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IMAGING IN BIOLOGICAL AND ENVIRONMENTAL RANDOM MEDIA

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Abstract

There has been increasing interest in the imaging of objects in the atmosphere, space, terrain, oceans, and biological tissues. This paper presents a review of several important problems and techniques which are available at present. Included are the effects of the atmospheric environment on antenna performance and the propagation effects on microwave, optical, and acoustic systems in various environments. We also discuss guide stars and adaptive optics, imaging and detection of objects in a clutter environment, and InSAR. Also included are medical imaging of tissues and recent work on time-resolved imaging, photon density waves, wave localizations, memory effects and interferometric techniques.

1. Atmospheric Effects on Antennas [1] [4] [7] [8]

Let us first consider the radiation pattern for a large reflector antenna. For a carefully designed antenna in free space, the radiation pattern can be calculated with great accuracy. However, there may be two factors that need to be considered. First, if the antenna size is large, the surface tolerance becomes important, which, in turn, gives rise to phase fluctuations. Second, as the wave propagates through the atmosphere, the wave experiences fluctuations in amplitude and phase. These wave fluctuations should affect the radiation pattern of the antenna, resulting in the reduction of gain, pointing errors, and sidelobe fluctuations.

Consider an imaging system consisting of an object observed through a random medium with a lens or a reflector antenna with diameter D. In the absence of a random medium, the image resolution is given by the Airy disk with λ / D. With the random medium, the coherence length ρ_o determines the resolution and the angular resolution becomes λ / ρ_o. The coherence length ρ_o is defined by the correlation distance at which the mutual coherence function reduces to exp(-1). For a spherical wave in turbulence, this is given by

$$\rho_o = [0.547 k^2 L C_n^2]^{-3/5} \tag{1}$$

where L is the propagation distance and C_n^2 is the structure constant of the refractive index fluctuation. This ρ_o is proportional to the Fried coherence diameter r_o.

For a short distance, the Fresnel size $(\lambda L)^{1/2}$ is smaller than the coherence length and the Fresnel size determines the correlation characteristics of the wave. However, for a large distance, the coherence length becomes smaller than Fresnel size and the coherence length determines the wave characteristics. Therefore, depending on whether the lens or antenna diameter is greater or less than the coherence length, the antenna characteristics are different.

In terms of MTF (Modulation Transfer Function), the random medium acts as a low-pass spatial filter with the cut-off frequency lower than that of the aperture if the coherence length becomes smaller than the aperture size. The peak value of the intensity at the focal point is then reduced from that of an ideal lens in free space. This ratio is called the "Strehl ratio." Also the random medium effect becomes dominant if the coherent intensity becomes less than the incoherent intensity.

2. Guide Star and Adaptive Optics [4]

An attempt has been made to eliminate and reduce the effects of random media on the quality of the image of an object. An early attempt was made to use a deformable mirror to observe an object in such a way as to compensate for the phase fluctuations created by turbulence. This is called adaptive optics and it has been used for observation of stars. However, for this technique to work effectively, a reference is needed to adjust the mirror surfaces. A guide star, which is artificially created, can serve as the reference. Several techniques for creating such a guide star have been proposed.

3. Detection and Imaging of an Object in Clutter Environment [5]

Recently, important angular correlation effects in multiple-scattered waves were discovered. The memory effect is that the scattered waves exhibit strong correlation as the incident wave changes its direction if the differences in the wave numbers for incident and scattered waves along the surface are unchanged. This effect is drastically different depending on whether the medium is random or deterministic, and therefore, this effect can be used to detect an object in the presence of clutter.

The memory effects can be expressed in the memory diagram which shows the strong correlation along the memory line and very little correlation outside of this memory line. However, for a deterministic object, the correlation is strong in all parts of the memory diagram. This difference is advantageously used to detect an object in the presence of clutter.

4. InSAR [6]

In recent years, there has been a strong interest in determining the topographic images of terrain by remote sensing techniques. This has been done by using interferometric technique and is called "InSAR." This can be extended to include the memory effect, and it is shown that the surface profile can be determined by using two transmitters and two receivers placed along the "memory line."

For "InSAR," the correlation between the scattered waves at two receivers is used to obtain the topographic profile. This can be extended to show that the phase of the mutual coherence function is proportional to the average height of the rough surface.

5. Medical Imaging

(a) Time-Resolved Imaging [2]

When a short pulse is incident on a random medium, the coherent part propagates with the propagation constant given by $K=[k^2+4\pi f\rho]^{1/2}$, where $k=\omega/c$, f = forward scattering amplitude, and ρ = number density. However, the diffuse component spreads out in time.

Pulse scattering in turbulence in the ocean, atmosphere, and ionosphere has been studied extensively in terms of the two-frequency mutual coherence function. Pulse scattering in biological media has been studied using the diffusion approximation. In a diffuse medium, such as tissues or blood, considerable multiple scattering takes place, and optical imaging for tissues is still a challenging problem today. Ultrasound imaging of tissues has been investigated extensively. For lower frequencies, the wavelength limits the resolution, while for higher frequencies, attenuation becomes excessive. Therefore, the usable frequencies are normally limited to 1 to 5 MHz (1.5 to 0.3 mm).

The imaging through a random media with a coherent field gives a good resolution, but it is usually dominated by the large incoherent intensity. It is possible to reduce the incoherent intensity by choosing the wavelength at the absorption band. Recent advances on femto-second optical pulse technology should give a promising imaging technique.

(b) Photon Density Waves [2]

Another important development in tissue optics is the use of photon density waves. If the light is modulated at low frequencies (200 MHz for example), the modulated wave satisfies a wave equation similar to the wave equation for a conducting medium. Therefore, the modulated wave propagates with attenuation. This is similar to the temperature variation inside the earth. This modulated wave is called the "photon density wave" and can be used to image biological media. However, the attenuation constant is of the order of a $(\text{wavelength})^{-1}$ and a sensitive detector is needed.

The formulation for the photon density wave is obtained from the time-dependent radiative transfer equation or the two-frequency radiative transfer equation. Under diffusion approximation, we obtain a wave equation similar to the electromagnetic wave equation for a conducting medium. The solution is, therefore, a highly attenuated wave with the phase constant being equal to the attenuation constant. Even though it is highly attenuating, the phase information is present, which can be utilized to image tissues. Several attempts have been made to image biological media with some success.

Another imaging approach for tissue optics is the use of "snake" propagation. The coherent wave propagates with a definite propagation constant, but it is often highly attenuated. The incoherent wave is scattered in all directions, but a part of the incoherent wave propagating towards the detector can be approximated by a wave with small deviations from the line-of-sight similar to a "snake." This forward scattering part can be effectively used to image an object or tissue. Some successful experimental work has been reported.

6. Localization of Waves [3]

It has been recently discovered that the backscattering by a random medium is enhanced due to multiple scattering. This enhanced backscattering can be effectively used to improve the resolution of an image. Some optical experiments have been reported on this problem.

The wave propagating in a random medium towards a target and the wave backscattered from the target are correlated because both forward and backward waves propagate through the same medium. Therefore, the apparent cross section of an object in a random medium is greater than that in free space.

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