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Wave Chaos and Complexity in Electromagnetic Environments

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The research and dissemination activities pursued by URSI Commission E concern the investigation of electromagnetic interferences in natural and man-made environments. Inherently, the propagation of waves through structures, channels and media involves multiple components and space-time scales. It is a physical process that takes place with a large number of degrees of freedom.

Typically, the knowledge of both problem geometry and physical properties is either uncertain or not treatable mathematically. Therefore, the modelling of high frequency fields poses computational challenges when the environment is large and irregular. Furthermore, wave interference driven by multiple reflections and scattering often ignites collective phenomena whose physics is beyond the obvious, e.g., wave localisation, diffusion, and rogue states. Those phenomena are universal in the sense that depend on system generic symmetries and can be predicted by chaos theory.

Recently, statistical methods have been used to study complex wave systems in the high frequency asymptotics regime, where the collective dynamics of partial rays can be simulated with reasonable computational effort. More recently, universal fluctuation laws of Hamiltonian chaos have led to the development of new statistical wave models for overmoded cavities, disordered waveguides, quantum dots and random media.

Wave chaos theory stands on two main paradigms: semiclassical analysis and random matrix theory. We review the basics of both, and show how they can be used to calculate probability distributions of relevant field observables from wave equations. In a linear eigenvalue problem, semiclassics is used to replace exact eigenfunctions with putative modes made of a superposition of random plane waves, while random matrix theory is used to replace the exact spectrum of resonances with universal distributions of eigenvalues. The two prescriptions are motivated by field mixing, ray instability, and high modal overlapping: collective phenomena of wave systems whose classical dynamics is chaotic. In particular, we derive a statistical model, the random coupling model, which describes the high-frequency excitation of irregular electromagnetic cavities through distributed sources.

Real-life scenarios supporting electromagnetic wave complexity include wireless channels in telecommunications, reverberation chambers in electromagnetic compatibility, and microwave applicators in material processing engineering.