. Gavrilov, "Millimeter wave tomograph for imaging of subsurface structures," *Proc. Mediterranean Microwave Symposium (MMS'2006)*, Genoa, Italy, 2006, pp. 416–418.