

Statistical Modeling of Electromagnetic Wave Scattering from the Ocean Surface

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Accurate modeling of electromagnetic (EM) wave propagation and scattering in complex random environments is crucial for evaluating the performance of radar and communication systems. In particular, modeling the scattering of EM waves from ocean surfaces plays a vital role in both scientific research and practical applications, including microwave remote sensing, radar performance assessment, and communication systems operating in oceanic environments. A robust statistical model that accurately captures the characteristics of EM waves scattered from ocean surfaces can significantly enhance the efficiency of these assessments. Such a model enables the rapid generation of scattered wave data across various conditions and scenarios, reducing reliance on costly and time-consuming field measurements. This capability is invaluable for advancing both commercial and defense technologies while supporting the broader understanding of wave interactions with complex surfaces.

As the initial step in developing a statistical model for scattering from ocean surfaces, it is essential to acquire scattered field data under various conditions. These conditions include different wind speeds, angular differences between the incident wave direction and wind direction, frequency, and incident wave polarization. This data can be obtained through either measurements or simulations, with simulation serving as a versatile and efficient tool for this purpose, as utilized in this work. To generate reliable data from simulations, accurate modeling of the ocean's random surface is critical. The surface model must precisely represent the ocean's profile at a resolution comparable to a fraction of the electromagnetic wavelength. This ensures fidelity in capturing the physical characteristics necessary for accurate scattering predictions under diverse environmental scenarios. This work uses accurate models for representing gravity and capillary waves, two constituent parts of ocean waves, to generate random ocean surfaces at different wind speeds. Because of the large wavelength of the gravity waves (hundreds of meters), numerical simulation of scattering from ocean surface deals with electrically large problems (typically thousands of wavelengths). The presence of capillary waves with wavelengths smaller than or comparable to the wavelength of typical frequencies used in naval scenarios (C-band to Ku-band) prevents using efficient methods like physical optics (PO). Here, the ocean surface is modeled as an impedance boundary condition which significantly simplifies the numerical calculations. The surface integral equation representing the scattering from the surface is solved by the multi-level fast multipole method (MLFMM).

Statistical modeling aims to provide a model to generate tangential components of the scattered field on a near-field plane above the ocean surface for a given ocean condition and incident wave attributes such as the incident angle, polarization, and wavelength. Knowing the tangential fields on a plane, the scattered waves can be calculated at any point above the plane. Assuming the incident plane wave is decomposed into horizontal (h) and vertical (v) polarizations, it can be shown that the real and imaginary parts of co-polarized components of tangential scattered fields due to incident h and v polarizations are Gaussian random variables with a joint probability density function described by the covariance of real and imaginary parts of co-polarized components (K. Sarabandi, "Derivation of phase statistics from the Mueller matrix," *Radio Science*, 1992). The same is also true for the real and imaginary parts of cross-polarized components. It can be shown that the power spectral density of the real and imaginary parts of each co/cross-polarized component of tangential fields are the same. To develop the model, parameters describing the joint pdfs and power spectral density of one of the co/cross-polarized components must be derived for different ocean conditions and incident wave attributes. To use the model, random samples of one component of co/cross-polarization are generated by using its power spectral density, and then the other components are generated knowing the samples of the first component at each location and their joint pdfs.