URSI AP-RASC, Sydney, Australia, 17-22 August 2025

4D Ionospheric Assimilation Based on Deep Operator Regression for GNSS Rays

H. Y. Fu* [(1)(2)], D. J. Cai [(1)(2)], T. Z.Wang[(1)(2)]
(1) Fudan University, Shanghai, DC, 200433, e-mail: haiyang_fu@fudan.edu.cn

(1) Key Laboratory for Information Science of Electromagnetic Waves (MoE), Fudan University, 200433, China
(2) School of Information Science and Engineering, Fudan University, Shanghai, 200433, China.

Accurate prediction of ionospheric parameters in four-dimensional spatiotemporal domains (time, longitude, latitude, and altitude) is critical for mitigating space weather ionospheric effects and ensuring robust GNSS operations. Extreme ionospheric disturbances caused by solar magnetic storms, significantly impact the performance and reliability of Global Navigation Satellite Systems (GNSS). With rapid development of machine learning, this study addresses the challenge of ionospheric modeling and prediction by introducing a novel deep learning-based data assimilation framework: the Deep Operator Network (DON) model for four-dimensional ionospheric parameter forecasting.

The proposed DON model is designed to achieve high spatiotemporal resolution and long-term prediction capabilities, making it particularly suitable for capturing ionospheric variations under extreme space weather conditions, such as solar magnetic storms. The model focuses on two four aspects: (1) high-resolution interpolation and mid-term prediction of the ionospheric slant total electron content (STEC) along the signal path between navigation satellites and ground stations; (2) global modeling and prediction of vertical TEC (VTEC) with high spatiotemporal accuracy; (3) prediction of the rate of TEC index (ROTI) and (4) electron density tomography. By assimilating multiple sources of data and leveraging the power of deep learning, the DON model can effectively capture the complex nonlinear relationships and dynamic behaviors of the ionosphere, providing reliable predictions even during periods of geomagnetic activity. To validate the model's performance, we applied GNSS navigation and radio occultation **(**RO) data collected during quiet and magnetic storm periods, including a major solar magnetic storm event in May 2024.

This study underscores the importance of advanced data-driven approaches for ionospheric modeling, particularly in the context of increasing reliance on GNSS for critical infrastructure and services. The DON model represents a significant step forward in addressing the challenges posed by space weather, offering a powerful tool for improving the resilience and accuracy of GNSS systems under extreme ionospheric conditions. Future work will focus on further refining the model's architecture, expanding its application to other space weather scenarios, and integrating it into operational forecasting systems to enhance real-time GNSS performance monitoring and mitigation strategies.

This work is supported by the National Key Research and Development Program of China (Grant No. 2021YFA0717300).

1. D. J. Cai, Z. H. Shi, H. Y. Fu, H. Liu, H. Y. Qian, Y. Sui, F. Xu, Y.Q. Jin., Global 4D Ionospheric STEC Prediction based on DeepONet for GNSS Rays, IEEE Transactions on Geoscience and Remote Sensing, 62(5801420), 1-20, doi: 10.1109/TGRS.2024.3422150, July 2024
2. Z. T. Wang, D. J. Cai, H. Y. Fu, Global Ionospheric ROTI Prediction Based on DeepONet, 1-4, 14th International Symposium on Antennas, Propagation and EM Theory (ISAPE), Hefei, Oct 23, 2024