Implementation of Machine Learning Methods for Ionospheric Scintillation Data Analysis

N. Gachancipa, C. Thakrar

EMBRY-RIDDLE Aeronautical University

SPRL Space Physics Research Laboratory

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INTRODUCTION

IONOSPHERIC SCINTILLATION & TOTAL ELECTRON CONTENT

- The ionosphere is a region in the Earth's upper atmosphere. The atoms and molecules present in this region often collide with incoming solar radiation, creating a layer of free electrons (UCAR, 2014).
- The number of electrons present in the ionosphere can be measured using Global Navigation Satellite Systems (GNSS) receivers. At any given moment and location, the Total Electron Content (TEC) is the number of electrons present between the GNSS receiver and the satellite (NOAA) .
- A high concentration of free electrons in the ionosphere can cause fluctuations in the phase and amplitude of radio-signals crossing the region. This phenomenon, known as ionospheric scintillation, can disrupt communications (Space Weather Services - Australia, 2020).
- The Global Navigation Satellite Systems (GNSS) team at the Space Physics Research Lab (SPRL) investigates the behavior of the ionosphere under the presence of natural phenomena such as hurricanes and eclipses.

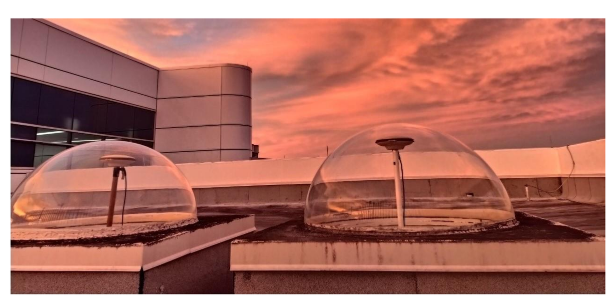

Figure 1: GNSS Antennas at the Space Physics Research Laboratory (SPRL)

RECURRENT NEURAL NETWORKS (RNNs)

- Recurrent Neural Networks (RNN) are a type of artificial neural networks useful for the analysis of temporal sequences, such as signal processing (IBM Cloud Education, 2020).
- An RNN model considers historical data to make predictions. Additionally, the input size has no limit, since input data is processed continuously (Amidi, N/A). The RNN implementation in this project processes one timestep input per minute.

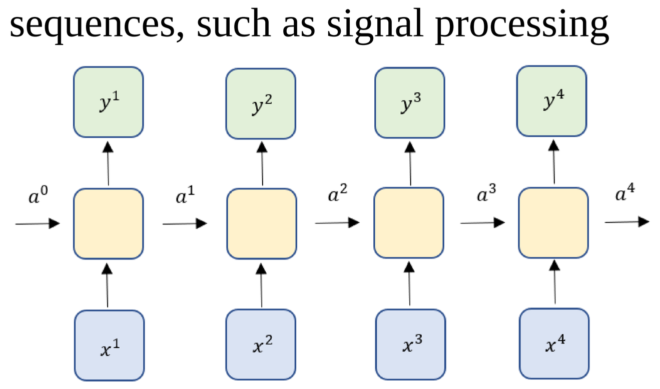

Figure 2: RNN architecture. The x (blue) variables represent the input arrays, which contain data for a specific timestep. The y (green) neurons are the output values at each instance.

OBJECTIVE

The purpose of this project is to develop a Machine Learning algorithm using Recurrent Neural Networks (RNNs) to automate the process of ionospheric event detection.

The end goal of the project is to integrate the RNN model with the Embry-Riddle Ionospheric Scintillation Algorithm (EISA), which is currently used by the Global Navigation Satellite Systems (GNSS) team to collect, parse and model ionospheric scintillation and total electron content (TEC) data.

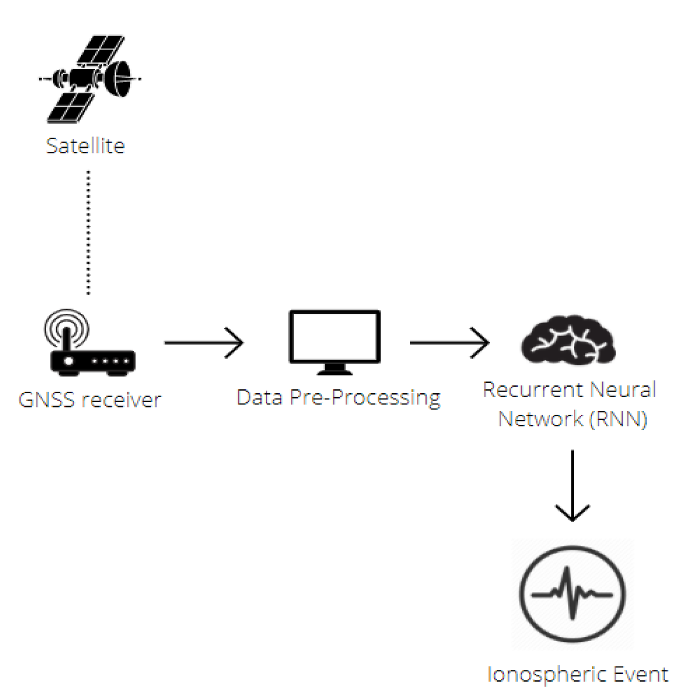

Figure 3: Process for Ionospheric data collection, processing and analysis.

METHOD

DATA COLLECTION

- The GNSS team currently operates two NovAtel GPStation-6 receivers (see Figure 4) at the Space Physics Research Lab, located in Daytona Beach, FL. The NovAtel GPStation-6 receivers can lock to signals from three satellite constellations: GPS, GLONASS, and GALILEO.
- The receivers can collect low and high-rate ionospheric scintillation and TEC data. For the purpose of this project, the Machine Learning model is being trained using low-rate data from GPS satellites.

Figure 4: NovAtel GPStation-6 GNSS Ionospheric Scintillation and TEC Monitor (GISTM) Receiver (below), and GPS-703-GGG Triple-Frequency Pinwheel® GNSS Antenna

- The GNSS team is also using data from the Canadian High Artic Ionospheric Network (CHAIN), operated by the University of New Brunswick. The CHAIN network is composed of 25 stations located across the Nunavut and Northwest Territories in Canada (CHAIN, 2020).
- Ionospheric scintillation events are more prominent in high-latitudes. The CHAIN data provides access to more atmospheric events than the data collected in Daytona. For this reason, the CHAIN data is used during the RNN model training process.

DATA PRE-PROCESSING

- The low-rate scintillation data from the CHAIN network was parsed using the Cray CS400™ supercomputer (Vega) at Embry-Riddle Aeronautical University. Over 100GB of the original binary files were converted to a CSV format.
- A total of six years of ionospheric scintillation and TEC data was parsed. The ionospheric events that occurred during the six-year period were identified and labelled manually.
- Signal amplitude scintillation (S4) values were used to label the training data of the RNN model. The S4 index measures signal fluctuation intensity. S4 values above 0.6 indicate extreme ionospheric scintillation activity.
- The S4 index measurements can be influenced by the multi-path effect (i.e. signal interference with nearby buildings or structures). To avoid the mislabeling of multi-path events as ionospheric scintillation, the data was filtered with an elevation threshold of 25°. All events under the threshold were labelled as multipath.
- Each instance of the CHAIN data was labelled using the following scale:

Ionospheric Event	S4 Index	Elevation	Label
No-Scintillation	Between 0 and 0.2	Above 25°	0
Low	Between 0.2 and 0.4	Above 25°	1
High	Between 0.4 and 0.6	Above 25°	2
Extreme	Above 0.6	Above 25°	3
Multi-Path	Above 0.2	Below 25°	4

Table 1: Data labelling for RNN training

MODEL IMPLEMENTATION

- The Recurrent Neural Network (RNN) model was developed using TensorFlow and Google Colab.
- As shown in Figure 2 (RNN architecture), the model's input is a set of arrays (x) which are provided to the model at each timestep (every 60 seconds). The input arrays contain data regarding the location of the satellite with respect to the receiver (azimuth and elevation), amplitude scintillation (S4), phase scintillation (σ), and TEC.
- At each timestep, the RNN model outputs a value (y) corresponding to one of the labels on Table 1, indicating if there is an ionospheric event occurring, and if so, its strength.
- A similar model is being developed for scintillation activity prediction; This model returns a value (y) which is a prediction of the upcoming S4 scintillation values given a series of timesteps.

RESULTS

- The RNN was trained using more than 20,000 data instances from the CHAIN network. A data instance contains location, scintillation and TEC measurements from one radio station and a specific satellite.
- The preliminary results show that the RNN is capable of detecting amplitude scintillation events from the CHAIN data, as shown in Figures 5 and 6. The model identifies the presence and strength of the ionospheric event.

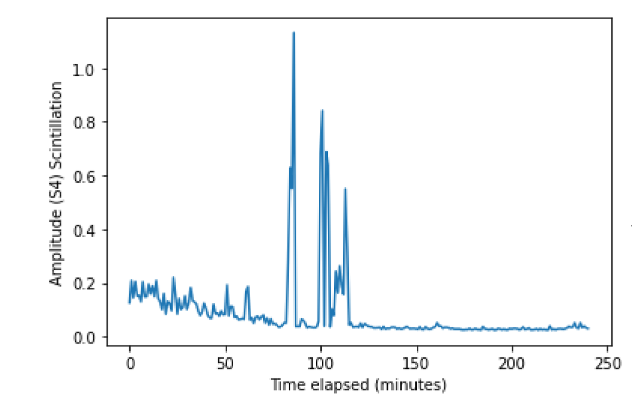

Figure 5: Ionospheric Scintillation event from July 31st, 2014. Data collected by the CHAIN station at Fort McMurray, Alberta.

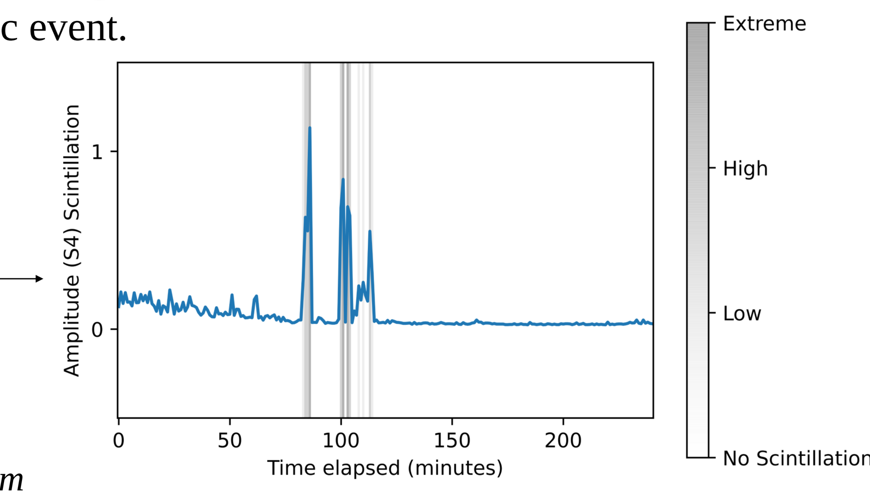

Figure 6: Ionospheric event detection using the Recurrent Neural Network model.

- The RNN model is also capable of distinguishing between atmospheric events and signal interference (multi-path). Often, the multi-path effect affects signals when the elevation angle is low, as shown in Figure 8.

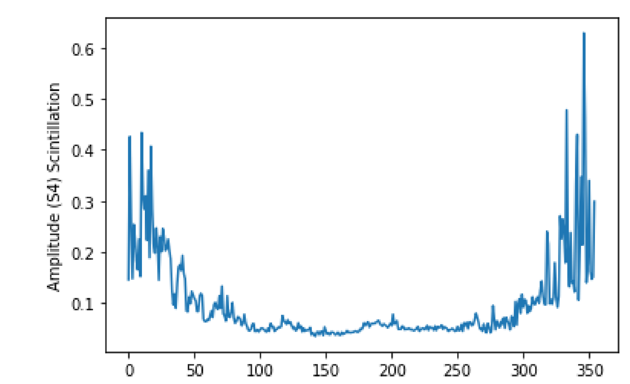

Figure 7: Multi-path event detection from June 6th, 2013 (CHAN station in Churchill, Manitoba)

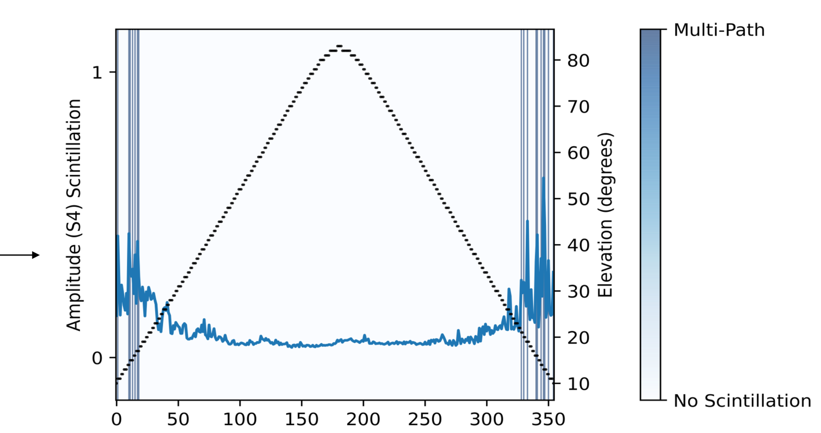

Figure 8: Multi-path effect detected using an RNN. Dotted line: Satellite elevation angle.

CONCLUSIONS & FURTHER WORK

- The existing model is capable of detecting amplitude (S4) scintillation events, and to categorize them between low, high, and extreme depending on their strength,
- The model can distinguish between ionospheric scintillation events and events caused by signal interference with nearby buildings (multi-path).
- The RNN model is currently in early stages of development and testing. Further work will include phase scintillation (σ) event detection, as well as a short-term scintillation prediction feature.
- Further work includes testing the model with data from receivers in low and mid latitudes, in locations such as Kenya, Florida, and Chile.

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