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Scientific and applied rationales of remote sensing study

This chapter will outline the scientific and applied rationales of the remote sensing of the Earth, the role and value of radiophysical methods, the basic statements of electromagnetic theory, the physical features of thermal radiation, and the possibilities of passive and active methods of microwave diagnostics.

1.1 WHAT IS MEANT BY REMOTE SENSING?

A person acquires an overwhelming amount of information about the surrounding world by the remote sensing method, i.e. without direct contact with physical objects. This equally relates both to ordinary human life and to obtaining information for the purposes of scientific research and applications. Here we should mention, first of all, the aerospace investigations of our planet and surrounding space, which have been intensively developed in the last 40 years and have equipped mankind with new knowledge both of space, and of our home planet. Certainly, it is impossible, in principle, to obtain information on physical objects in deep space by any other method except remote sensing. The material carrier of information about physical objects in space is the long-range electromagnetic field. In the hundred years that have passed since the experimental discovery of the electromagnetic field, mankind has learned to fairly efficiently control this form of matter and to understand the information which can be conveyed ('encoded') in the values of electromagnetic field parameters. In dense media (such as the air and water environment) other material carriers of information exist – acoustic fields and temperature fields are efficient carriers of remote information in the World Ocean.

However, in the interaction between physical bodies there exists, along with the electromagnetic field, another more long-range field, namely, the gravitational field, which efficiently reveals itself under the conditions of outer space and the rather large masses of physical bodies. Alhough the most general regularities of the gravitational field are understood by researchers, they strongly diverge in their views on the structure and basic characteristics of this field. Attempts to discover the wave structure of the gravitational field (gravitational waves) have not been successful yet. Therefore we cannot (at least at the present stage of knowledge) consider the gravitational field as a useful material carrier of remote information.

Thus, by remote sensing is meant the science of obtaining physical information about a physical object at some distance from it by means of the purposeful processing of a received electromagnetic field which, in its turn, has interacted with the object under study. Electromagnetic field energy can belong both to the thermal radiation of a physical body, and to be the energy reflected from a body from some extraneous source (the Sun, for instance). In actual observational practice these electromagnetic fields exist in the 'mixed' mode, and sometimes the fairly complicated problem of separating these radiations arises, since they 'carry' in themselves completely different physical information.

The remote sensing process is usually subdivided into various components (or units) (Sabins, 1987; Pease 1991; Megie and Readings, 2000; Kramer, 1996; Danson and Plummer, 1995).

(1) The source of electromagnetic energy – the first requirement in remote sensing concerns the presence either of a source of energy, or of natural radiation, or of an external source with respect to the object under study.
(2) The interaction with the object – during interaction with an object its physical and geometrical properties are represented ('encoded') in the values of electromagnetic field parameters.
(3) The radiation and a medium – in the passage of the electromagnetic field from an object to the receiver of radiation it can be additionally distorted (for example, by the presence of the atmosphere) and weakened.
(4) The reception of radiation is carried out by special onboard devices (sensors), which receive the electromagnetic field from empty space and then process it in order to obtain the steady characteristics.
(5) The transmission, reception and processing – the received information is usually transformed by the onboard device into electronic form and then translated through special communication channels (by means of the electromagnetic waves of other ranges) to receiving stations where, in its turn, it undergoes primary processing and is then transmitted to archival carriers.
(6) The interpretation and analysis – the received information undergoes thematic processing with the purpose of obtaining necessary physical parametres for thematic analysis and the solution of particular physical or administrative tasks.

In this book we shall deal with each of the aforementioned components of sensing as applied to passive microwave remote sensing.

1.2 THE WAVE NATURE AND SPECTRUM OF ELECTROMAGNETIC RADIATION

The emission, propagation and interaction of electromagnetic energy with physical bodies can be considered and described from two quite identical points of view: classical electromagnetic wave theory and quantum mechanics. In accordance with classical electromagnetic Maxwell theory, the energy of radiation propagates as electromagnetic waves and, in accordance with the quantum-mechanical approach, as separate, discrete quanta. These approaches are both equally applied in remote sensing problems. So, electromagnetic theory results are widely applied in calculating the radiation properties of physical surfaces (water, land), such as the degree of blackness and reflectivity of media, as well as in designing and manufacturing the radiophysical instruments for remote sensing. The quantum theory results are used in the determination of radiation energy emitted by physical bodies in the given frequency range, depending on its physical temperature, as well as in studying the radiation properties of gases, which can be explained and calculated from the quantum mechanics position only. In studying natural systems, however (for example, the radiation of hydrometeors in the Earth's gas atmosphere), the fundamental results were obtained using mixed approaches. It is important to note that the strict quantum-mechanical analysis of radiation interaction with substance leads, in a number of important applications, to equations and results which are substantially similar to the classical approach. For this reason, in solving practical remote sensing tasks, researchers adhere to the wave theory, since the latter has undoubted advantages, both in the observational practice of remote sensing and in the development and utilization of remote sensing instruments.

Within the wave theory framework electromagnetic radiation is described by the laws determining the behaviour of transverse waves, in which the synchronous oscillations of electric and magnetic fields occur in directions perpendicular to each other and perpendicular to the wave propagation direction. The oscillations propagate in space at a finite velocity, which depends on the properties of the medium. The velocity of electromagnetic waves in a vacuum is equal to $c_0 = 2.9979 \times 10^8\ \mathrm{m\,s^{-1}}$.

The types of electromagnetic radiation can be classified according to their wavelength in a vacuum or to their frequency of oscillation. These two characteristics of an electromagnetic field are especially important for understanding the physics of the interaction of radiation with the physical objects being studied. By the wavelength is meant the length of one cycle of oscillations, which is measured as a distance between two neighbouring crests of a wave (λ). The wavelength is measured in metres (m), or in corresponding fractions of a metre, such as nanometres (nm, 10^{-9} m), micrometres (μm 10^{-6} m) or centimetres (cm, 10^{-2} m). The frequency refers to the number of cycles of a wave passing a fixed point per unit of time. The frequency is normally measured in hertz (Hz), equivalent to one cycle per second, and various multiples of hertz.

The frequency (designated as ν or **f**) of oscillations of coupled electrical and magnetic fields is associated with the wavelength by the following important relation: $c_0 = \lambda\nu$.

The understanding of electromagnetic radiation characteristics in terms of their wavelength and frequency is crucial to understanding the information to be extracted from remote sensing and space research data. Below we shall consider in detail the scale and ranges of electromagnetic waves, mainly in their application to remote sensing and space research problems.

Figure 1.1 presents the scale of electromagnetic waves (the electromagnetic spectrum) and its accepted subdivision into ranges, as well as the types of artificial and natural radiation and the physical mechanisms of electromagnetic radiation. It should be noted first of all that the separation of electromagnetic spectrum ranges has a long (and sometimes complicated) history and was determined not only by physical and astronomical laws (for example, by the presence of a medium-class star – the Sun – at a fairly short distance from the Earth and by the physical properties of the Earth's atmosphere), but also by the development of ways and methods of excitation, generation and recording of electromagnetic waves. There are no strict boundaries between the spectrum ranges separated and determined till now, and, apparently, it is impossible (and also inexpedient) to present these ranges in a strictly fixed form, taking into account the rapid progress in remote sensing and radio communication technology, as well as in wave reception technology in ultraviolet, X-ray and gamma astrophysics.

The spectrum of electromagnetic waves used in space and physical investigations is extremely extensive – from the very short wavelengths of the gamma and X-ray ranges up to the superlow-frequency range (tens and hundreds of kilometres). The ranges that are directly used for remote sensing are the visible, infrared (IR) and radio ranges. This is mainly due to the fact that various types of electromagnetic radiation are generated by quite different factors and interact in quite different ways with the Earth's atmosphere. So, whereas gamma radiation arises in nuclear processes, in radioactive decay and in the fission of nuclei, X-ray radiation arises in atomic processes – when a substance is bombarded by high-energy electrons. The electromagnetic radiation formed in the visible, IR and radio ranges has been called thermal radiation. It arises due to the internal energy of a substance caused by transitions between rotation-vibration levels of molecules in gases, as well as by the oscillations of molecules in liquid and solid bodies and by the vibrations of a lattice in solid bodies (Figure 1.1(a),(b)). Thus, whereas in the reception and processing of electromagnetic waves in the gamma and X-ray ranges it is possible to obtain information on nuclear and atomic processes occurring in the substance studied, the reception and processing of electromagnetic waves in the visible, IR and radio ranges provides principally new information – data about the macro-characteristics of a substance, such as its physical and chemical composition, and its thermal properties, as well as about the geometrical properties of an object (Figure 1.1(b)). Along with thermal radiation in the microwave and radio ranges, a number of electromagnetic radiations arise, which are formed in plasma and plasma-like media – the emissions from the corona of the Sun, from the Earth's magnetosphere and ionosphere, and from thunderstorm activity in the Earth's atmosphere (Figure 1.1(b)). The powerful artificial radiation sources in the radio range are also well known: broadcasting radio stations, television stations, radars and space communications systems (Figure 1.1(a)). The activity of these systems sometimes erects very serious obstacles to remote sensing of the Earth in these ranges.

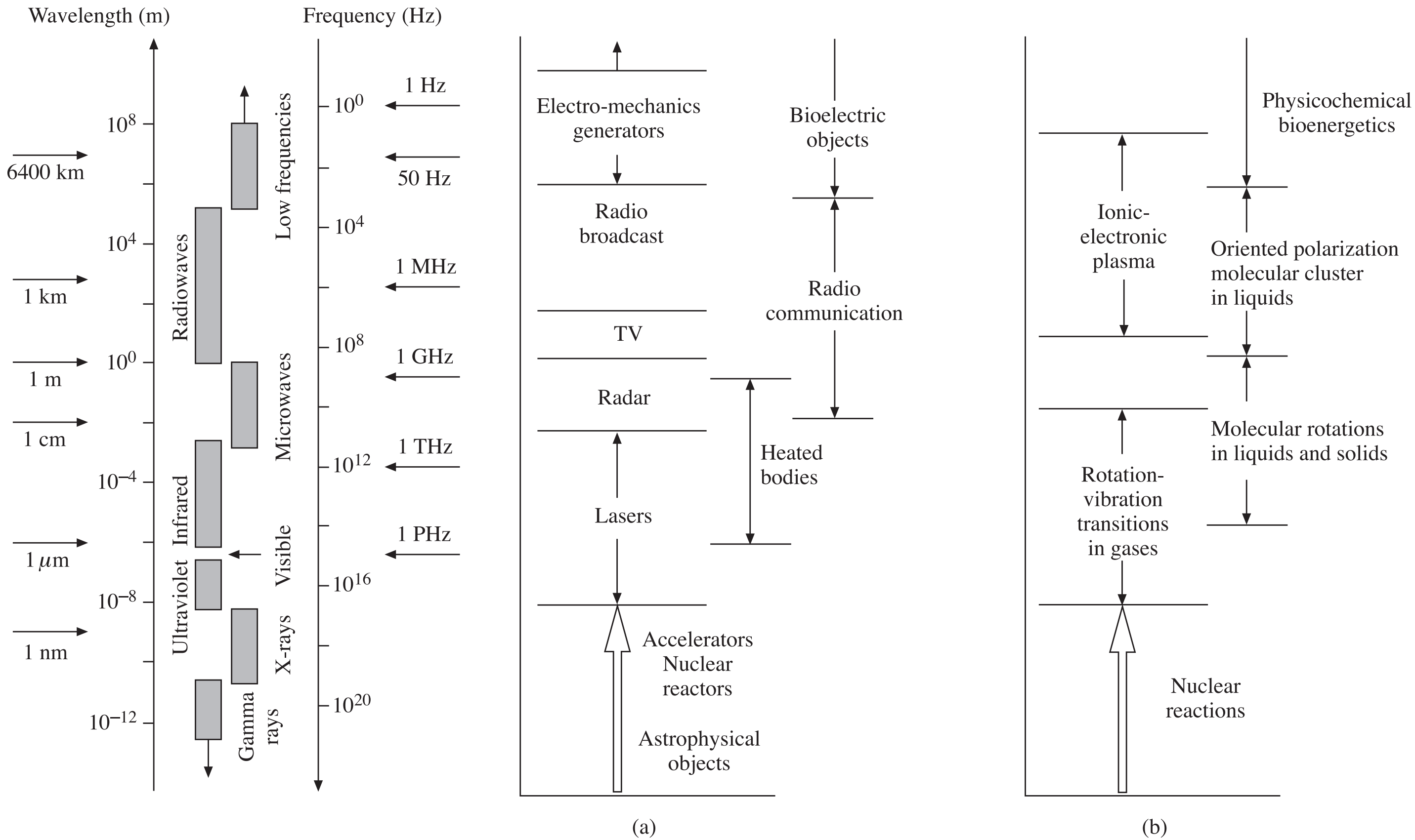

Figure 1.1. The spectrum of electromagnetic radiation. (a) The sources of radiation. (b) Physical mechanisms of electromagnetic radiation.

For direct human activity, the most important, range of the electromagnetic spectrum (which was historically first in mankind's practical activity) is the visible range, covering the interval from approximately 0.4 μm to 0.7 μm. Certainly, we should be aware of how amazingly small the visible part of a spectrum is in comparison with the whole range of electromagnetic radiation surrounding mankind which is not perceived at all by human organs of sense. The separation of six subranges within this range underlies the psycho-physiological concept of human colour vision (the concept of colours):

- Violet: 0.4–0.446 μm
- Blue: 0.446–0.500 μm
- Green: 0.500–0.578 μm
- Yellow: 0.578–0.592 μm
- Orange: 0.592–0.620 μm
- Red: 0.620–0.7 μm

Optical observations are formed on the basis of a complex combination of solar radiation scattered and re-scattered by physical bodies. This radiation is strongly transformed in intensity and spectral composition, which just generates a bright-colour picture of mankind's environment. For efficient remote investigation of various types of surfaces on the Earth (such as the water surface, mountain rocks, minerals, vegetation) specialists subdivide the total visible range into a number of subranges, which are determined by the physical properties of substances and do not correspond at all to the psychological perception of colours by humans. A vast specialist literature is devoted to studying these issues, and so they are not considered in this book.

The next portion of the electromagnetic spectrum, which is intensively used in remote sensing and in a number of important applied areas (such as rocket technology and nuclear power engineering), stretches from the red boundary of the visible spectrum to wavelengths of the order of 100 μm. This range comprises the major part of thermal radiation energy (taking into account, certainly, those thermodynamic temperatures that can be achieved under Earth's conditions). This spectral range is called the infrared. From the viewpoint of technological applications this range is subdivided into the near-infrared region, which extends from the visible range to wavelengths of approximately 25 μm, and the far-infrared region corresponding to longer waves, up to 1000 μm (0.1 cm). The remote sensing specialists, however, adhere to the other concept concerned with the physical features of remote observations in these ranges. So, the main IR range can be subdivided into two subranges in accordance with their radiation properties – reflected IR and emitted, or thermal, IR. Reflected IR covers wavelengths from approximately 0.7 μm to 3.0 μm and radiation in the reflected IR region is used for remote sensing purposes in ways very similar to solar radiation in the visible portion. It is important to note that the thermal IR region essentially differs from the visible and reflected IR regions, since the source of radiation in this range is the physical body itself that is subject to investigation. Thermal IR covers wavelengths from approximately 3.0 μm to 100 μm. Inside the thermal range is the important subrange, whose value can hardly be exaggerated.

This range, extending from 8 μm up to 12 μm is characterized by the fact that the information obtained when using it strictly corresponds to the thermodynamic temperature of any physical object on the Earth. Actually, each modern operative and research satellite system carries remote sensing devices of this range in its structure. It should also be noted that the range from 100 μm to 1000 μm is intensively explored now from the viewpoint of using it in remote sensing tasks. Radiophysicists often call it the submillimetre range, and often include it in the 'radiowaves' notion.

The huge range of wavelengths, from 1×10^{-5} to 10^{10} m (and, accordingly, with frequencies from 3×10^{12} Hz to several Hz), is called radiowaves. After successful experiments by the Russian physicist A. S. Popov (1895–1899) and G. Marconi (1897–1901) on using electromagnetic waves in the range of 1–200 m for accomplishing a wireless communication at a distance, a wide practical application of electromagnetic waves in the metre and decametre ranges began. The experimental discovery by A. S. Popov in 1897 of the phenomenon of the reflection of electromagnetic waves from physical bodies (military ships) can be considered as the first example of using electromagnetic waves as a remote information carrier. The practical usage of radiowaves from various frequency subranges is dependent on the features of the propagation of radiowaves of various wavelengths and on the conditions of their generation and directional emission. Proceeding from these physical circumstances, the International Radio-Communication Regulation approved the division of radiowaves into ranges strictly corresponding to the wavelengths (millimetre, centimetre, decimetre, metre, kilometre etc.), as well as into some special subranges allocated for the operation of radio stations, television stations, communication systems, mobile communications, space communications. Low-frequency and hyperlow-frequency electromagnetic waves are widely used in industry (the alternating current of 50-Hz frequency with the wavelength of 6000 km is best-known in domestic conditions). Waves in these ranges are generated both in electronic circuits and by means of electromechanical generators. Figure 1.1 specially marks the wavelength corresponding to the length of radius of the Earth globe, as well as the wavelengths corresponding to the spatial dimensions actually encountered in ordinary human life (1 km, 1 m, 1 cm). In view of the saturation of the radio range with various kinds of radio communication, e.g. TV, broadcasting and radar, international organizations (URSI, in particular), have accepted rules that regulate (and sharply limit) the activity of any type of radiation by rigid frequency frames and, accordingly, new frequency classifiers are introduced. Similar frequency limitations have also been introduced for radio-physical remote sensing systems and for radio-astronomical investigations (Zuzek, 2000; Zuzek *et al.*, 2000; Wende, 2000; Rochard, 2000; Huneycutt and Zuzek, 2000). As problems related to exploration of the radio range increase, the boundaries of the frequency ranges undergo (and, undoubtedly, will continue to undergo) significant variations. So, in view of the active exploration of the millimetre and submillimetre ranges for studying the content of and variations in the small gas components (greenhouse gases) in the troposphere and stratosphere, a new frequency classification of these ranges has now been elaborated (Maeda *et al.*, 2000; Maier *et al.*, 2000; Konig *et al.*, 2000; Hartmann *et al.*, 1996; Greving, 2000).

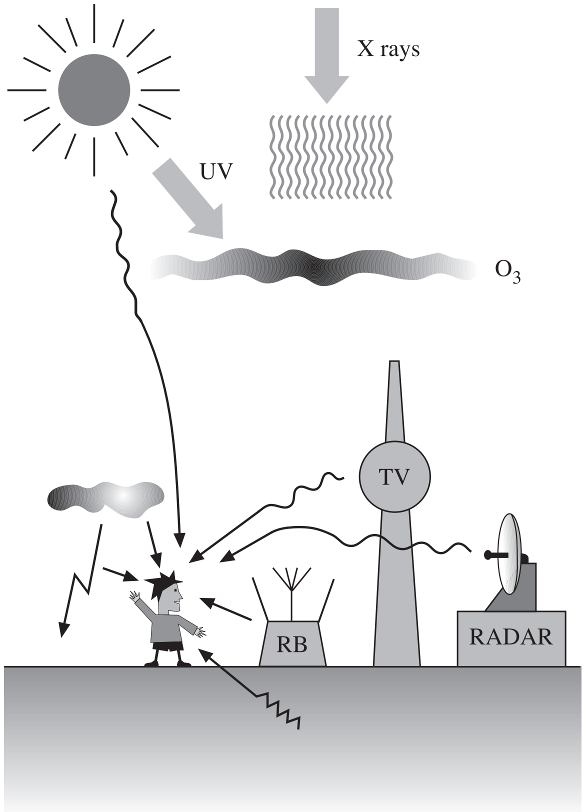

Figure 1.2. Schematic presentation of the influence on a human of the surrounding electromagnetic radiation fields. UV is ultraviolet waves; O_3 is ozone layer; RB is radio broadcasting transmitter.

For the purpose of simplifying the qualitative approach, remote sensing specialists have accepted the following separation of the radio range: microwaves, with wavelengths from 1 mm to 1 m; and radiowaves, with wavelengths from 1 m to 10 km. Until now, from the viewpoint of remote sensing activity, the 'long' millimetre and centimetre and 'short' decimetre ranges have been well explored. The advance into the metre and decametre ranges meets, however, some major difficulties, first of all the problems of insufficient spatial resolution and external 'parasitic' emissions. On the other hand, in exploring the submillimetre range, problems of insufficient power sensitivity of the equipment arise; but they have been successfully overcome.

Though the energy of electromagnetic radiations of quite different types and huge intensity permanently surrounds us (Figure 1.2), we, nevertheless, do not actually notice this, since our organs of sense are capable of detecting directly only a very small portion of this energy, first of all in the visible range and, to an essentially lower degree, in the IR thermal range. For detecting all the rest of the electromagnetic spectrum, special instruments are required. Our eyes, being very sensitive and direct receivers of electromagnetic waves in the visible range, represent a perfect optical interferometer with a slightly fluctuating base (the distance between the pupils), which forms a signal for subsequent processing in our brain as a spatial-correlation function of the three-dimensional image (the hologram, in essence). Our brain possesses the unique property of processing and restoring (with a particular time constant of about 0.05 s) the received hologram into three-dimensional colour images. With the help of eyesight we receive (according to different estimations) from 80% to 95% of the information we need. On the other hand, because of the psycho-physiological mechanism of image interpretation, human eyesight and visual perception by the brain has many limitations, among which are both physical and physiological fatigue and optical illusions. The generalization of images in the human brain sometimes assumes fantastic forms, which have nothing in common with reality. For these reasons human eyesight is far from being a reliable physical tool in all cases.

Our skin is sensitive to electromagnetic waves of IR thermal range, but to an insufficient degree to be a source of serious remote information (which is well known from daily life). However, some biological organisms from the animal world (for example, the rattlesnake) orient themselves in space mainly using precisely this range of electromagnetic radiation.

We are not susceptible at all to emissions in the radio range, and this is a great boon for us, since the effective radiation from TV and radio stations and radars is many millions of times greater than the radiation we receive from the Sun. This human unreceptiveness to waves in the radio range is associated, first of all, with a very small value of the radiophoton quantum, which does not influence the physical-chemical links in the biological molecules of the human body. If this were not the case, the biological life of a man in the modern environment of super-power radio emission would be impossible.

It is the full absorption of these emissions by the upper layers of the atmosphere which saves a man (and the entire biological community on the Earth in general) from the X-ray and gamma radiation of powerful extraterrestrial sources, which are very dangerous to the biological life. The ultraviolet radiation of the Sun is essentially suppressed in the ozone layer of the stratosphere.

1.3 PASSIVE AND ACTIVE SENSING

In relation to the objects studied, remote sensing methods are subdivided into passive ones, i.e. providing only reception of the electromagnetic field, and active ones, which provide both emission of an electromagnetic field with given characteristics (its form, amplitude and phase – the coherent signal), and reception of a signal, reflected from the studied object, whose characteristics incorporate physical information about the object. In the first case, the physical information on a studied object is incorporated both in the intensity of a received fluctuation signal and in its spectral characteristics. In the second case it is incorporated both in the amplitude and form of a reflected signal, and in its phase distortions. The data on the phase features of a reflected signal qualitatively change the information obtained about physical objects, thus making it possible to determine their kinematic properties, to measure the distance to an object and to implement essentially new signal processing modes (the so-called aperture synthesis modes). The latter methods increase the resolution of the entire system (certainly, after specialized processing) 100–1000 times with respect to the so-called Rayleigh diffraction limit.

Along with coherent signals, in the active modes there are also used the so-called incoherent (noise) sources, which do not allow the recording and the handling of the phases of oscillations because of the wide range frequencies used in these cases. A striking representative of this kind of source is the Sun – the star nearest to the Earth – which plays for remote sensing the part of a fairly 'standard' source of 'illumination' in the visible range for an illuminated part of the globe. Part of the electromagnetic energy of the Sun in the visible range is absorbed by the surface–atmosphere system, transfers into heat and only then is re-emitted, but now in quite other ranges of electromagnetic wavelengths – IR and microwave.

An obvious advantage of artificial active sources is the possibility of using them as required during the experiment, regardless of the time of day and the season. However, the operation of active systems under onboard conditions requires the presence of considerable sources of energy on the flying vehicle, for the generation of electromagnetic waves of appropriate range and power, corresponding to the orbital conditions of flight and the reflective properties of an object.

The passive methods are based on the reception of the so-called thermal radiation of physical objects due to the internal (thermal) energy of matter, which enables spontaneous transitions between rotation-vibration levels of molecules in gases, the oscillations of molecules in liquid and solid bodies and vibrations of a lattice in solid bodies. We shall devote the basic part of this book to studying this type of radiation. The instruments, which carry out the reception and processing of such radiation, are called radiometers (in the corresponding range of wavelengths).

The passive methods include: the radiothermal location of the Earth and planets, radio-astronomy, optical and IR astronomy, X-ray astronomy, and various modes of thermal IR survey of the Earth and planetary surface. The active methods include: scatterometry, radar survey in the modes with a real aperture and with a synthesized aperture, Doppler radar, and optical measurements with active illumination (the Sun, lidars). The important direction is now the study of the possibilities of radiothermal (passive) reception in the Michelson-type interferometre mode and in the aperture synthesis mode. The implementation of such modes of a typically coherent type for noise signals seems surprising at the first sight. However, as will be studied in Chapters 2 and 7, any narrowband noise signal possesses some kind of coherent-noise dualism, i.e. under some conditions the noise signal behaves as if coherent (for example, a sine wave).

It is emphasized once again that the principal distinction between passive and active remote sensing methods consists in the fact that the data obtained by passive systems (radiometers) comprise information on the thermal state of a studied object, whereas the data of active systems convey information on the kinematics and surface roughness of an object. So, for instance, no information can be obtained (by active methods) about the state (physics and chemistry, pressure, temperature) of gases in the pure atmosphere, because the scattering of electromagnetic waves on gas molecules is extremely insignificant (as opposed to the scattering on hydrometeors and aerosols in the Earth's atmosphere). At the same time, thermal radiation, being a purely quantum effect, provides amazing (in its information capacity) data about the state of gas media on the Earth, on planets (their atmospheres) and in outer space (molecular clouds, stellar atmospheres). In addition, we mention one more important peculiarity: the information on dielectric, geometric and volumetric properties and on the state of surface (the degree of roughness) of a studied object is 'incorporated' in the passive and active sensing data with various degrees of information capacity. This is precisely the reason why these methods do not duplicate each other at all, despite their being treated as if they did in some manuals. On the contrary, these methods mutually supplement each other and enrich the information on a physical object. In recent years the curious tendency has arisen for simultaneous (complex) processing of the data obtained by active and passive radio-physical remote instruments, by using some specialized synergetic retrieval algorithms. New results, obtained by means of such processing, obviously provide evidence of the mutual supplementation of these two approaches in radiophysical sensing. Similar conclusions can be drawn with respect to sensing in other ranges too (laser active sensing in the visible and IR ranges supplement the traditional methods).

1.4 THERMAL RADIATION: THE ROLE AND SOURCES

One of the fundamental factors explaining the major importance of thermal radiation in remote sensing and astrophysical applications is its rather transparent physical linkage with the internal thermal structure of a physical object and with its physical and chemical features. The role of thermal radiation is also large in a number of industrial-technological applications, such as power engineering, rocket technology and metallurgy.

All physical objects, having physical temperatures that differ from the absolute zero, continuously emit the fluctuation electromagnetic field arising due to the internal energy, which enables spontaneous transitions between rotation-vibration levels of molecules in gases, oscillations of molecules in liquid and solid bodies and vibrations of a lattice in solid bodies with subsequent de-excitation of electromagnetic quanta. The radiation has a typically quantum character. The energy of radiation covers a very wide range of wavelengths and has (according to radiophysical terminology) a continuous spectrum of rather complex form, the position of maximum of which depends on the thermal temperature of the substance. As this temperature increases, the total energy of emitted thermal radiation grows, and the spectrum maximum shifts to the region of short wavelengths. Thermal radiation is emitted both by all physical bodies under Earth conditions (including our own planet) and by stars, galaxies, nebulae and molecular clouds situated in the deep space, and even by such exotic objects as black holes, one of which is situated at the centre of our galaxy (the Milky Way). Certainly, along with thermal radiation, the whole spectrum of other electromagnetic emissions falls on the Earth from space. One much emission is the so-called maser radiation from peculiar huge areas near stars consisting of molecules and atoms of gases, which are permanently in the excited state due to the presence of external emissions. Physical ties between the intensity and the spectrum of maser radiation and a quantum structure of substances are rather complicated and cannot be described in frameworks of thermal radiation theory.

Thermal radiation arises under the detailed equilibrium conditions in a substance for all emissionless processes, i.e. for various types of collisions of particles in gases and plasma, and for the exchange of energies of electronic and oscillatory motions in liquids and solid bodies. At local thermodynamic equilibrium, where thermal radiation is characterized by the value of temperature at a given point, thermal radiation is not at thermodynamic equilibrium with the substance. And in this case the emission of radiation to external space with redistribution of a temperature regime within a body is possible. To maintain the stationary state, in which the gradient thermal field must be sustained, the loss of thermal energy must be replenished from extraneous sources. The radiation spectrum at full thermodynamic equilibrium (the equilibrium or black-body radiation) possesses striking properties – it does not depend on the nature of the substance and is determined by the fundamental law of nature: Planck's law of radiation.

For black and non-black bodies Kirchhoff's law of radiation (or, in a more general form, the fluctuation-dissipation theorem) is valid. This law relates the emissive and absorptive powers of these bodies with the emissive power of an absolutely black body. Applying the aforementioned radiation laws under the local thermodynamic equilibrium conditions to the emission and absorption of thermal radiation in physical bodies, we can study the radiation transfer processes within the framework of the so-called phenomenological theory of radiation transfer. The importance of this theory for remote sensing tasks and astrophysical applications is difficult to overestimate. In fact, all the fundamental results of remote sensing and astrophysics obtained till now, are based to an overwhelming degree on using the methodology and interpretation of outcomes of radiation transfer theory (rather than on Maxwell's wave theory of electromagnetism, however surprising this may be). In the appropriate chapters (Chapters 9–12) we shall study in detail the issues of the construction of radiation transfer theory and the application of its results for practical remote sensing tasks.

Concerning remote investigations under Earth conditions, we can indicate three basic sources of thermal fluctuation electromagnetic radiation:

- the star nearest to us – the Sun – which represents black-body radiation with a physical temperature of 6000 K;
- our planet Earth properly, which possesses radiation close to black-body radiation with a physical temperature of 287 K;
- the microwave background radiation of the universe, possessing black-body radiation with a high degree of spatial-angular isotropy and a temperature of 2.73 K.

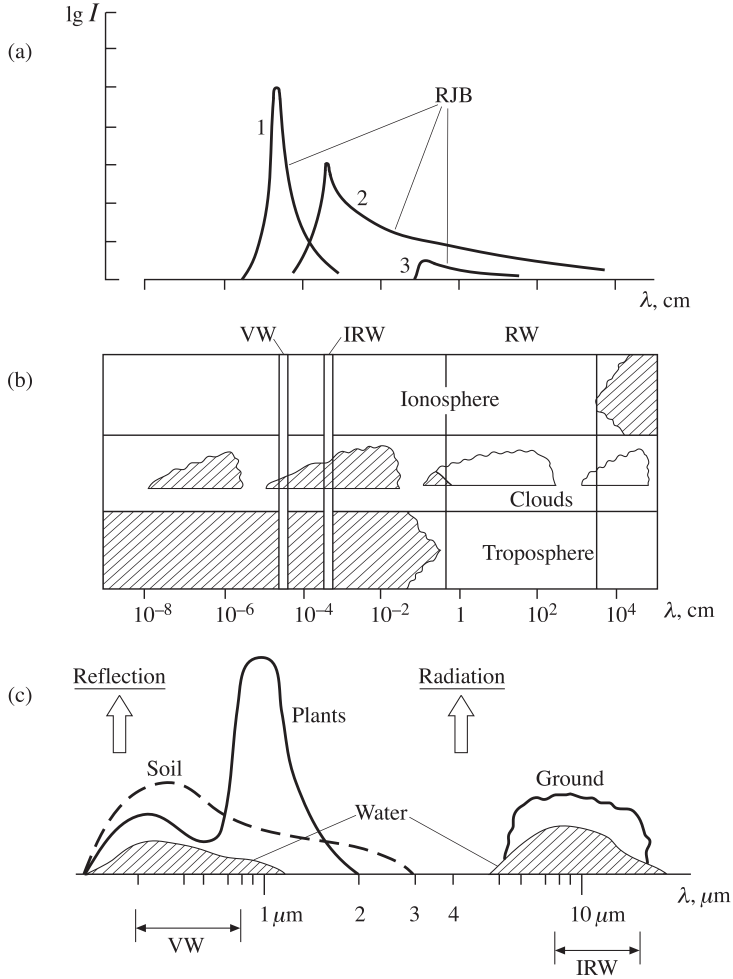

Figure 1.3. The qualitative picture of the correlation between the main sources of radiation and features of the Earth's atmosphere. (a) Large-scale spectra of Sun reflection radiation (1), the Earth's thermal emission (2), the background microwave radiation (3). RJB are Rayleigh–Jeans branches. (b) Simplified schematic presentation of the propagation of electromagnetic waves though the ionosphere, cloud systems and the troposphere. VW is the visible window; IRW is the infrared window; RW is the radio window. (c) Detailed (in wavelength range 0.3–14 μm) spectra (in arbitrary units) of Sun radiation reflected from soil, plants and water surface, and of thermal radiation emitted from ground and water surface and soil.

The qualitative picture of radiation spectra of all three sources of radiation is presented in Figure 1.3(a), where the solar spectrum is shown as radiation reflected from a conventional object with a reflection coefficient of about 0.05.

The discovery of the latter type of radiation (microwave background radiation) was the major experimental evidence in favour of the ideas of the hot universe model and isotropy of its expansion and its homogeneity. The black-body character of background radiation was retained as a relic, as the 'memory' of the early period of evolution (after the Big Bang). The maximum of relict radiation intensity is reached at the wavelength of 1 μm and then (at higher frequencies) its intensity sharply drops (Figure 1.3(a)). Thus, the contribution of the relict background radiation to IR and the visible ranges is actually insignificant, whereas for fairly fine measurements in the radio range (mm, cm and dm) the relict background radiation must be taken into account without fail. Properly speaking, A. Penzias and R. Wilson (Nobel prize, 1978) discovered the relict background radiation in 1965 during experiments of a purely radiophysical type (the measurement of antenna system parametres) in the centimetre range.

The Sun – the star nearest to us – is a necessary component in the support of the biological life on our planet. The radiation, coming from the Sun to the external observer on the Earth, arises in the thin superficial layer – the photosphere – and represents thermal radiation (Planck radiation) with a temperature of 6000 K. More than 30 000 narrow lines of absorption (Fraunhofer lines) of atoms, situated in the Sun's chromosphere and absorbing radiation of the photosphere, were discovered and identified in the continuous radiation spectrum. However, their presence has virtually no effect on the total power of photosphere emission in the optical range. Advancing into the far-IR and radio ranges, the situation drastically changes: the chromosphere and corona of the Sun, being transparent for the visible range, become opaque for radiowaves and, as the wavelength increases, the radiation comes from ever higher and hotter levels of the Sun's atmosphere. So, in the centimetre range, the radiation intensity corresponds to the temperature of 10 000 K and monotonically increases up to 10^6 K in the range from 3 cm to 100 cm. The intensity of radio emission of the chromosphere and corona undergoes considerable changes, both slow and fast (up to millisecond scales). The latter are associated with non-thermal plasma processes in the solar corona and can cause bursts and noise storms with a radiation intensity in the metre range, corresponding to a temperature up to 10^9–10^{11} K. Such powerful emissions can be sources of serious interference for remote sensing in the ranges mentioned.

The third source, which perhaps is the most important for remote sensing tasks, is the thermal radiation of the planet Earth, which has a huge wavelength range, from thermal IR up to the metre radio range. The principal point here is the great distinction between the thermal radiation of a planet and that of a black body, in the radio range especially. It is this distinction which bears the most important remote information on the state and characteristics of the surface–atmosphere system. The formation of the distinction mentioned between the thermal radiation of the Earth and that of a black body is caused by the presence of some important physical properties of the Earth's atmosphere and, primarily, of the transparency bands – the atmospheric windows (and, accordingly, the bands of opacity) for electromagnetic waves. The Earth's atmosphere has three ground windows of transparency for electromagnetic radiation (Figure 1.3(b, c)):

- the visible and near-IR window (wavelengths from 0.3 to 1.0 μm),

- the thermal IR window (8–12 μm),
- the radio window (2.5 mm to 20–50 m).

Actually, the Earth receives all its energy from the Sun in the form of electromagnetic radiation concentrated in the spectral range of 0.3–2 μm. About 30% of this energy is reflected by the Earth's atmosphere system back into space. A considerable portion of energy (more than 51%) passes through the visible atmospheric window and is absorbed by the Earth's surface (land and ocean), while the remainder (19%) is absorbed in the atmospheric gases. This radiation is frequently called short-wave solar radiation. The absorbed part of short-wave energy transfers into heat and then is redistributed over the planet by means of dynamic and turbulent-convection processes and through the radiative transfer of the long-wave atmospheric radiation. It is this part of the energy that in the long run determines the whole variety of conditions of the atmosphere and surface below it. A certain part of long-wave radiation is de-excited back into space through the IR and atmospheric radio windows; however, the majority of it is absorbed by minor gas components of the atmosphere (H_2O, CO_2, O_3, N_2O, CO, CH_4). And, first of all, we should mention here the generation of greenhouse warming in the ocean–atmosphere system, which provides the mean temperature on the planetary surface of about 287 K ($t = +14°C$) and, accordingly, the possibility of the existence of biological life and huge reservoirs of liquid water on the Earth.

The short-wave boundary of the radio-window is determined by absorption of water vapour and oxygen molecules, whereas the long-wave boundary is determined by absorption of ionosphere medium (the plasma processes). The radio-window possesses a remarkable feature: radiation with wavelengths greater than 1 cm virtually freely passes through the cloudy cover of the Earth's atmosphere. Taking into account the fact that clouds shield 55% of the Earth's surface on average, this window offers the only opportunity 'to glance' under the clouds and to observe the processes occurring between the cloud and the surface of the Earth. On the other hand, the possibility of measuring the thermal radiation of the atmosphere and observing the Earth's landscape in the microwave region may seem surprising at first sight, because the intensity of emission of long-wave radiation drops sharply as the square of frequency (the Rayleigh–Jeans formula), and at the transition from the 10 μm to the 10 cm wavelength the radiation intensity value decreases 10^8 times! Nevertheless, sensitive modern instruments for noise signals in the radio range (microwave radiometers), the measurement of such levels of electromagnetic emission (and their variations) does not present any difficulties (see Chapter 3).

Note one more important circumstance. Whereas in forming the thermal balance of a planet the role and meaning of a radio-window is, obviously, insignificant, for the information maintenance of remote sensing the principal role and meaning of a radio-window is beyond any doubt now. First of all, this is due to the fact that, unlike the IR range, the radiative properties of Earth's surface essentially differ from black-body emitters and, thus, the high recognizability of Earth's surface elements from radiation intensity variations is made possible. (This possibility, by the way, is completely absent in the IR thermal range.) In addition, considerable frequency variations of radiation intensity are observed with advancement from millimetre to decimetre ranges, which makes it possible to use the spectral images of objects as reliable information attributes. The further advance into the metre range encounters serious difficulties related to powerful external emissions of artificial and natural origin (the emission of television stations, radio-transmitters, noise storms on the Sun, radio-emission of our galaxy).

Undoubtedly surprising (and also, by the way, a necessary condition for biological life on the Earth) is the fact that the maxima of spectra of basic sources (under Earth's conditions certainly) exactly correspond to the transparency windows of the Earth's gaseous atmosphere (Figure 1.3(a), (b)).

1.5 RECOGNITION AND UNDERSTANDING OF MICROWAVE SIGNATURES

In this section, for a specific example of considering the data of remote sensing of the Earth's surface with vegetation, we shall try to reveal the principal information possibilities provided by studying Earth objects with active and passive methods in the radio range.

By measuring the electromagnetic energy that is reflected (or emitted) by a physical object in various wavelength ranges, we can generate a spectral response for that object. Then, by comparing the space–time peculiarities of spectral responses received in various ranges, we can recognize and identify the objects, which sometimes cannot be done when you have the data at one frequency only. So, for example, water surfaces and vegetation can reflect solar radiation in a very similar manner in the visible range and, accordingly, they can actually be indistinguishable in optics, whereas they differ considerably in their recognition and identification in the radio range. A set of spectral responses and their spatial features are called signatures. The knowledge of signatures and understanding of the laws of their formation in various ranges are the principal conditions for generating geographical and geophysical bases of data about physical objects on the Earth's surface.

Before considering microwave signatures, we summarize the qualitative features which are revealed in observation of objects in various wavelength ranges attributed to atmospheric windows.

Optical observations are characterized by the reception of scattered and rescattered solar radiation with its very strong transformation in spectral structure of the reflected radiation and in its intensity, which creates the colourful picture of the world surrounding us. The thickness of a layer forming the reflected electromagnetic energy of physical bodies (the skin-layer) is of the order of 1 μm which causes a very strong and non-unique dependence on the degree of roughness of the surface. In reflection from physical surfaces a rather complicated picture arises, which represents a mixture of mirror and diffusion components giving rise to strong spectral variations (spectral responses) within the visible range. The observed picture very heavily depends on the time of day and on the season, and on the state of cloudiness, and on the presence of various types of aerosols of natural and artificial origin, and is characterized by rapid time variability. For certain unification of the results of satellite measurements, the ballistic parametres of a spacecraft are specifically chosen so that the crossing of the equator takes place on each orbit at a strictly defined local time (for example, at 9.30 a.m.). Such a type of orbit is called Sun-synchronous.

Observations in the thermal IR range are completely independent of the solar radiation (and, accordingly, of the time of day). The intensity of thermal radiation almost exactly corresponds to the thermodynamic temperature of an object (to an accuracy of 1–2%); it virtually does not depend on the dielectric properties of physical emitting bodies; the radiation is diffusive; it is very weakly dependent on the degree of roughness. The skin-layer of radiation of solid and liquid bodies (i.e. the thickness, on which the basic portion of radiation is formed) equals about 10 μm; the skin-layer of cloudy systems equals about 50–200 m. The observed picture represents, in essence, the temperature field of the surface–atmosphere system and heavily depends on the presence of cloudiness which, in its turn, can be rather clearly recognized in the values of intensity (the temperature of the upper boundary of cloudy systems is essentially lower than the Earth's surface temperature). No specific choice of ballistic maintenance for satellite systems is required in this case (unless related to spatial resolution problems).

Observations in the radio range are completely independent of solar illumination (the time of day), and are virtually independent of the presence of cloudiness and aerosols. The intensity of radio emission of a physical object is strictly proportional to its thermal temperature and radiative properties (the corollary of the Rayleigh–Jeans approximation). And, as a consequence of this circumstance, the radio emission of physical bodies strongly depends on the dielectric properties of an object, on its physical and chemical structure, and on the internal geometrical and phase structure. It is important to note a significant depth of a skin-layer of radiation and scattering of radiowaves – for Sakhara sands the skin-layer equals 6–10 m; for glaciers of the Antarctic Continent and Greenland the skin-layer reaches 1–3 km! In view of the high sensitivity of radiowaves to diffraction interactions, a strong (sometimes non-unique) dependence on the structure of a surface roughness is observed in the radio range. (This fact, properly speaking, underlies quite efficient radio-methods of sounding the sea surface.) The active methods are quite sensitive to the kinematic characteristics of an object (Doppler radar). In addition, the coherency of the emitted signal (the knowledge of the signal phase) makes it possible to accomplish very important modes of observation called the aperture synthesis, which make it possible to sharply increase the spatial resolution of radars. At present, the possibility of using such modes for passive sensing is being actively studied.

No specific choice of ballistic maintenance for satellite systems with passive microwave equipment is required (unless related to spatial resolution problems). For spacecraft with active equipment the optimum ballistic maintenance of a vehicle plays a major part, since this is strictly associated both with the power of a transmitter (and, accordingly, with the power supply of the spacecraft) and with the sensitivity of receiving equipment and with the type of surfaces under study.

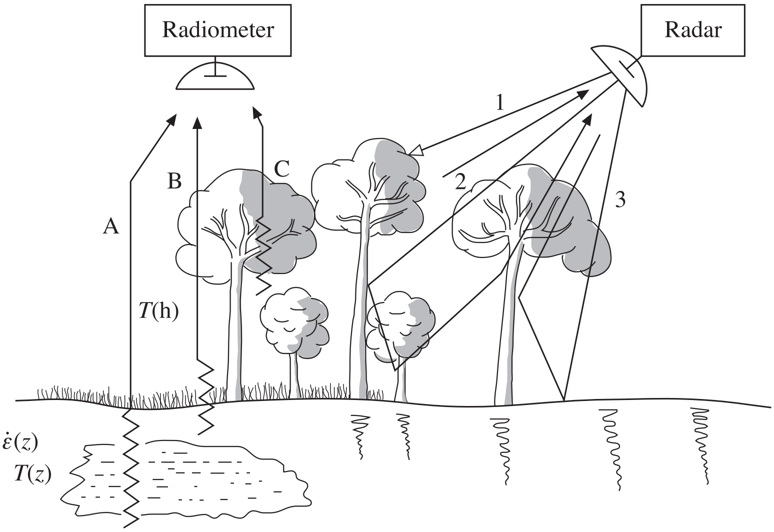

Figure 1.4. Simplified model to demonstrate the possibilities of emitted and backscattering signals in vegetation. 1: The generated signal is reflected on the canopy. 2: The signal is reflected by stems. 3: The signal is reflected from the soil and then the stem back to the antenna. A: Thermal signal is emitted from subsurface layers. B: Thermal signal is emitted by surface structures. C: The signal is emitted by the volume of the canopy. $T(z)$ and $\dot{\varepsilon}(z)$ are temperature and dielectric profiles (in depth). $T(h)$ is temperature profile (above the ground).

Taking into account the above analysis, we shall return to the consideration of a qualitative picture of the formation and recognition of microwave signatures obtained while observing a conventional Earth surface with vegetation. A schematic (simplified) picture of signal formation is presented in Figure 1.4, where the left half of the drawing relates to the passive method of sensing and the right half to the active one.

The microwave instruments carried by satellites have the important potential to provide us with information on vegetation, agricultural crops and the soil in which they grow. As well as generating images when visible/IR sensors are unavailable because of cloud, the information from microwave instrumentation may not only be complementary to that from optical systems but may also carry new information. The reason for this is the difference in the processes and scale sizes of vegetation and agricultural features with which microwave and optical wavelengths interact. The response of a field of vegetation to optical radiation is determined by structures on micrometre scales and by processes of chemical absorption. Microwave radiation, by contrast, penetrates significant distances into a vegetation canopy and interacts most strongly with structures (leaves, stems etc.) on scales comparable with the radiation's wavelength (a few centimetres to a few tens of centimetres). Thus, microwave instruments may be thought of as probing, in a very direct manner, the structural components of a plant canopy.

Owing to its penetrative power, significant amounts of radar (active instrument) energy can, in certain circumstances, pass completely through a crop canopy to reach the soil below (Figure 1.4). When this happens, the radar image will be influenced by the reflective properties of the soil.

Passive microwave radio sets (radiometers) receive emission from soil and vegetation layers (Figure 1.4). As distinct from active regimes, thermal emission is rigidly bound up with thermal regimes in soil layers and vegetation volumes.

Thus, in very broad terms, imaging vegetation with radar and radiometers raises the possibility of exploiting differences both in plant structure and in soil properties for the purposes of differentiating vegetation and crop types, thermal and moisture conditions or agricultural management practices.

The properties of vegetation and the soil which influence the amount of microwave power scattered back towards the radar, and emitted towards the radiometer, fall under the principal headings of geometric structure and dielectric constant, and (for the passive regime) of thermal features.

In structure we include the major plant constituents on scales greater than a few millimetres (leaves, stems, flowers, fruits/seed heads). Their sizes, shapes and orientation determine the interaction of individual isolated components with the microwaves. A flattened leaf, for example, scatters microwaves in a different directional pattern to a vertical stem. Below the plant canopy, the soil surface does not act as a simple mirror; rather the scattering from it is influenced by its roughness properties, especially on scales comparable to the radar wavelength. The moisture of the soil influences, through local chemistry, its dielectric constant. For different soil types, there is a different relationship between moisture content and dielectric constant, determined by the soil constituents.

It is very important to note that the contributions of these components (headings) to passive and active measurements differ essentially. Hence the useful information embedded in the passive and active signatures is also very different.

Understanding the interactions with individual vegetation and plant components or the soil is not straightforward. Electromagnetic modelling has at its disposal a range of techniques and approximations to describe the scattering by at least the more simple shapes which may be encountered in vegetation and crop canopies and by a soil surface with a known roughness profile. The real situation, however, is rather more complex than just microwaves scattering off isolated structures or the soil. The relative positions and spatial densities of plant constituents determine how they respond as an ensemble to the radar, through multiple scattering events or coherent interactions. Similarly, the soil cannot always be considered separately from the crop above it. Rather, a radar wave may be scattered by a leaf before being reflected off the ground and back to the radar. Furthermore, the relative importance of different interactions, whether single or multiple (some involving reflecting off the ground and others not) is believed to change significantly as a crop develops during the growing season.

Developments in the modelling of microwave scattering for agriculture have taken advantage of the increasing availability of computing power, to create ever more realistic and explicit models for the structures with which the radiation interacts. The models aim to explain or predict the brightness in radar and passive images of different crop types under changing environmental conditions or different stages of growth during a season. Early developments in the 1970–1980s were based around empirical or semi-empirical models for scattering at particular wavelengths. These did not attempt to represent crops as recognizable structures, but invoked tunable parametres and were limited in their applicability over the wide range of microwave and vegetation parametres which may be encountered (see Chapters 8 and 12).

Widespread recent work has placed greater emphasis on realistic descriptions of plant components, which can be related very directly to measurable parametres (the shapes of leaves, their thickness and moisture content, etc.). It is conceivable that significant improvements in the accuracy of predictions will entail even more explicit models of plants 'grown' in the computer, which include descriptions of the spatial interrelationships between leaves, stems and fruits.

One more factor should be pointed out. It is known that the scattered field carries the passive and active signatures of the target. Also, it is held that the microwave brightness and backscattering cross-section could be an effective discriminant for inverse target problems for non-fractal scatterers. However, any type of vegetation is a multifractal target (Mandelbrot, 1982). There is no doubt that the passive and scattered fields from vegetation carry the fractal signatures of targets, modelling experiments have confirmed these assumptions. The question is raised as to whether fractal characteristics may be experimentally determined from microwave signatures.

1.6 BASIC STATEMENTS OF WAVE ELECTROMAGNETIC THEORY

As we have already noted, the wave approach to electromagnetic phenomena plays a fundamental part in remote sensing. Below we shall outline the basic components and statements of Maxwell's electromagnetic theory which shall be used throughout the presentation of the material in this book.

The features of electromagnetic waves, the laws of their excitation and propagation are described by Maxwell's equations as being a fundamental law of nature and a direct consequence (from the viewpoint of modern geometry) of fundamental properties of space–time (Dubrovin *et al.*, 1986).

The equations were formulated by J. Maxwell in the 1860s on the basis of a generalization of the empirical laws of electric and magnetic phenomena and using phenomenological mechanistic concepts. The modern symmetric form of the equations was proposed by H. Hertz and O. Heaviside (Krug, 1936; Stratton, 1941; de Broglie, 1941; Alpert *et al.*, 1953).

Maxwell's equations associate the quantities characterizing the electromagnetic field with its sources, i.e. with the spatial distribution of electrical charges and currents. In a vacuum the electromagnetic field is characterized by the electric field strength $\mathbf{E}$ and the magnetic induction $\mathbf{B}$, vector quantities depending on spatial coordinates and time. These quantities determine the forces acting from the field side on charges and currents, whose distribution in space is specified by the volume density of charge ρ and electric current density **j**. To describe electromagnetic processes in a material medium the auxiliary vector quantities are introduced in addition to **E** and **B**. These quantities, which depend on the state and properties of a medium, are the electric displacement **D** and the magnetic field strength **H**. The second pair of vectors, **D** and **H**, are determined from the charges and currents in the field, as the lines of force originating from the charges and currents.

Maxwell's equations enable us to determine the basic characteristics of the field (**E**, **B**, **D** and **H**) at each point of space and at any time instant, if the sources of the field **j** and ρ are known as functions of position and time.

If electric charges and currents exist in any region of space, then their variation in time results in emission and propagation of electromagnetic waves in space. The character of electromagnetic wave propagation is essentially influenced by the medium they propagate in. In real media the waves can undergo refraction and dispersion; near inhomogeneities the diffraction and interference of waves are observed, as well as total internal reflection and other phenomena inherent in waves of any nature.

Maxwell's equations can be written both in the integral and the differential form. In the integral form the equations determine not the vectors at separate points, but some integral quantities depending on the distribution of these characteristics of the field. In electromagnetic wave propagation and remote sensing tasks the differential Maxwell's equations are most frequently used, which characterize the fields at each point in space:

$$\operatorname{rot} \bar{\mathbf{H}} = j + \frac{\partial \bar{\mathbf{D}}}{\partial t}, \tag{1.1a}$$

$$\operatorname{rot} \bar{\mathbf{E}} = -\frac{\partial \bar{\mathbf{B}}}{\partial t}, \tag{1.1b}$$

$$\operatorname{div} \bar{\mathbf{B}} = 0, \tag{1.1c}$$

$$\operatorname{div} \bar{\mathbf{D}} = \rho. \tag{1.1d}$$

The physical sense of the first equation consists in Maxwell's generalization of the Biot–Savart law of magnetic field excitation both by electric conductivity currents and displacement currents to the variable fields. The second equation represents the mathematical formulation of Faraday's electromagnetic induction law. The third equation reflects the experimental data on the absence of magnetic charges (the magnetic field is generated by electric currents only). And the fourth equation represents the generalization of the law of interaction of motionless electric currents – Coulomb's law.

However, in the form presented above, Maxwell's equations do not form a complete closed system allowing us to calculate the electromagnetic processes in the presence of material medium. They must be supplemented by the equations of state, or the constitutive equations of the medium, which determine the relationship between the properties of a medium and its state, namely:

$$\mathbf{D} = \mathbf{D}(\mathbf{E}), \mathbf{B} = \mathbf{B}(\mathbf{H}), \mathbf{j} = \mathbf{j}(\mathbf{E}). \tag{1.2}$$

The set of the equations of field (1.1) and the equations of state (1.2) just form the complete system of Maxwell's equations.

The constitutive equations of the medium are very complicated in the general case, because the fields **D**, **B** and **j** at a given point and at a given time instant may depend on the fields **E** and **H** at all points of a medium and at all previous time instants (the after-effect). However, for the majority of natural isotropic media that the remote sensing activity deals with, the constitutive equations of the medium have a simple linear form (which is proved by direct experiments):

$$\mathbf{D} = \varepsilon(x, y, z)\varepsilon_0\mathbf{E}, \mathbf{B} = \mu(x, y, z)\mu_0\mathbf{H}, \mathbf{j} = \sigma\mathbf{E}. \tag{1.3}$$

Here $\varepsilon(x, y, z)$ and $\mu(x, y, z)$ are the relative (and dimensionless) permittivity and relative permeability of a material medium, and $\sigma(x, y, z)$ is called the electrical conductivity of a medium. The latter relation in (1.3) represents the well-known Ohm's law for a conducting medium. In materials not obeying Ohm's law the relation between the field and current is more complicated.

Note one principal point now: in relations (1.3) ε_0 and μ_0 are dimensional constants, which depend on the chosen system of units and are called permittivity and permeability constants. Unlike the relative permittivity, which depends on the type of substance, on its physical and chemical composition, on the geometrical volume properties, on temperature, pressure and other parameters, the permittivity constant depends on the choice of a system of units only. A similar conclusion can also be drawn for the relation between the relative permeability and the permeability constant. In this case it should be noted, however, that the majority of natural media possess a relative permeability value equal to unity. For empty space the values of relative permittivity and permeability are equal to unity, which is a proven experimental fact. In the International System of Units (SI) we shall adhere to (see Appendix A), the values of permittivity and permeability constants are equal to:

$$\varepsilon_0 = (\mu_0 c_0^2)^{-1} = \frac{10^7}{4\pi c_0^2}\,\mathrm{F\,m^{-1}}, \tag{1.4}$$

$$\mu_0 = 4\pi \times 10^{-7}\,\mathrm{H\,m^{-1}}. \tag{1.5}$$

In the symmetric Gaussian system of units $\varepsilon_0 = \mu_0 = 1$ (this system of units is mainly used in theoretical works).

In the original phenomenological Maxwell's theory the macroscopic characteristics of the electromagnetic properties of a medium ε, μ, and σ should be found by the experimental method or calculated proceeding from particular concepts of the structure of substance. These concepts can be either purely phenomenological, or must be obtained from the Lorentz–Maxwell equations formulated for microscopic fields with subsequent averaging of microfields over space–time intervals and finding the particular form of the constitutive equations of the medium. For remote sensing activity the set of aforementioned procedures is very important, because their application closely relates to the problems of interpretation of the physical-chemical composition and geometrical volume properties of physical bodies, based on the data of measurement of their thermal radiation or, in other words, on the solution of reverse remote sensing problems (see Chapters 7, 8 and 13).

Maxwell's equations are valid at any point of space, where the fields do not undergo discontinuity. On the surface of discontinuities (two adjacent media) the fields can undergo discontinuities (jumps). In this case the basic equations (1.1) are supplemented by the boundary conditions, which are obtained as limiting transitions of the basic equations to the surface element:

$$[\mathbf{n} \cdot \mathbf{H}]_2 - [\mathbf{n} \cdot \mathbf{H}]_1 = \mathbf{j}_s, \tag{1.6a}$$

$$[\mathbf{n} \cdot \mathbf{E}]_2 - [\mathbf{n} \cdot \mathbf{E}]_1 = 0, \tag{1.6b}$$

$$[\mathbf{n} \cdot \mathbf{D}]_2 - [\mathbf{n} \cdot \mathbf{D}]_1 = \rho_s, \tag{1.6c}$$

$$[\mathbf{n} \cdot \mathbf{B}]_2 - [\mathbf{n} \cdot \mathbf{B}]_1 = 0. \tag{1.6d}$$

Here $\mathbf{j}$ and ρ_s are surface current and charge densities; the square and round brackets correspond to vector and scalar products of vectors, $\mathbf{n}$ is the unit vector of a normal to the interface surface and of the direction from the first medium to the second one ($1 \to 2$); the subscripts relate to different sides of the interface boundary. The physical sense of these conditions is as follows: the tangential component of the electric field (1.6b) and the normal component of the magnetic induction vector (1.6d) are continuous on the interface; the tangential component of the magnetic field (1.6a) and the normal component of the electric induction (1.6c) undergo discontinuity in the presence of currents and charges on the surface.

The spatial distribution of electromagnetic fields (the time-dependencies of electric and magnetic fields) which determine the type of wave (planar, spherical, cylindrical etc.), the type of polarization and other features of electromagnetic waves are specified, on the one hand, by the character of radiation source, and, on the other, by the properties of the medium in which the waves propagate. In the case of homogeneous and isotropic medium, far from the charges and currents, which generate the electromagnetic field properly (in the case of $\mathbf{j} = \rho = 0$), Maxwell's equations give rise to the familiar wave equations:

$$\Delta\mathbf{E} - \varepsilon_0\varepsilon\mu_0\mu\frac{\partial^2\mathbf{E}}{\partial t^2} = 0, \tag{1.7a}$$

$$\Delta\mathbf{H} - \varepsilon_0\varepsilon\mu_0\mu\frac{\partial^2\mathbf{H}}{\partial t^2} = 0. \tag{1.7b}$$

where Δ is the Laplace operator:

$$\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}.$$

Equations (1.7) express the fact that electromagnetic waves propagate in a medium, characterized by constants ε and μ, at velocity $c = c_0/\sqrt{\varepsilon\mu}$ and, in particular, at the speed of light in vacuum. This result represents one of the first major achievements of electromagnetic field theory. The general solution of this equation (which is presented here, for better physical clarity, for one component of the electric field E_x propagating in the direction z) has the form:

$$E_x = f\left(z - \frac{t}{c}\right) + g\left(z + \frac{t}{c}\right)$$

where f and g are arbitrary differentiable functions which describe the wave propagation in the positive and negative directions respectively of axis z. To determine the phase velocity of the wave we place the observer in the coordinate system, which moves together with the wave; then the value of the argument in the function will be fixed (constant). Taking the time derivative from the argument, we obtain the propagation velocity value presented above.

In linear media satisfying relations (1.3) and, in particular, in a vacuum, Maxwell's equations are linear, so that the wave superposition principle is valid for these media. And, in this sense, it is convenient to consider primarily the electromagnetic processes as being harmonic in time, namely, in the complex designation $e^{j\omega t}$. For harmonic (in time) processes equations (1.7) assume the form:

$$\Delta\mathbf{E} + \omega^2\varepsilon_0\varepsilon\mu_0\mu\mathbf{E} = 0, \tag{1.8a}$$

$$\Delta\mathbf{H} + \omega^2\varepsilon_0\varepsilon\mu_0\mu\mathbf{H} = 0. \tag{1.8b}$$

In this case the very important class of partial solutions of Maxwell's equations is found – the planar monochromatic waves, which are determined by the following relations:

$$E = E_0 \cos(\mathbf{k}\cdot\mathbf{r} - \omega t + \varphi), \tag{1.9a}$$

$$H = H_0 \cos(\mathbf{k}\cdot\mathbf{r} - \omega t + \varphi). \tag{1.9b}$$

Here E_0 and H_0 are the amplitudes of vectors of electric and magnetic fields, $\omega = 2\pi\nu$ is the circular frequency of oscillations, $\mathbf{r}$ is the radius-vector of the observation point, φ is the arbitrary phase shift and $\mathbf{k}$ is the wave vector, whose direction coincides with the direction of propagation of a running electromagnetic wave. The wave vector magnitude, the wave number, is associated with the circular frequency ω, phase velocity of wave v_p and its spatial period (wavelength λ) by the relation:

$$|\mathbf{k}| = \frac{2\pi}{\lambda} = \frac{\omega}{v_p}.$$

Note, that in optics and spectroscopy the wave number often designates the quantity reversal to the wavelength, $k = 1/\lambda$. Besides, it should be noted that the wave energy flux is directed along vector $\mathbf{k}$, generally speaking, in isotropic media only (for example, in a vacuum).

To determine the structure of electromagnetic waves it is necessary to address Maxwell's equations (with $\rho = 0$). It follows from relations (1.1c,d), that vectors **k**, **E** and **H** are associated by the following relations:

$$(\mathbf{k} \cdot \mathbf{E}) = 0, (\mathbf{k} \cdot \mathbf{H}) = 0, \tag{1.10}$$

The first two equations of (1.1a,b) for vectors **E** and **H** of a running planar wave form the following relation:

$$\mathbf{E} = -\frac{1}{|\mathbf{k}|}\sqrt{\frac{\mu_0\mu}{\varepsilon_0\varepsilon}}[\mathbf{k} \cdot \mathbf{H}]. \tag{1.11}$$

This implies, that the vector fields **E** and **H** are strictly transversal, i.e. both vectors are perpendicular to the propagation direction and, besides, both are perpendicular to each other and form the right orthogonal triplet of vectors. In a vacuum the values of fields themselves are equal between each other in magnitude, if they are expressed by means of the chosen system of units. In empty space the indicated mode of electromagnetic waves is the only one.

The relation between the amplitudes of electric and magnetic fields in a planar wave plays an important part when the wave propagation in various media is considered, and for these reasons this parameter was specifically called the intrinsic impedance of a medium (or the wave resistance of a medium) Z_0:

$$Z_0 = \frac{E_0}{H_0} = \sqrt{\frac{\mu\mu_0}{\varepsilon\varepsilon_0}}. \tag{1.12}$$

It follows from this relation, that the characteristic impedance depends only on the properties of a medium where the electromagnetic energy propagation takes place. For a vacuum ($\varepsilon = \mu = 1$) this is a universal constant, which in the SI system of units is equal to:

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 120\pi = 376.6\,\text{ohms}. \tag{1.13}$$

This circumstance is one of the entire spectrum of serious reasons, which result in important analogies between the wave propagation of electromagnetic energy and its propagation in transmission lines and, in particular, with the impedance approach (the method of impedances) (Krug, 1936; Stratton, 1941; Slater, 1942). Many problems of wave propagation of electromagnetic energy (and, in particular, the refraction of waves at media interfaces, and wave propagation in stratified media and in waveguides, as well as the emission of stratified media) can be successfully solved within the framework of the method of impedances. We shall repeatedly use this approach in various sections of this book.

Since the waves of any form can be presented as a sum of harmonic components, then for linear media, for which the wave superposition principle is valid, all emission, propagation and absorption problems are reduced to the solution of problems for harmonic electromagnetic waves. Certainly, this fully relates to remote sensing activity.

Now we consider the important question of energy transfer by the electromagnetic field, based on the ideas of the Russian physicist N. A. Umov. He introduced for the first time (1874) the general notion of energy flux in the continuous medium, as well as the notion of a physical field's energy flux vector, which is numerically equal to the energy transferred per unit time through the unit area perpendicular to the energy flux direction at a given point. The energy conservation law can be written in the following differential form (Stratton, 1941; Vinogradova *et al.*, 1979):

$$\frac{\partial W}{\partial t} + \mathrm{div}\mathbf{S} = 0, \qquad (1.14)$$

where W is the volume density of energy and $\mathbf{S}$ is the energy flux vector.

The physical sense of this expression consists in the fact, that the change of energy in some volume per unit time equals the energy flux through the surface confining this volume. To find the explicit form of quantities W and $\mathbf{S}$ for the electromagnetic field, we take advantage of the system of Maxwell's equations for the isotropic medium, in which $\sigma = 0$. Multiplying the first equation of (1.6a) by $\mathbf{E}$ and the second one by $\mathbf{H}$ and subtracting one from another, we obtain the following expression:

$$\frac{\partial}{\partial t}\frac{1}{2}(\mathbf{E}\cdot\mathbf{D} + \mathbf{H}\cdot\mathbf{B}) + \mathrm{div}\,[\mathbf{E}\cdot\mathbf{H}] = 0. \qquad (1.15)$$

Comparing (1.15) with (1.14), we can interpret the vector

$$\mathbf{S} = [\mathbf{E}\cdot\mathbf{H}], \qquad (1.16)$$

which is known as Poynting's vector, as the flux of the electromagnetic field energy, and the scalar quantity

$$W = \tfrac{1}{2}(\mathbf{E}\cdot\mathbf{D} + \mathbf{H}\cdot\mathbf{B}) \qquad (1.17)$$

as the density of volume energy of the electromagnetic field. Since in the isotropic medium vectors $\mathbf{E}$, $\mathbf{H}$ and $\mathbf{k}$ form a right-handed screw system, $\mathbf{S}$ coincides with the direction of propagation of electromagnetic waves. In anisotropic media (and also near conducting surfaces) $\mathbf{S}$ may not coincide with the wave propagation direction. Besides, as seen from (1.16–1.17), the electromagnetic field always possesses the energy, and the energy flux differs from zero only in the case where both electric and magnetic fields exist simultaneously, their vectors being not parallel to each other.

Since the vector fields are often used in the complex form, after rather simple transformations and with account taken of the fact that the mean value of a square of sine and cosine are equal to 1/2, we obtain the mean value of Poynting's vector $\bar{\mathbf{S}}$ over the period in the following form (Slater, 1942):

$$\bar{\mathbf{S}} = \tfrac{1}{2}\,\mathrm{Re}\,[\mathbf{E}\cdot\mathbf{H}^*]. \qquad (1.18)$$

Of interest also is the vector relation between the mean value of the flux density in a planar electromagnetic wave and the volume density of energy. Using relations (1.11), (1.17) and (1.18), we obtain, after some transformations,

$$\bar{\mathbf{S}} = \tfrac{1}{2}\,\mathrm{Re}\,[\mathbf{E}[\mathbf{k}\cdot\mathbf{E}^*]]\sqrt{\frac{\varepsilon\varepsilon_0}{\mu\mu_0}}\,\frac{1}{|\mathbf{k}|} = \mathbf{c}\cdot W, \tag{1.19}$$

where $|\mathbf{c}| = c_0/\sqrt{\varepsilon\mu}$, and the direction of transfer velocity coincides with the wave propagation direction (vector **k**). Also, remembering the expression for the impedance of a medium (1.12), we obtain the following expression for the mean value of Poynting's vector:

$$\bar{\mathbf{S}} = \tfrac{1}{2}\,\mathrm{Re}\,\frac{|\mathbf{E}|^2}{Z_0}. \tag{1.20}$$

Thus, Poynting's vector becomes a complete analogue of the current-by-voltage product (i.e. the power) in transmission lines and in circuits with concentrated elements (resistors, capacitors, inductors). And, hence, we arrive once again at the possibility of using (certainly, within a limited framework) the impedance approach to wave problems. So, for example, on an ideal conductor's surface the tangential component of the electric field is zero (see the boundary conditions) and, accordingly, the impedance at this point of the surface is also zero, which is equivalent to a shorted electrical circuit. On the ideal magnetic surface the tangential component of the magnetic field is zero and, accordingly, the impedance is equal to infinity, which is equivalent to a disconnected electrical circuit.

Now we consider one more aspect that is revealed in electromagnetic wave propagation in material media, that is, dispersion effects – the change in a medium's properties when an electromagnetic field of different frequencies is imposed on the medium. These effects play a primary part in microwave remote sensing problems, providing the possibility of obtaining information on physical and chemical volume properties of physical bodies based on their thermal radio emission data (see Chapters 7 and 8). (This, by the way, cannot be done based on the direct data from optical and IR ranges.)

The physical essence of these effects is as follows. As we have noted, the properties of a medium in Maxwell's electrodynamics should be taken into account in the constitutive equations of the medium, which for static ($\lambda \to \infty$) and slowly varying fields can be written in the linear form (1.3). In this case the values of **D**, **B** and **j** at some point of a medium and at some time instant are determined by the values of **E** and **H** at the same point and at the same time instant. However, if the external electromagnetic field varies more rapidly, then, owing to the inertia of internal motions and the particular spatial structure of a physical body (the medium), the values of **D**, **B** and **j** at the point of the medium under study will depend on the fields at other points of the medium and at other (previous) time instants. Although for gaseous, liquid and solid media the specific physical mechanisms, causing dispersion effects in media, very strongly differ from each other (some of them will be discussed in Chapter 8), nevertheless, the dispersion properties of media can be described in a unified and convenient manner using the notion of a complex relative permittivity (remember, that the relative permeability of the majority of natural media is equal to unity). For this purpose fields are considered which depend on time according to a sine law (the Fourier presentation), and complex quantities are used for describing these fields.

If only the frequency dispersion in a medium is taken into account, the constitutive equations of the medium (1.3) have the following form:

$$\mathbf{D}(\omega, r) = \varepsilon(\omega)\mathbf{E}(\omega, r); \mathbf{j}(\omega, r) = \sigma(\omega)\mathbf{E}(\omega, r). \tag{1.21}$$

Whereas in the non-dispersed medium the relative permittivity is a purely reactive parameter and the conductivity is purely active one, in the medium with dispersion this distinction is lost (see, for example, Alpert *et al.*, 1953). As the frequency of the external field approaches some natural frequencies in a medium, the distinction between the properties of dielectrics and conductors completely disappears (for fresh water this wavelength equals about 1 cm). So, the presence of an imaginary part of the relative permittivity in a medium is indistinguishable, from the macroscopic point of view, from the existence of conductivity – both of them cause release of the heat. Thus, for high-frequency monochromatic fields it is convenient to introduce, instead of relative permittivity and conductivity, the complex relative permittivity, which combines both these notions. The same characteristic includes the so-called dielectric losses, which are determined by that part of the external variable electric field that is transformed into heat at re-polarization of a dielectric. All motions of particles in a substance are related to dissipation of the part of energy imparted to particles by the electric field. Finally, this part of energy transfers into heat. If the small displacements of electrons and ions play a basic part in the polarization of a dielectric, then they can be considered as a set of harmonic oscillators, which undergo forced oscillations in the variable field. The losses of energy in such oscillations are maximal when the frequency of external effects is close to the frequency of the natural oscillations of the oscillators (the resonance). At exit from the resonance region the amplitudes of oscillations and the velocities of particles sharply decrease, and the dielectric (relaxation) losses become small. For the electronic polarization mechanism the maximum of losses falls on optical frequencies (about 10^{15} Hz). For polarization caused by displacement of ions, the maximum of dielectric losses displaces into the IR range (10^{12}–10^{13} Hz). The lower frequencies (in the radio range) correspond to the maximum of losses with orientation-type polarization of individual molecules (fresh water) or of clusters of molecules (salted water). In electrically non-homogeneous media, intersurface polarization can be observed. It is caused by the motion of free carriers of charges accumulating near interface boundaries between the regions with heightened specific resistance (intercrystal layers, microcracks, fluctuations of physical-chemical composition, etc.) The maxima of dielectric losses for such media are situated in a wide range of frequencies (10^3–10^9 Hz). Remarkable natural examples of such media are various modifications of sea ice and fresh-water ice, the moist soil with combined water electrolytes inside the ground volume, as well as the water–ice system and the snow cover at the phase transition instant.

To introduce the complex relative permittivity we consider the propagation of a planar electromagnetic wave in the isotropic homogeneous medium with a finite value of conductivity in the z direction of a right-handed-screw coordinate system (x, y, z). The electric field is directed along axis x and the magnetic field along axis y. Then Maxwell's equations will assume the following form of a wave equation for E_x:

$$\frac{\partial^2 E_x}{\partial z^2} - \varepsilon_0 \varepsilon \mu_0 \mu \frac{\partial^2 E_x}{\partial t^2} - \mu_0 \mu \sigma \frac{\partial E_x}{\partial t} = 0. \tag{1.22}$$

A similar equation can also be obtained for the magnetic field component H_y. The solution of equation (1.22) with respect to E_x can be written in the following compact complex form:

$$E_x = E_{x0} \exp\left(\mathrm{j}\omega t + \mathrm{j}\dot{\psi}\right), \tag{1.23}$$

where $\dot{\psi}$ is the total complex phase, $\dot{n}$ is the complex refractive index for the conducting medium:

$$\dot{\psi} = \frac{\omega}{c_0} \dot{n} z, \dot{n} = n + \mathrm{j}\chi. \tag{1.24}$$

Now we introduce the complex relative permittivity of a medium as:

$$\dot{\varepsilon} = \varepsilon_1 + \mathrm{j}\varepsilon_2 = (\dot{n})^2. \tag{1.25}$$

From this definition we can easily obtain the direct relation:

$$\operatorname{Re}\dot{\varepsilon} = \varepsilon_1 = n^2 - \chi^2, \operatorname{Im}\dot{\varepsilon} = \varepsilon_2 = 2n\chi, \tag{1.26}$$

and the opposite one:

$$n^2 = \frac{\varepsilon_1}{2}\left(1 + \sqrt{1 + \operatorname{tg}^2\delta}\right), \tag{1.27}$$

$$\chi^2 = \frac{\varepsilon_1}{2}\left(\sqrt{1 + \operatorname{tg}^2\delta} - 1\right). \tag{1.28}$$

Here the quantity $\operatorname{tg}\delta = \varepsilon_2/\varepsilon_1$ was called the tangent of the angle of losses in a medium.

In the presence of complicated relaxation mechanisms of polarization in a medium the introduced complex relative permittivity (and, accordingly, the complex refractive index) can be a rather complicated function of frequency (or of the wavelength). So far we have considered the simplest version of a non-dispersed (in dielectric properties) medium with a finite conductivity.

Substituting (1.23) into (1.22), we obtain the required solution in the form of two exponents, the first of which describes the total attenuation in a medium, and the argument in the second exponent determines the time delay of a signal, when it passes distance z in a medium:

$$\dot{E}_x = E_{x0} \exp\left(-\frac{\omega}{c_0}\chi z\right) \exp\left(\mathrm{j}\omega\left(t - \frac{n}{c_0}z\right)\right), \tag{1.29a}$$

$$\dot{H}_y = \frac{E_{x0}}{\dot{Z}_c} \exp\left(-\frac{\omega}{c_0}\chi z\right) \exp\left(\mathrm{j}\omega\left(t - \frac{n}{c_0}z\right)\right). \tag{1.29b}$$

The wave resistance of a medium in the case under consideration (of finite conductivity) is a complex quantity:

$$\dot{Z}_c = \sqrt{\frac{\mu\mu_0}{\dot{\varepsilon}\varepsilon_0}} = \sqrt{\frac{\mu\mu_0}{\varepsilon_0\varepsilon_1(1 + \mathrm{j}\,\mathrm{t}\,g\delta)}} = |\dot{Z}_c| \exp(\mathrm{j}\varphi), \tag{1.30}$$

where

$$|\dot{Z}_c| = \sqrt{\frac{\mu_0\mu\cos\delta}{\varepsilon_0\varepsilon}}, \varphi = \frac{\delta}{2}.$$

The presence of losses in a medium leads to a decrease in the magnitude of wave resistance of a medium, i.e. to an increase in the magnetic field value for a given electric field value. In addition, the phase shift appears between vectors **E** and **H**, the magnetic field vector being delayed in phase with respect to vector **E** by the angle equal to a half of the angle of losses ($\delta/2$). The phase velocity of a planar wave is $v_\mathrm{p} = c_0/n(\sigma)$, and the wavelength in a medium $\lambda = \lambda_0/n(\sigma)$ is less than its values in a loss-free medium with the same dielectric parameters, and at a given frequency they decrease with increasing conductivity (see (1.27)). Complex Poynting's vector contains both the real and imaginary part, which implies that there exist both active (transfer) and reactive heating fluxes of energy.

Proceeding from the solution obtained, important propagation parameters are introduced, namely, the coefficient of attenuation in a medium per unit length along the field $\gamma_\varepsilon = (\omega/c_0)\chi$ (neper/m), and the time delay of a signal $\Delta t = (n/c_0)z$. These propagation parameters play an important part in practical observation, since they can be measured experimentally to a high accuracy.

Taking into account relation (1.28), we obtain the important relationship between the value of specific coefficient of attenuation in a medium with its dielectric characteristics:

$$\gamma_E = \frac{2\pi}{\lambda_0}\sqrt{\frac{\varepsilon_1}{2}}\sqrt{\sqrt{1 + \mathrm{tg}^2\delta} - 1}. \tag{1.31}$$

For semi-transparent media with a small value of the tangent of the angle of losses, $\mathrm{tg}\delta \ll 1$, relation (1.31) is transformed into the well-known expression, which is often used for experimental estimations in various ranges of wavelengths (from optical to radiowaves):

$$\gamma_E = \frac{\pi}{\lambda_0}\sqrt{\varepsilon_1}\,\mathrm{tg}\delta. \tag{1.32}$$

Note here one important circumstance: the specific coefficient of attenuation in a medium depends both on the real part of the relative permittivity, and on the imaginary part.

Since the energy flux through the surface unit, transferred by the electromagnetic wave (Poynting's vector) is proportional to the square of the amplitude of the electric field strength (1.20) and, in other words, to the radiation intensity, then, on the basis of (1.20) and (1.29), the specific attenuation in a medium for the radiation intensity is equal: $\gamma_p = 2\gamma_E$.

In experimental practice, for convenient coordination of the total attenuation in a medium, expressed in terms of the first component in relation (1.29), with specific coefficient of attenuation in a medium, an approach is used that determines the characteristics of attenuation in a medium in the logarithmic scale. The physical sense of this approach is fairly obvious. The expression for intensity of radiation, past the distance z in a medium, can be presented as

$$|S(z)| = |S(0)| \exp(-\gamma_p z).$$

Taking the logarithm from both parts of the equality, we obtain the expression in the logarithmic form for the total attenuation in a medium occurring at the distance z. This expression, expressed in decibels (dB), is as follows:

$$\gamma(\text{dB}) = 10 \lg |S(0)|/|S(z)| = 20 \lg |E(0)|/|E(z)| = 4.3\gamma_p z, \tag{1.33}$$

and the expression for the total attenuation in a medium per unit length is written as:

$$\gamma(\text{dB/m}) = 4.3\gamma_p\,(\text{neper/m}) = 8.69\gamma_E\,(\text{neper/m}). \tag{1.34}$$

It can easily be seen from (1.33) that the total attenuation in a medium of 1 dB corresponds to a 1.26-fold change of radiation intensity (a 1.12-fold change of the field), 3 dB corresponds to a 2-fold change of intensity (a 1.41-fold change of the field), 10 dB corresponds to a 10-fold change of intensity (a 3.16-fold change of the field), and 20 dB corresponds to a 100-fold change of intensity (a 10-fold change of the field), etc. When the radiation passes through various media with different attenuations, its total attenuation is the sum of individual attenuations expressed in the logarithmic scale. This circumstance is very often used, both in observational experiments and in technological applications.

Consider now another important characteristic whose value for various natural media will be fairly frequently used in remote sensing data analysis. We mean the distance (depth), passing which the electromagnetic field weakens e times in a medium and, accordingly, the information on the physical properties of a substance can be obtained from this layer based on the thermal radiation data. This characteristic is called the depth of field penetration into the medium (the skin-layer), and it is determined as a quantity the reciprocal of the coefficient of attenuation:

$$L_S = \frac{1}{\gamma_E} = \frac{\lambda_0}{2\pi} \left[\frac{\varepsilon_1}{2} \left(\sqrt{1 + \text{tg}^2 \delta} - 1 \right) \right]^{-1/2}. \tag{1.35}$$

So, as we have noted, Maxwell's wave equations describe an extensive area of physical phenomena. These equations underlie electrical engineering and radio engineering and play a fundamental part in the development of such topical directions of modern physics and geophysics as remote sensing of the Earth, planets and interplanetary space, plasma physics, magnetic hydrodynamics, nonlinear optics, astrophysics and other disciplines. Maxwell's equations are directly inapplicable only at high frequencies (in the X-ray and gamma ranges), where purely quantum effects become essential. However, in a number of problems, quantum effects can also be essential in lower-frequency bands – optical and IR – and even in the microwave band (the thermal emission of gases). The solution of such problems necessitate the use of quantum concepts, such as the flux of quasi-particles – photons (see Chapter 11).

The complete solution of Maxwell's equations is fairly labour-intensive and cannot be obtained in the general form. However, depending on the relation between the wavelength (λ) of the electromagnetic field used in science experiments or in technological applications, and the geometric size of physical objects (L), a number of important approximations can be obtained. So, for $\lambda \gg L$ the quasi-stationary approximation is used. It is characterized by the fact that electromagnetic processes can be concentrated at separate components (resistors, capacitors, inductors) and that the method of complex impedance (or, in other words, complex Kirchhoff's rules for branched electrical circuits (Krug, 1936)) is used in calculations. This approach has been successfully used in both electrical engineering and radio engineering applications, as well as in physical experiments and in radio communication and TV broadcasting practice. For the reverse relation $\lambda \ll L$ the approximation approach is called the geometrical optics approximation; it uses beam concepts for electromagnetic radiation propagation, including such features as the rectilinearity of light beams, geometrical shadow and the reflection and refraction of light. All these features are well known from daily life. Owing to the achievements of calculus, the methods for the calculation of electromagnetic processes in the geometrical optics approximation have reached high perfection. For the relation $\lambda \leq L$ the approximation approach is called the theory of long lines, which is characterized by the use of the ideology of dispersed (distributed in a line) capacitive and inductive parameters and the use of the impedance approach in calculations. The most complicated case is the area, where the relation is $\lambda \approx L$, and, thus, the use of complete diffraction approaches and complete solutions of Maxwell's equations is necessary. Till now a great diversity of modifications of the approaches mentioned has been obtained, so that it is actually impossible (and, apparently, inexpedient) to give any completed form of approaches with their frequency – spatial differentiation. There exist a lot of interdependent approaches; so, the geometrical and wave approaches are formally combined in the geometrical diffraction theory, in which, along with rectilinear beams, the existence of various types of diffracted (curved) beams is postulated. At present, the solution of virtually any physical problem of the interaction of electromagnetic radiation with physical bodies can be obtained in various approximations (or in combinations of approximations), and the major problem in interpreting the solutions is understanding the adequacy of the accepted approximation to the given physical problem.

As far as the electromagnetic field of thermal radiation is concerned, we have already paid attention to the fact that this wave process has a random (chaotic) character, both during its development in time and during its propagation in space. For these reasons, the determination and measurement of the energy flux (in essence, the intensity of the flux) in such random processes and the separation of determinate components from data obtained (which just bear the information content in remote investigations) represent a special problem which will be considered in detail in Chapters 2 and 3 – and results of solving this problem will be used throughout the book.