IMAGING AND DETECTION OF OBJECTS IN RANDOM MEDIA AND NEAR ROUGH SURFACES

Akira ISHIMARU and Yasuo KUGA
University of Washington
Department of Electrical Engineering
Box 352500
Seattle, WA 98195-2500, USA
Email: ishimaru@ee.washington.edu

1. Introduction

Imaging and detection of objects are important current problems with applications to optical and ultrasound imaging in biological media, detection of landmines and other objects in geophysical media, multiple scattering effects on wireless communications, and detection of targets near land and sea. One of the important questions is the multiple scattering effects on imaging. When the object is in or near the random medium, the scattered wave undergoes random multiple scattering in the medium, and the resolution of the image is seriously affected by clutter. Therefore, the important question is how to reduce the clutter effects and improve the resolution.

There are several techniques proposed to alleviate these effects. In this paper, we will discuss several techniques including short pulse [1,2], correlation techniques [3,4], confocal SAR imaging [5-8], and objects near rough surfaces [9].

2. General Description of the Problem

Consider a transmitter illuminating an object in or near a random medium. The transmitter may be a single dipole or an array of antennas, or an aperture antenna or an optical source or transducer. The wave radiated from the transmitter propagates through the random medium and in general consists of the coherent and the incoherent waves. The description of these waves in a random medium is known in some cases, but there are several important cases, for which the descriptions are not adequate. These waves are then incident upon the object. Interaction of the waves and the object in a random medium takes place [10]. The wave scattered by the object is then propagated through the random medium reaching the receiver. If the receiver and the transmitter are the same, the backscattering enhancement takes place.

The coherent wave and the incoherent wave satisfy Dyson's and Bethe-Salpeter equations, respectively. The interaction with the object is described by the stochastic integral equation which may be solved iteratively or using the perturbation technique. For backscattering, the wave propagates through the same medium twice, and therefore, the fourth order moment needs to be evaluated.

The image resolution in the range is related to the pulse width or the frequency band, and therefore, the dispersion due to the random medium becomes an important factor. In addition to the medium dispersion, there are dispersions due to multiple scattering which is expressed by the coherence bandwidth of wave propagation through the random medium. The velocity of wave propagation in a random medium is given by the group velocity of the coherent wave which is given in terms of the spectrum of the random medium or the particle scattering characteristics. For UWB (ultra-wideband), the group velocity at carrier frequency is no longer applicable, and the two-frequency correlation needs to be considered. The image resolution in the lateral direction is related to the angular spectrum of the incoherent wave which can be described by the specific intensity or the Wigner distribution. For discrete scatters, they satisfy the radiative transfer equations or the Bethe-Salpeter equations. In addition to intensities, we consider correlation functions of the scattered waves both in space and time.

3. Pulse Scattering [1] [2]

When a pulse wave is propagated through a random medium, the propagation and the scattering is given by a two-frequency mutual coherence function which in turn satisfies the two-frequency radiative transfer equation. If the optical depth is less than one, the first-order solution gives a good approximate solution. If the optical depth is large and the albedo is close to one, the diffusion approximation can be used. We have conducted a study on a focused beam in a random medium, showing the broadening of the spot size due to multiple scattering. If a plane wave is incident on a plane-parallel medium, numerical techniques are available, and we have conducted a study using the Chebyshev spectral method to reduce computer time which is necessary for pulse scattering. Polarization characteristics can be obtained by two-frequency vector radiative transfer solutions.

If the medium is dispersive, the two-frequency radiative transfer equation includes the group velocity. However, if the medium is close to resonance, the wave may be localized and considerable reduction of the velocity of propagation takes place. For backscattered pulse, the short-time behavior is dominated by first-order while the long-time behavior exhibits the diffusion characteristics. There are several diffusion approximations. Even though all approximations have proper behaviors for long-time in a mostly scattering medium, the short-time behaviors are quite different and the behaviors between the short and long times are difficult to evaluate. This is the transition between the first order and the diffusion regions.

In medical optics, the diffusion approximations are extensively used. Short pulse and temporal resolution are used to image an object, but in a scattering medium, pulse dispersion is significant, and the resolution is seriously affected by scattering. The photon density wave is equivalent to the two-frequency specific intensity and has a wave characteristic with amplitude and phase. It is interesting to note that the intensity obeys an equation similar to the wave equation. However, the photon density wave has significant attenuation, and the attenuation distance is comparable to a wavelength of the density wave, and thus, the high resolution with small wavelength is accompanied by the high attenuation.

Backscattering from a random medium is important in remote sensing. In particular, the backscattered pulse can be used to identify the surface surrounding the scattering medium, and it is important to relate the pulse shape, the moments, or the peak to the actual surface as in the case of the determination of the earth surface by satellites.

4. Correlation Techniques and Confocal SAR Imaging [3] – [7]

If the correlation function of the scattered wave is observed rather than amplitude, phase, and intensity, it has additional information on the object. The clutter and the scattered wave from a deterministic object have different correlation characteristics and this difference can be used to differentiate the object from the clutter. In addition, the confocal SAR imaging technique can be used to enhance the resolution of the image. This is also related to the memory effect and the backscattering enhancement.

The memory effect refers to the phenomena that even under multiple scattering, the scattered wave "remembers" the direction of the incident wave and gives strong correlation if the phase difference along the surface of the random medium is matched. The backscattering enhancement and the memory effects are separately discovered, but it can be shown that the backscattering enhancement is a part of the memory effect phenomena in which the incident and the scattered waves are observed in the same direction.

If SAR observation is made through the ionosphere at low microwave frequencies, considerable dispersion takes place, and the pulse broadening, the pulse delay, and resolution are affected by TEC (Total Electron Content). This work is important for FOPEN (Foliage

Penetration Radar) which requires P-band SAR to observe the earth surface through vegetation, since high frequency microwave can not penetrate through foliage, and therefore, SAR can not reach the earth surface. The wave propagated through the ionosphere experiences fluctuations due to the ionospheric turbulence, and the coherent length at the antennas can be comparable or smaller than the equivalent aperture size of SAR. At lower frequencies, the wave fluctuations due to the ionospheric turbulence are increased as the inverse fourth power of the frequency, and therefore at P-band, the coherence length is reduced to less than the aperture size and the cross-range resolution is seriously affected. In addition, Faraday rotations become significant at P-band.

Since the wave propagates through the ionosphere twice in the forward and backward directions, the two-frequency mutual coherence function is expressed by the fourth order moments. It is shown that considerable degradation in the cross-range resolution occurs while the range resolution is affected by the ionospheric dispersion.

5. Objects In Random Media and Near Rough Surfaces [9] [10]

Consider an object located near a rough finitely conducting surface illuminated by a transmitter located close to the surface. For TM (vertical) polarization, the problem of a wave propagating over the surface is similar to the Sommerfeld dipole problem over a conducting earth, and the solution can be obtained using the flat surface Green's function. The Dyson and Bethe-Salpeter equations can be constructed for the coherent and incoherent waves using the flat surface Sommerfeld solution in the kernel of the integral equation. The solution is then given by the Zenneck wave pole and the numerical distance including the rough surface effects. The effective impedance and the cross section per unit area of the rough surface can be obtained for rough land and sea surfaces. These coherent and incoherent waves are then incident on the target, creating the fluctuating current on the target. The wave scattered by the target is then propagated over the surface reaching the receiver. Since the wave propagates over the same rough surface in both forward and backward directions, the backscattering enhancement takes place. Some analytical results and numerical Monte Carlo simulations are obtained, particularly for LGA (Low Grazing Angle) scattering problems.

The LGA problem for slightly rough surfaces can be solved by the modified perturbation technique. However, completed analytical solutions for polarimetric scattering have not been fully studied. Also, if the roughness is much greater than the wavelength, high frequency approximations may be used but they have not yet been applied to LGA problems since they involve scattering by breaking waves for which analytical solutions are still inadequate. Imaging of a target near the rough surface involves the interaction of the coherent and incoherent waves with the deterministic target which is expressed by stochastic integral equations. This aspect of the imaging problems has not received detailed attention at present [10].

6. Conclusion

Several techniques to improve the image resolution of the object in the random medium are discussed including problems which have not been fully addressed. This includes UWB pulse scattering, interactions between objects and surrounding random media and low grazing angle scattering from rough surfaces. This paper discusses some recent research work on imaging of objects in random media together with several outstanding problems in this field.

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