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Combining Data-Driven and Physics-Based Methods for EM Propagation and Imaging Through Inhomogeneous Turbulent Media and During Extreme Events

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Combining Data-Driven and Physics-Based Methods for EM Propagation and Imaging Through
Inhomogeneous Turbulent Media and During Extreme Events
PI: Alex Mahalov. Arizona State University
School of Mathematical and Statistical Sciences
15 Dec 2018-14 Dec 2021
Final Report

Project Outcomes

The research approach developed in this project combined data-driven and physics-based computational methods for EM propagation through inhomogeneous turbulent atmosphere and during extreme events such as geomagnetic storms in ionosphere.

Major Outcomes: (1) Developed novel methods for EM propagation through inhomogeneous random media by taking into account gradients and curvature of the refractive index, thus capturing non-paraxial physics effects of lensing, mirages, and reduction of focal length by stochastic fluctuations. (2) Analyzed electromagnetic propagation using the 3D Maxwell vector wave equation; recent interest in vectorial sensors requires application of vectorial propagation methods, rather than scalar wave equation approaches. (3) Discovered and analyzed permittivity gradient induced depolarization effects in EM propagation through inhomogeneous random media. (4) Characterized electromagnetic waves and scintillations associated with Rayleigh–Taylor and Richtmyer-Meshkov instabilities and turbulence in ionosphere. (5) Improved data accuracy for critical ionospheric electron layers by incorporating new data assimilation algorithms into computational scales of the physical models, accounting for their dynamics and changes in curvature during geomagnetic storms.

This project created a new data-driven paradigm for integrated studies of 3D EM wave dynamics and propagation beyond conventional paraxial models to include non-paraxial physics, inhomogeneities of refractive index coupled with stochastic fluctuations, vectorial and depolarization effects.

Summary of Main Results

1. Long-range propagation through inhomogeneous turbulent atmosphere: analysis beyond phase screens

Many applications rely on the propagation of electromagnetic waves through extended regions of the atmosphere over which the refractive index can vary in a complex manner. Gradients and curvature of the mean refractive index profile result in ray bending and the associated phenomena of mirages, atmospheric lensing, and wave trapping in parabolic cavities. Stochastic refractive index fluctuations due to turbulence cause a random displacement of the trajectory and give rise to the wander, or spot dancing, of a propagating optical beam. In our work we modeled these features of the refractive index profile locally and described propagation through the corresponding regions. We derived formulas for the mean ray path that capture the effects of both atmospheric turbulence and variations in the mean refractive index profile, including the nonparaxial effects associated with the bending of the guiding ray path. We also derived formulas for the mean-squared transverse displacement of a ray from the mean trajectory, which can provide for example an estimate of the magnitude of the beam wander due to turbulence.

2. Multi-scale analysis of Helmholtz equations in randomly layered media: extension of EM propagation modeling beyond conventional paraxial approximation

In our work, we combined stochastic geometric optics (non-paraxial) and extended paraxial wave optics methods to get more complete and accurate description of atmospheric effects on EM propagation. Conventional paraxial equations assume that the propagating wavelength is much smaller than the correlation length of random medium. In our work, we covered a larger range of scales including regimes in which the propagation wavelength is of the same order as the correlation length of the random fluctuations of the refractive index. We derived and analyzed extended paraxial equations for propagation through atmospheric turbulence with the new term which describes interactions between the EM propagation wavelength and correlation length of medium fluctuations. Our theory gives correct phase and decay factor for coherent field. We also studied the simultaneous paraxial and white-noise limit of the Helmholtz equation in randomly layered media where the refractive index fluctuations are in the direction of propagation. We showed that this simultaneous limit can be taken in this regime by introducing into the equation a small regularization parameter. The corresponding approximation that we derived is different from that of the previously studied paraxial approximations in high frequency regimes. Since the correlation length of the refractive index fluctuations due to atmospheric turbulence varies substantially, our results are more accurate for propagation scenarios including microwave and radio wave propagation through atmospheric layers. Combining stochastic geometric optics and extended paraxial wave optics, we described the strong effects (refraction, EM wave trapping, beam wander, scintillation) of the inhomogeneous and anisotropic atmospheric fluctuations on horizontal propagation; these effects are not accounted for by conventional phase-screen methods.

3. Permittivity gradient induced depolarization: Electromagnetic propagation with the Maxwell vector wave equation

Recent interest in 3-D vectorial sensors and non-equilibrium EM wave dynamics requires development of time-dependent vectorial propagation methods, rather than scalar wave equation approaches. We used the 3D Maxwell Vector Wave Equations derived from the Maxwell system for a random medium which has an inhomogeneous dielectric permittivity dominated by variation along one dimension. It is well known that the electric field components decouple for homogeneous media. However, permittivity variations in a dominant direction yield an upper triangular system of scalar wave equations with the wave polarization component parallel to the inhomogeneous direction/axis acting as a forcing term for the orthogonal components. The main implication is that waves with polarization oriented parallel to the permittivity gradient act as a forcing term and excite other polarization components and, thus, induce depolarization. Contemporary studies treat the permittivity as a constant when deriving a wave equation or paraxial approximation, and then re-introduce via inhomogeneous wave speed, variable permittivity, thus missing important terms and physical mechanisms in their resulting equations. Conventional models neglect the term in the Maxwell vector wave equation responsible for the depolarization effects. In our work, application of the electromagnetic propagation depolarization effects was demonstrated numerically for an air-sea interface evaporation duct with a 500 MHz source.

4. EM propagation through scintillation producing irregularities associated with Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM) instabilities and turbulence in ionosphere

Motivated by EM propagation through ionospheric electron layers, we extended classical results on Rayleigh-Taylor (RT) and Richtmyer-Meshkov (RM) instabilities and turbulence to include electromagnetic forces. Fundamental aspects of RT/RM theories were developed for ionospheric applications including the underlying plasma physics and electrodynamics describing the linear, nonlinear and fully turbulent stages. The ionospheric environments significantly impact EM wave propagation primarily through the development of electron density irregularities and plasma turbulence in the vicinity of large electron density gradients created by RT/RM instabilities and turbulence. Our work included studies of scintillation producing irregularities associated with RT and RM instabilities and turbulence in ionospheric settings impacted by electromagnetic forces. We discovered the role played by the Kelvin-Helmholtz (KH) instability as the mechanism that underlies mixing in RT and RM flows, as a result of the shear between the growing ionospheric plasma bubbles and spike structures. In our work we decomposed the refractive index profile into an ensemble averaged deterministic part + stochastic fluctuations, and described propagation through the corresponding regions (electron layers). We discovered that gradients and curvature of the mean refractive index profile result in ray bending and the associated phenomena of mirages, atmospheric lensing, and wave trapping in parabolic cavities.

5. *Data assimilation for ionospheric EM forecasting in the presence of model bias*

The dynamics of many models of physical systems depend on the choices of key parameters. In our work, we performed observing system simulation experiments using a first-principles model of the Earth's ionosphere, the Thermosphere Ionosphere Electrodynamics Global Circulation Model (TIEGCM), which is driven by parameters that describe solar activity, geomagnetic conditions, and the state of the thermosphere. Of particular interest in our studies was the response of the ionosphere electrodynamics during geomagnetic storms. Errors in the overall specification of driving parameters for the TIEGCM (and similar dynamical models) may be especially large during geomagnetic storms, because they represent significant perturbations away from more typical interactions of the earth-sun system. Such errors can induce systematic biases in model predictions of the ionospheric state and pose difficulties for data assimilation methods, which attempt to infer the model state vector from a collection of sparse and/or noisy measurements. Typical data assimilation schemes assume that the model produces an unbiased estimate of the truth. We developed a new approach to handle the case where there is some systematic bias in the model outputs. Our work focused on the TIEGCM when it is driven with solar and magnetospheric inputs that are systematically misspecified. We also performed observing system experiments in which synthetic electron density vertical profiles were generated at locations representative of the operational satellite observing platforms during a moderate geomagnetic storm event. The synthetic data were assimilated into the TIEGCM using the Local Ensemble Transform Kalman Filter with a state augmentation approach to estimate a small set of bias-correction factors. We showed that our method can significantly reduce root-mean-square errors in 1-hour forecasts of total electron content (a key ionospheric variable in EM propagation models), compared to no bias correction. These results showed that our approach is computationally efficient and can be further refined to improve short-term predictions (1-hour) of ionospheric EM dynamics of electron layers during geomagnetic storms.

Publications in Refereed Journals

A. Mahalov and A. McDaniel. Long-range propagation through inhomogeneous turbulent atmosphere: analysis beyond phase screens. *Physica Scripta*, Institute of Physics UK, 94 (3): 034003 (2019).

<https://doi.org/10.1088/1402-4896/aaf32c>

B. Cheng and A. Mahalov, General results on zonation in rotating systems with a β -effect and the electromagnetic force, *Zonal Jets: Phenomenology, Genesis, and Physics* (Cambridge Atmospheric & Space Science), Publisher: Cambridge University Press, 2019.

DOI: <https://doi.org/10.1017/9781107358225.012>,

A. McDaniel and A. Mahalov. Coupling of paraxial and white-noise approximations of the Helmholtz equation in randomly layered media. *Physica D: Nonlinear Phenomena*, 409:132491 (2020).

<https://doi.org/10.1016/j.physd.2020.132491>

S. R. Shaffer and A. Mahalov. Permittivity gradient induced depolarization: Electromagnetic propagation with the Maxwell vector wave equation. *IEEE Transactions on Antennas and Propagation*, 69 (3):1553-1559 (2020).

DOI: [10.1109/TAP.2020.3016463](https://doi.org/10.1109/TAP.2020.3016463)

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<https://doi.org/10.1016/j.physd.2020.132838>

J. A. Durazo, E. J. Kostelich, and A. Mahalov, Data Assimilation for Ionospheric Space-Weather Forecasting in the Presence of Model Bias. *Frontiers in Applied Mathematics and Statistics: Mathematical and Statistical Physics*, *Front. Appl. Math. Stat.*, published 07 May 2021,

<https://doi.org/10.3389/fams.2021.679477> (2021).

Project Participants: Barclay (current PhD student), Dr. Durazo (former PhD student, now at Intel computational math kernel library group), Dr. Kostelich, Dr. Mahalov (PI), Dr. McDaniel (former postdoc, now at AFRL), Dr. Shaffer.

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