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

Large-scale Travelling Ionospheric disturbances detection and forecasting

Claudio Cesaroni* [1], Luca Spogli[1], Marco Guerra[1,5], Vincenzo Ventriglia[1], David Altadill[2], Antoni Segarra[2], Anna Belehaki[3]. Nicola Fiorentino[4], Federico Tosone[4]

(1) Istituto Nazionale di Geofisica e Vulcanologia, Roma, Rome, Italy
(2) Observatori de l'Ebre, University Ramon Llull – CSIC, Roquetes, Spain
(3) National Observatory of Athens, IAASARS, Athens, Greece
(4) Spindox, Rome, Italy
(5) Sapienza University of Rome, Rome, Italy

Large-scale travelling ionospheric disturbances (LSTIDs) are wave-like ionospheric fluctuations, often triggered by geomagnetic storms, that significantly impact space weather dynamics. Their influence on radar and satellite navigation systems necessitates accurate forecasting and timely detection.

We have developed a machine learning model capable of forecasting LSTID occurrence over Europe up to three hours in advance. This model utilizes the CatBoost gradient boosting framework, trained on a human-validated LSTID catalogue incorporating diverse physical drivers, including ionogram data, and geomagnetic and solar activity indices. Three distinct forecasting modes are implemented, each tailored to specific operational scenarios with varying relative costs of false positives and false negatives. Crucially, model explainability is prioritized through the application of the game-theoretic SHapley Additive exPlanation (SHAP) formalism, visualizing the contribution of each input parameter to the model's output. Validation, encompassing global evaluation and interpretation, followed by event-level validation against independent detection methods, demonstrates the model's robust predictive performance. Compared to a rule-based benchmark, the model achieves a performance improvement ranging from +72% to +93%, depending on the operational mode. Future research directions are discussed, including probabilistic forecasting from a cost-sensitive learning perspective, performance-centric model monitoring, and uncertainty quantification for end-user risk management and mitigation using the conformal prediction framework.

Complementing our forecasting efforts, we present a novel technique for the automated detection of LSTIDs over Europe. This method leverages travel-time diagrams derived from detrended Total Electron Content (TEC) data to autonomously identify LSTID occurrences and estimate their latitudinal velocities. A network of GNSS dual-frequency receivers, strategically selected using K-Means clustering to optimize spatial coverage, provides the raw data. Geometry-free linear combinations (GFLC) of phase measurements are detrended, and travel-time diagrams are generated, visually representing the meridional propagation of LSTIDs. Image processing techniques identify regions of interest, highlighting propagating features of positive and negative amplitude. These features are then fitted using the RANdom SAmple Consensus (RANSAC) method to determine the propagation speed. LSTID occurrences are identified by merging positive and negative features, with false positives filtered based on established physical criteria. A catalogue of LSTID events for 2021-2024 has been compiled, enabling statistical analysis and validation of the technique. Analysis of two specific events, along with the overall statistical behavior, highlights the strengths and limitations of the proposed methodology. The typical LSTID over Europe exhibits a velocity of 644±211 m/s and a period of 61±11 minutes. Correlation with the auroral electrojet (AE) index reveals that increased auroral currents correlate with faster, stronger, and shorter-period LSTIDs. Furthermore, correlation with magnetic indices confirms a clear relationship between LSTID occurrence and increased geomagnetic activity, consistent with previous findings. This automated detection technique provides a valuable tool for building LSTID catalogues and validating the forecasting model described above.