Data Science and Machine Learning in Geo-electromagnetics

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SUMMARY

Over the past two decades, data science and machine learning (ML) techniques have attracted increasing attention within the electromagnetic (EM) community, opening up significant potential for applications while also presenting challenges. This review provides a comprehensive survey of the advancements ML has contributed to the EM field, exploring existing challenges and future development trends. We begin by introducing the basic concepts and recent advances in ML, ranging from shallow learning algorithms such as clustering methods and Gaussian processes, to advanced neural networks, physics-guided and generative models. Then, practical applications are thoroughly investigated across a variety of EM techniques, including magnetotellurics (MT), electrical resistivity tomography (ERT), transient electromagnetics (TEM), ground-penetrating radar (GPR), among others. For each technique, we offer a detailed review of ML applications through various data analysis processes, including denoising, signal detection, forward simulation, inversion, and joint interpretation with other geophysical data. Furthermore, we discuss extensive applications of ML in fields such as understanding Earth's deep structure, mineral exploration, groundwater management and hazard monitoring. We also address the ongoing challenges, such as dependency on training datasets, model generalization and interpretability. Looking forward, we highlight emerging trends like the advancement of uncertainty evaluation, the development of physics-guided models, enhancements in data management and accessibility and the integration of cloud computing technologies. This comprehensive overview aims to establish a clear scope for current achievements and future potential of integrating ML with EM, thus laying a foundation for continued research and practical applications within the EM community.

Keywords: Electromagnetics; machine learning; data science; deep learning; geophysics.