You do not really understand something unless you can explain it to your grandmother.

The important thing is not to stop questioning.

A theory is something nobody believes, except the person who made it. An experiment is something everybody believes, except the person who made it.

Albert Einstein
Nobel Prize Laureate (Physics)
Preface

When the first volume of the *Ultra-Wideband, Short Pulse Electromagnetics* book series was published in 1993, the terms ultra-wideband (UWB) and short-pulse (SP) were acronyms for challenging technologies. In 1992, the DARPA Ultra-wideband Radar Review Panel defined UWB by the need for special techniques to overcome challenging problems facing conventional systems and technologies when attempting to operate over a broad range of frequencies.

Since then notable progress in UWB and SP technologies has been achieved. As a result, wideband systems are now being used for an increasingly wide variety of applications. UWB radar systems are used for collision avoidance, concealed object detection, mine detection, and oil pipeline inspections. In the communication area, the need for increasing bandwidth boosted the development of UWB communication systems such as the impulse radio. Many high-power electromagnetic (HPEM) environments are generated employing short-pulse technology. With the advent of HPEM sources capable of interrupting and/or damaging sensitive electronics, there has been an increasing interest in protecting critical infrastructure and systems. Recently, the literature has reported the usage of SP techniques in microwave tomography systems for biomedical applications.

Through the whole development of UWB and SP technologies, *Ultra-Wideband, Short Pulse Electromagnetics* books provided new and state-of-the-art information on the tendencies and current achievements in UWB- and SP-related technologies, analyzing methodologies, theoretical models, and time domain data processing. The objectives of the *Ultra-Wideband, Short Pulse Electromagnetics* book series are as follows:

- To focus on advanced technologies for the generation, radiation, and detection of UWB and SP signals
- To report on developments in supporting mathematical and numerical methods, which are capable of analyzing the propagation of UWB and SP signals, as well as their scattering from and coupling to targets and media of interest
- To describe current and potential future applications of the UWB and SP technology

"*Ultra-Wideband, Short Pulse Electromagnetics 9*" (UWB SP 9) presents recent developments in the areas of UWB and SP technology, components, application, numerical analysis, modeling, and electromagnetic theory. The editorial board selected the initial set of contributions from presentations at the UWB-SP 9 conference that was held in conjunction with EUROEM 2008 in Lausanne, Switzerland. The editorial board’s goal was to cover the complete range of aforementioned topics with articles of deep technical content and high scientific quality. Wherever we felt that something was missing, we invited selected authors to contribute additional articles to complete the overall picture. Therefore we hope that this book contains something of interest for every scientist and engineer working in the area of UWB and SP electromagnetics.
Following the tradition in the odd-numbered volumes of *Ultra-Wideband, Short Pulse Electromagnetics* (UWB SP) books, which are related to EUROEM conferences, the cover displays the picture of a renowned scientist. This ninth volume honors Albert Einstein, who is well known for his various achievements in theoretical physics. From the view point of the editorial board, Einstein is eminently well qualified for the cover picture from multiple aspects. First, Einstein started his professional life at the Swiss Patent Office in Bern and later in life was professor at the ETH Zurich. He introduced the theory of special relativity in 1905 in a paper entitled “The electrodynamics of moving bodies.” The editorial board liked the idea of honoring this contribution to physics, as well as showing the link to electromagnetics. Second, there is a special relation among Maxwell, Hertz, and Einstein. A cover picture showing Einstein completes the series started with the *UWB SP 5* book. The cover of the *UWP SP 5* book shows a picture of James Clerk Maxwell, the Scottish theoretical physicist and mathematician, who developed the classical electromagnetic theory. The well known set of Maxwell’s equations is the physical foundation of the research presented in the *UWB SP* books. The next odd-numbered volume, *UWB SP 7*, showed a picture of Heinrich Rudolf Herz, a German physicist, who was the first scientist to demonstrate electromagnetic waves by building an apparatus that produced radio waves. Therefore the cover of the *UWB SP 7* book continued the series by featuring the scientist who clarified Maxwell’s theory. The next, and for the moment final, improvement of Maxwell’s theory was Einstein’s development into the special theory of relativity. Einstein noted that the special theory of relativity owes its origins to Maxwell’s equations of electromagnetic fields.

Finally, I would like to express my gratitude to all persons who contributed to this book. In particular, I thank the authors for writing articles of deep technical content and high scientific quality, and the members of the editorial board, Farhad Rachidi, D.V. Giri, and Armin Kaelin, for reviewing all articles and numerous discussions, which helped improve the quality of this book.

Last but not least, I thank my family, particularly my wife Martina, for her great patience and for granting me the time to work on this book.

Bonn, Germany

Frank Sabath
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Part I

Electromagnetic Theory and Modeling
Modeling of Electromagnetic Wave Propagation in Flows of Turbulent Plasma Inhomogeneities

V. Spitsyn and I. Fedotov

Abstract The subjects of this chapter are analytical and numerical models of electromagnetic wave propagation in flows of a slightly ionized plasma. The different shapes of a flow (cone, paraboloid, and a surface created by rotation of fourth-order curves) are addressed in this chapter. The indicatrices of turbulence reradiation (isotropic, Lambert, and quasi-mirror types) are considered. Calculations are used to determine the angular and frequency spectra of singly and multiply scattered signals. The calculated frequency spectrum of each scattering signal is compared with well-known experimental data from radio sounding of an exhaust plume of a spacecraft.

Keywords Wave propagation · Radio wave · Scattering · Turbulent plasma · Spacecraft

1 Introduction

Analytical and numerical models of interactions of electromagnetic waves with moving turbulent inhomogeneities in the flows of slightly ionized plasma are considered. The authors assume that turbulent inhomogeneities in a flow of a slightly ionized plasma correspond to statistically independent discrete scatterers [1–3].

Single and multiple scatterings of electromagnetic waves from turbulent plasma inhomogeneities near a body-of-rotation surface are investigated. Radio wave scattering from a cone, a paraboloid, and a surface created by rotating a fourth-order curve is analyzed under the assumption that the size of a body of rotation is on the order of the ratio of the wavelength of the incident field over the average size of the turbulent inhomogeneities.

Section 2 is devoted to radio wave scattering from the outer surface of the expanding turbulent flow of a plasma. The results of investigations of multiple radio wave scattering from the inner surface of a turbulent body of rotation are presented in Section 3. Conclusions are given in Section 4.

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2 Radio Wave Scattering from the Outer Surface of Expanding Turbulent Flow of a Plasma

Electromagnetic plane wave scattering from turbulent plasma inhomogeneities near the surface of a body of rotation in the form of a cone and a paraboloid is considered in this section. The geometry of the task is presented in Fig. 1. The radio wave frequency $f$ is governed by the inequality $f \leq [N_i/N_0i]^{1/2}f_p$, where $f_p$ is the plasma frequency and $N_0i$ and $N_i$ are the equilibrium and disturbed ionic concentrations, respectively, at the height of a spacecraft’s motion.

It is supposed that the turbulent inhomogeneities are distributed evenly on the surface of a body of rotation. Further, the inhomogeneities are assumed to have an equally directed velocity oriented along the generatrix of the body and a stochastic isotropic velocity distributed by the normal law. Three types of over-radiation diagrams of the turbulent inhomogeneities are studied: isotropic, Lambert, and quasi-mirror. Radiation transport theory is applied for solving this problem [4].

The solving of the task is implemented in a spherical coordinate system ($\theta, \phi, r$) that is shown in Fig. 2. The origin of the coordination system is located at the tip of the body of rotation. The polar angle $\theta$ is measured from the rotation axis of the body (positive $z$-axis). The azimuthal angle $\phi$ is calculated in a plane perpendicular to the rotation axis ($z$-axis) and with regard to the direction of propagation of the incident field $\vec{e}_i$. The index $i$ corresponds to the coordinates of the surface of the body of rotation, and the indices $i$ and $s$ correspond to the parameters of the incident and scattered waves, respectively. The angle between the incident and scattered fields is $\phi_s$, and $\vec{e}_s$ is the unit vector in the direction of propagation of the scattered wave.

The diagram of reradiation of the turbulent inhomogeneities does not depend on the direction of propagation of the incident wave $\vec{e}_i$ and can be represented by

![Fig. 1 Geometry for radio sounding on the outer surface of a turbulent plasma formation](image1)

![Fig. 2 Coordinate system for calculating radio wave scattering from a turbulent body of rotation](image2)
\[ P(\vec{e}_s) = A_j (\vec{e}_s \vec{n})^j, \]

where \( \vec{n} \) is a normal to the surface, \( A_j \) is a coefficient determined from the condition of normalization \( \int P(\vec{e}_s) \, d\Omega = 1 \), and \( d\Omega \) is an element of the spatial angle in which the scattering occurred. The normalization implies that \( A_j = (j + 1)/2\pi \). The cases \( j = 0 \) and \( j = 1 \) correspond to the isotropic diagram of turbulence reradiation and the Lambert diagram, respectively.

The diagram of reradiation of quasi-mirror type, considering the direction of propagation of the incident wave \( \vec{e}_i \), can be given as

\[ P(\vec{e}_s) = A \left( \Delta e_m^2 - \Delta e^2 \right), \]

where

\[ \Delta \vec{e} = \vec{e}_s - \vec{e}_s0, \quad \vec{e}_s0 = \vec{e}_i - 2\vec{n} (\vec{n} \vec{e}_i). \]

In this case, the diagram of reradiation is asymmetrical, and most of the energy of the scattered signal is concentrated in the vicinity of vector \( e_s0 \), which corresponds to the direction of a mirror reflection of the wave from the surface. The formulas for \( \Delta e^2 \), \( \Delta e_m^2 \), and \( A \) in (1) are

\[ \Delta e^2 = 2 (1 - \vec{e}_i \vec{e}_s + 2 (\vec{n} \vec{e}_i) (\vec{n} \vec{e}_s)), \]

\[ \Delta e_m^2 = 2 \left( 1 + \left( 1 - (\vec{n} \vec{e}_i)^2 \right)^{1/2} \right). \]

\[ A = 1 \sqrt{4\pi \left( \sqrt{1 - (\vec{n} \vec{e}_i)^2} - \vec{n} \vec{e}_i \right)}. \]

The formula for the spectral density of the energy scattered from a turbulent plasma body of rotation is [1]

\[ dI_s/I_0 = -(\vec{e}_i \vec{n}) P(\vec{e}_s) \, dS \, d\Omega/2\pi, \]

where \( dI_s \) is the energy scattered in a fixed direction, \( I_0 \) is the energy of the incident wave, and \( dS \) is an areal element of the scattering surface.

The magnitude of the non-dimensional Doppler shift of frequency is defined by

\[ f_s = (\Delta fc) / (f_0 V_u) = (\vec{e}_s - \vec{e}_i) (\vec{e}_u (1 + \delta V/V_u) - \vec{e}_i V_0/V_u), \]

where \( c \) is the propagation speed of an electromagnetic wave in the plasma, \( f_0 \) is the frequency of the incident wave, \( V_0 \) is the speed of the spacecraft, \( V_u \) is the directed speed, and \( \delta V \) is the speed of the stochastic motion of the turbulences along the generatrix.

In spherical coordinates, formula (3) has the form

\[ f_s = (\sin \theta_s \cos \varphi_s - \sin \theta_i \sin \theta_s \cos \varphi_u + \sin \theta_s \sin \varphi_s \sin \theta_s \sin \varphi_u + \cos \theta_s \cos \theta_i \sin \theta_s \sin \varphi_u + \cos \theta_s \cos \varphi_i \cos \theta_i - \cos \theta_i V_0/V_u), \]
Solving (4) relative to the azimuthal angle $\varphi_u$ and substituting the received dependence $\varphi_u(f_\ast)$ into (2) yields an expression for the frequency spectrum of the wave scattered from the plasma formation

$$S_n(f_\ast) = \frac{dI_{\ast} 4\pi}{I_0 z_m^2 \cos \theta u} = \frac{\tan \theta u}{\cos \theta u} P(\bar{e}_s) \frac{\mathrm{d}\varphi_u(f_\ast)}{\mathrm{d}f_\ast},$$

(5)

where $S_n(f_\ast)$ is the normalized magnitude of the spectral density of energy scattered in the unit spatial angle and $z_m$ is the size of a body of rotation along the $z$-axis.

In the case of backscattering, (4) and (5) lead to the frequency spectrum

$$S(f_\ast) = D \tan \theta u (\bar{e}_i \bar{n}) P(\bar{e}_s) \left( 1 - (f_\ast D + B)^2 \right)^{-1/2},$$

(6)

where

$$D = -\frac{1}{2 (1 + \delta V/V_u) \sin \theta_i \sin \theta u},$$

$$B = \frac{V_0}{V_u \sin \theta_i \tan \theta_i (1 + \delta V/V_u)} - \frac{1}{\tan \theta_i \tan \theta u},$$

$$\bar{e}_i \bar{n} = \sin \theta_i \cos \theta u (Df_\ast + B) - \cos \theta_i \sin \theta u.$$

The results of calculating the frequency spectrum of a scattered signal from a cone of turbulent flow are illustrated in Fig. 3 for several angles of incidence. The solid curves in Fig. 3 are calculated according to formula (6) with $V_0/V_u = 2$, $\theta_0 = 26.6^\circ$, and $\delta V/V_u = 0$. The histograms correspond to frequency spectrum averaging over the frequency interval. The results of these calculations show that for inverse scattering the frequency spectrum of a signal is characterized by monotonically increasing energy with an increasing Doppler shift.

### 3 Multiple Radio Wave Scattering from the Inner Surface of a Turbulent Body of Rotation

In this section, suppose that the plane electromagnetic wave is reduced along the negative $z$ direction (Fig. 4). Turbulent inhomogeneities are chaotically disposed on the surface of a body of rotation (cone, paraboloid, surface created by rotation of the fourth-order curve). These inhomogeneities have velocities that are equally distributed between the directed velocity $V_u$, oriented along the generatrix of the body of rotation, and the stochastic isotropic velocity $\delta V$, distributed according to the normal law. Recall that the size of a body of rotation is assumed to be on the order of the ratio of the wavelength of the incident field over the average size of the turbulent inhomogeneities.

In this case, the field of the scattered wave is the result of multiple wave reflections from the dynamic rough surface. Because of the presence of chaotically disposed moving turbulent inhomogeneities on the surface of a body of rotation, the wave phases after reflections from the surface are stochastic. The energy of the scattered signal is proportional to the number of photons scattered in the defined element of a spatial angle.
The method of Monte Carlo is applied for determining the energy. The incident electromagnetic wave is simulated by non-commuted photons, uniformly distributed in the plane of the wave front [1]. Figure 5 displays the frequency spectrum of a signal that is incoherently scattered from the dynamic rough surface of a body of rotation for different ranges of the polar angle $\theta$, in the form of an isotropic diagram of reradiation of the turbulent inhomogeneities. The magnitude
The frequency spectrum of signal scattered from the inner surface of the turbulent plasma body of rotation for different ranges of $\theta$

$f_*= (c\Delta f_\lambda f_0 V_u)$ is calculated on the horizontal axis. The energy of the signal, normalized by maximum spectral energy, is calculated on the vertical axis of every spectral frame.

The first, second, and third columns of frequency spectra correspond to scattering from the cone, the paraboloid of rotation, and the surface created by rotating a fourth-order curve, respectively. In each column, the frequency spectra differ by the value of the polar angle $\theta$. The bottom frames
represent the integral frequency spectrum for all photons emanating from plasma formation in the angular range of $0 < \theta < \pi / 2$.

As the reader can observe, the spectra typically have two components for small $\theta$ and the integrated spectrum: a discrete contribution at $f^* = 0$ that is caused by the mirror reflection of the radio wave from the plasma surface and a continuous component that is the aggregate of multiple scattering from the moving inhomogeneities. On the basis of these calculations, we arrive at the next conclusion: increasing the order of the equation describing the scattering surface leads to increasing the energy of a spectral component with a negative frequency shift and to focusing the signal energy near the axis of a body of rotation.

As Fig. 6 illustrates, the calculated frequency spectra of a scattered signal (dashed and dotted curves) and the experimental data (solid curve) from radio sounding of an exhaust plume of a launched rocket [5] are in good agreement. The dashed curve corresponds to the paraboloidal surface, and the dotted curve corresponds to the surface created by rotating the fourth-order curve. On the basis of this comparison, the authors conclude that indeed multiple scattering of a radio wave from the inner surface of a turbulent plasma body of rotation was realized. The form of a scattering surface was enclosed between the paraboloid and the surface created by rotation of the fourth-order curve.

![Fig. 6](image)

**4 Conclusions**

The results of this analysis demonstrate that, for backward radio sounding of the outer surface of a turbulent body of rotation, the frequency spectra of such scattered signals are characterized by a monotonic increase of energy with the growth of the Doppler frequency shift. In addition, two other phenomena were observed when the order of the equation governing the surface of the body is increased: (1) the energy of a spectral component with a negative frequency shift is increased and (2) the scattered energy from the inner surface of the turbulent plasma formation is focused along the axis of the body of rotation.

Comparisons of calculations and known experimental data from radio sounding of an exhaust plume of a rocket during the launch phase show good agreement. Thus the authors conclude that in the experiment the scattered field is formed as a result of multiple scattering from the inner surface of a turbulent body of rotation.
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References

Ultra-wideband Propagation Loss Around a Human Body in Various Surrounding Environments

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Abstract Ultra-wideband (UWB) technologies have been anticipated for use in wireless body area networks (WBAN) because of their low power consumption and anti-multipath capabilities. This chapter presents the UWB (3.1–10.6 GHz) propagation loss in WBAN scenarios between on-body antennas in three different surrounding environments. The measurements were performed in a 3-m radio anechoic chamber, a classroom, and a small room. The propagation paths were roughly divided into line-of-sight (LOS) and non-LOS (NLOS) ones. Small rooms, particularly NLOS, yielded higher reception power than larger rooms. This was attributed to the ample multipath from the nearby floor, walls, and ceiling. The UWB maximum propagation losses in three surrounding environments were smaller than ones of CW (6.85 GHz). This is because nulls caused by interference were cancelled out by the ultra-wide bandwidth. The propagation losses of low-band (3.4–4.8 GHz) and high-band (7.25–10.25 GHz) UWB were also evaluated. In WBAN scenarios, the low-band yielded lower propagation loss than the high-band and approximately the same loss as the full-band UWB (3.1–10.6 GHz).

Keywords Ultra-wideband (UWB) · Wireless body area networks · Radio propagation · Propagation loss · Multipath propagation

1 Introduction

Wireless body area networks (WBAN) have been discussed for medical and non-medical applications [1]. For medical applications, wireless electroencephalography (EEG), electrocardiography (ECG), electromyography (EMG), and other health-care monitoring are proposed applications. Ultra-wideband (UWB) technologies were anticipated for use in WBAN because of their low power consumption and anti-multipath capabilities. In the last few years, researchers investigated UWB indoor and outdoor radio propagation modeling and characterization [2, 3]. A number of measurements were also carried out to characterize on-body UWB propagation in the WBAN scenarios [4]. However, previous WBAN studies treated mainly the cases when propagation was measured in either a radio anechoic chamber or a particular room [5–7]. It is necessary to evaluate the variation of propagation losses in various surrounding environments from the viewpoint of WBAN device design.

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