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Physics-Informed Loss function for vTEC Forecasting

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1 Introduction

Machine Learning (ML) models are widely used and flourishing in several fields of study, including image processing and computer vision, for tasks such as classification, object detection and recognition, language translation and regression. In recent years, many related works have been done using ML techniques for the vertical Total Electron Content (vTEC) forecasting. Several of these multivariate ML models learn appreciably well the quiet events besides the stormy events available in the training dataset.

In this work we develop, for the first-time, a physics-informed loss function for vTEC forecasting from 1 to 24 hours in advance, which would help in improving the learning process of an Artificial Neural Network (ANN) model by considering constraints imposed by quiet and storm events. The designed physics informed loss function will be shown together with the results obtained when the ANN model is applied for vTEC forecasting during quiet and storm events.

2 Data and Method

The NASA Archive of Space Geodesy provides 30-second GNSS data from regional IGS data gathering facilities (https://cddis.nasa.gov/archive/gnss/data/daily). Daily, these data are collected in RINEX files and sent to the Crustal Dynamics Data Information System (CDDIS). We evaluate vTEC for the mid-latitude station Tsukuba, Japan (36.06^o N, 140.05^o E) for one solar cycle (January 2006 - December 2018) by using the TEC calibration technique developed by Ciraolo et al [1], and assuming the ionosphere as a thin shell at 350 Km (Ionospheric Pierce Point, IPP) so that the slant TEC (sTEC) can be projected to the vTEC by applying a geometric mapping function (details in Cesaroni et al. [2, 3]). The external drivers (solar and geomagnetic indices) used as input to the ANN model during training, validation and testing phases are downloaded from https://cdaweb.gsfc.nasa.gov.

To reduce the influence of multicollinearity and to select the most important external drivers to be used for the multilayer perceptron model, we use a threshold set to one half of the Pearson correlation coefficient to discard some of them. After this, the permutation of feature importance technique is applied in order to select the most significant two external drivers with respect to the forecasting horizons from 1 to 24 hours.

To begin with the ANN architecture, we design physics-informed loss functions using some of the external parameters as constraints imposed on the Mean Square Error (MSE) loss function. These constraints help in the training phase of the ANN to learn appreciably well the quiet and stormy events in comparison with the traditional MSE loss function.

3 Conclusion

The proposed ANN model for vTEC forecasting from 1 to 24 hours in advance using one of the physics-informed loss function we designed, outperforms the traditional MSE in all phases of the ML algorithm, although the performance of the model decreases with increasing the forecasting horizon and under strong disturbed geospatial events. The results obtained by using the physics-informed loss function are statistically significant as verified by applying the Wilcoxon signed-rank test. The idea of incorporating physical constrains into the ANN for vTEC forecasting is promising for further development using ML techniques.

References

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