

## Precise GNSS Atmospheric Corrections and Services for Mass-market Applications

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**Defense Date:** June 20, 2025

### Abstract

Global Navigation Satellite Systems (GNSS) have seen a broad expansion in applications over recent decades. With the growth of multi-constellation systems including Global Positioning System (GPS), GLOBal Navigation Satellite System (GLONASS), Galileo and Beidou, GNSS is increasingly used in diverse areas, from disaster monitoring, autonomous driving to smartphone-based navigation. However, as standard positioning methods often lack the precision needed for emerging technologies, advanced techniques like Precise Point Positioning (PPP) have been developed. To achieve high-precision positioning results, various corrections must be applied to mitigate various errors in GNSS measurements. Among major GNSS errors, the atmospheric effects including tropospheric and ionospheric errors have become the most significant error sources. Developing accurate atmospheric corrections and distributing them in real-time is crucial to enable fast convergence of PPP. The International GNSS Service (IGS) has been providing Real-Time Global Ionosphere Maps (RT-GIM) which are the combined products from the IGS real-time ionosphere centers. With the latest interpolation improvements, the RT-GIM accuracy is close to that of the IGS rapid GIMs. However, the prediction methods still need globally distributed real-time GNSS stations.

This thesis explores the development of a regional precise atmospheric service, incorporating ionospheric and tropospheric models using machine learning techniques. For ionospheric prediction, a sequence-to-sequence long short-term memory (LSTM) deep learning method is used to predict ionospheric vertical delay maps. The Recurrent Neural Network (RNN) model, which evolved from feed-forward neural networks, is designed to deal

with complex temporal problems. LSTM, a special form of the powerful Artificial Neural Network (ANN) model, is used to overcome the gradient vanishing issue from the traditional RNN. In this work, the IGS rapid GIMs are used as prediction bases so real-time GNSS datalinks are not needed. Various time windows are selected based on different Kp-index to represent different solar activity strengths over a region of southwestern Canada and northwestern US. The ionospheric corrections estimated from GNSS stations within the testing region are used to verify the model performance. Since the training is based on the IGS rapid GIM product and no more real-time GNSS data is needed, the model can provide improved cost-effective regional ionospheric services with high stability. Regarding tropospheric prediction, the IGS has provided precise troposphere correction data in TRO format post-mission, but its long latency of 1 to 2 weeks makes it unable to support real-time applications. In this work, a real-time troposphere prediction method based on the IGS post-processing products was developed using FFNN and LSTM machine learning techniques to eliminate the long latency problem. The test results of tropospheric predictions over the year of 2023 using the proposed method indicate that the new method can achieve a prediction zenith tropospheric accuracy (RMSE) of 2 cm, making it suitable for real-time applications.