ADVANCED MODELING AND SENSOR NETWORK DESIGN FOR REAL-TIME CHARACTERIZATION OF THE IONOSPHERIC D-REGION

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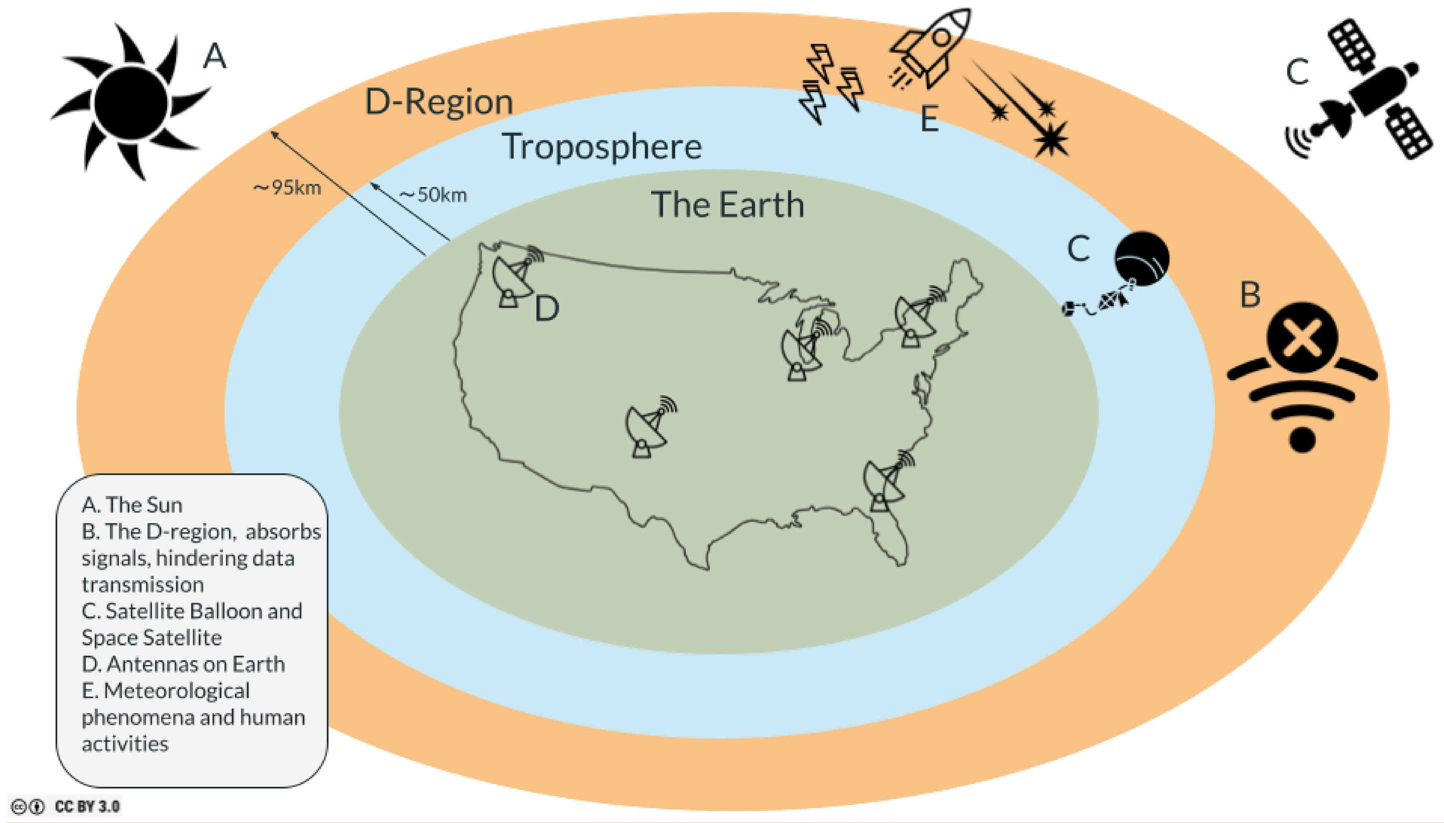
Motivation

The Earth's D-region, part of the mesosphere, is a complex and variable region containing a dusty plasma of electrons, ions, neutrals, and charged dust particles from meteoric origins [1]. This plasma affects radio wave propagation with disturbances that vary with dust charge fluctuations. Our research uses numerical models to study phenomena like the impact of radar echoes in HF to UHF bands and then validates the models through experiments at radar facilities [1]. Ionospheric irregularities, like the ones during SAPS events influenced by space weather, disrupt communication systems like GPS and StarLink [2]. Our advanced models, including three-dimensional electrostatic fluid models and gyrokinetic equations, are important for understanding these instabilities.

Real-Time Ionospheric D-Region Characterization

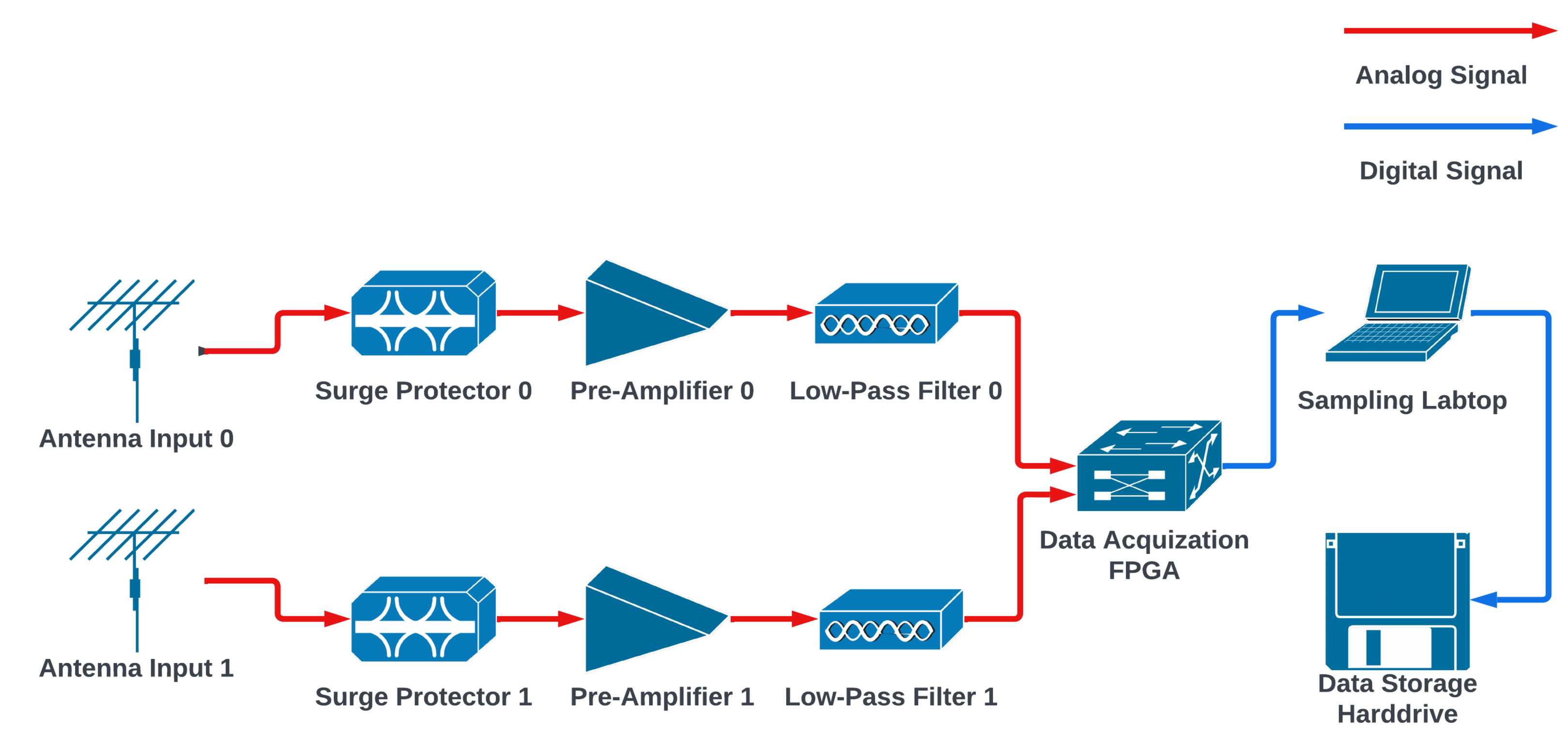


Project Objective

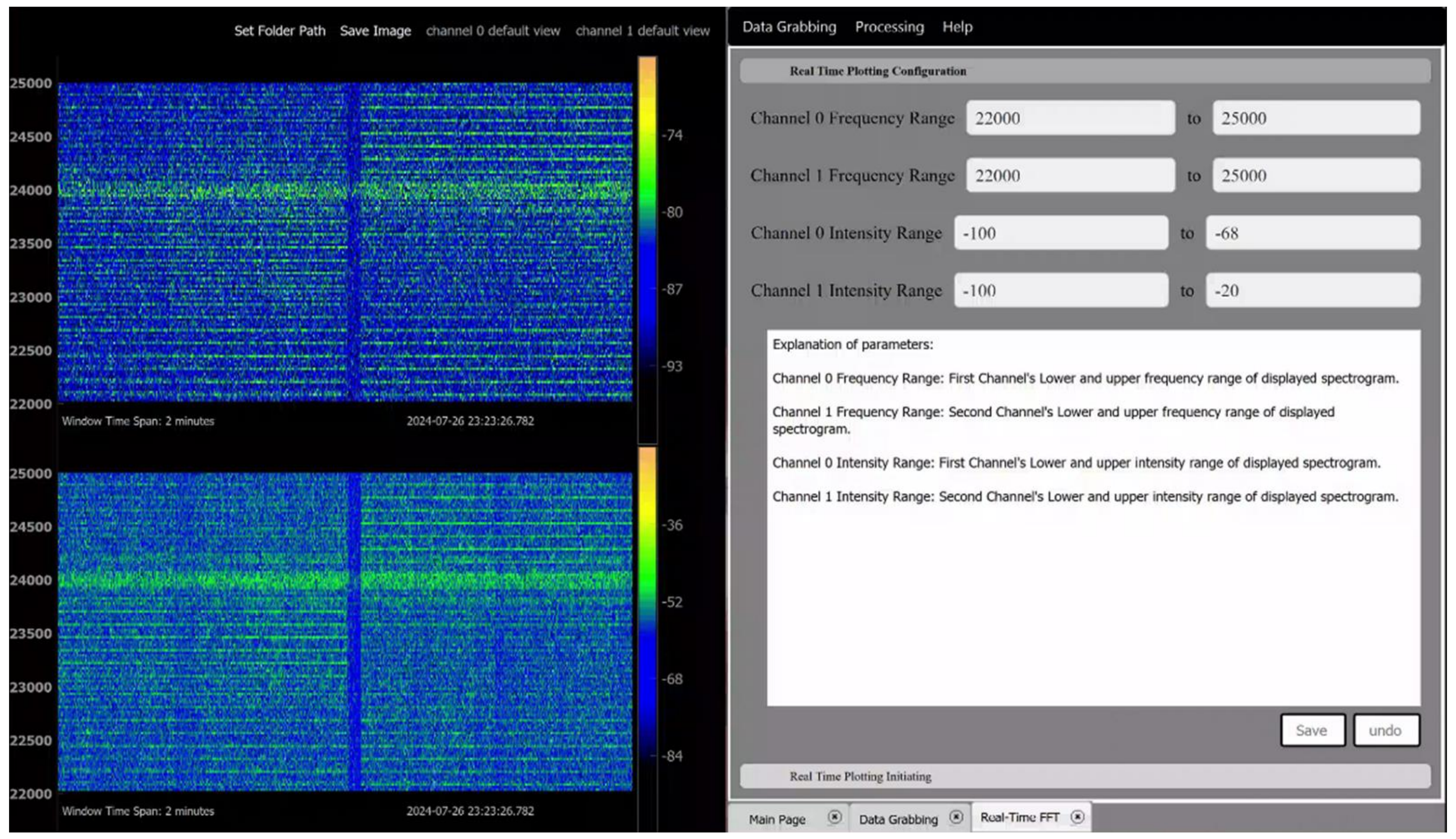
To accurately model the D-region in real-time, we propose to deploy a multi-modal sensor network using VLF antennas. This network must solve the ill-posed inverse problem with robust regularization techniques, given the lack of ground truth data. Our design includes advanced data acquisition systems capable of handling large data volumes and integrating auto-tuning mechanisms for dynamic adjustments. Furthermore, we draw on our experience with the NeSSI initiative to create a standardized, modular sensor network with a digital communication bus architecture for centralized control and real-time data processing. This effort will enhance real-time monitoring, predictive maintenance, and the overall understanding of the ionospheric D-region and improve the reliability of critical communication systems.

System Design

The RF system can capture ultra-low-frequency (ULF) and very-low-frequency (VLF) EM signals with improved modularity and reliability. Key components include surge protectors, pre-amplifiers, low-pass filters, and a high-speed data acquisition unit (DAQ). The components were configured to prioritize adaptability and ease of component interchangeability, which were two of the limitations we identified in previous designs

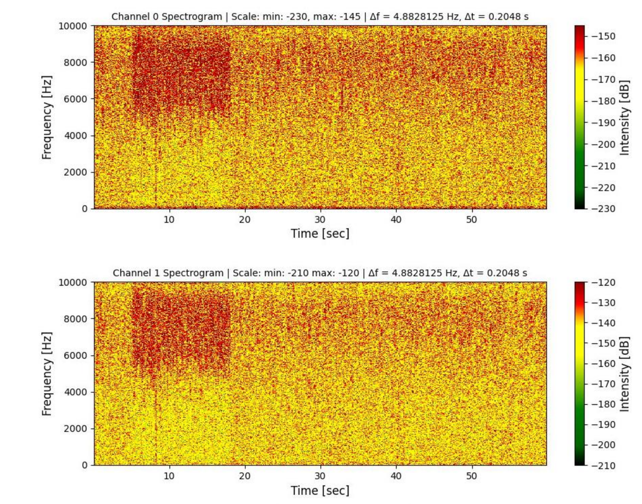


The software has been designed to overcome the limitations of temporary data storage during continuous data collection. It emphasizes real-time data logging and processing, minimizes data loss, and efficiently handles large volumes of data through advanced signal processing techniques (e.g., Fast Fourier Transforms (FFTs)). A high-performance portable workstation is used to manage large volumes of data and process data during sampling. The sampled data is transferred to a high-speed, high-capacity solid-state drive (SSD) via Thunderbolt for data capture and handling. The data is safeguarded post-sampling by creating two copies: one on a Hard Disk Drive (HDD) disk array (for cold backup) and another on cloud storage (for backup and remote access).



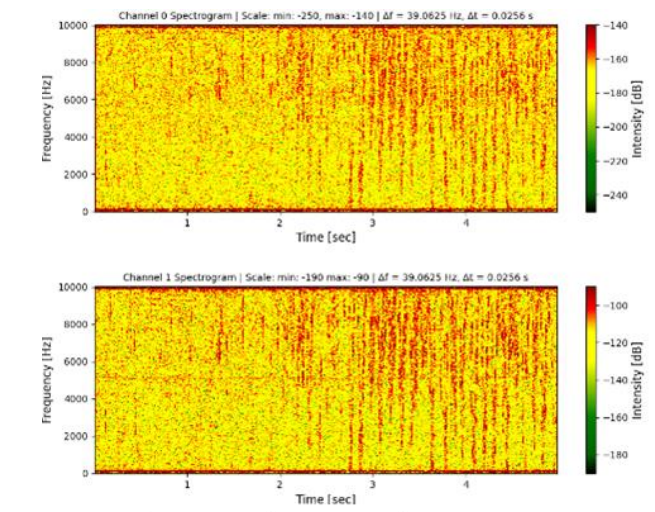
Our Results

Meteor Trail.
Credit: Winston B.



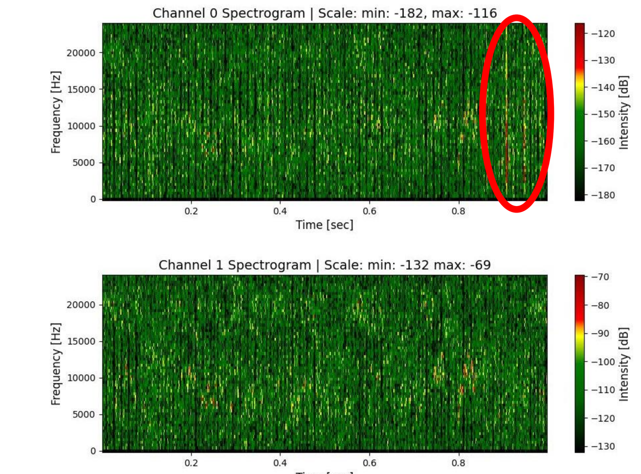
Meteor Signals Signature

Rocket Trail.
Credit: SpaceX



Rocket Signals Signature

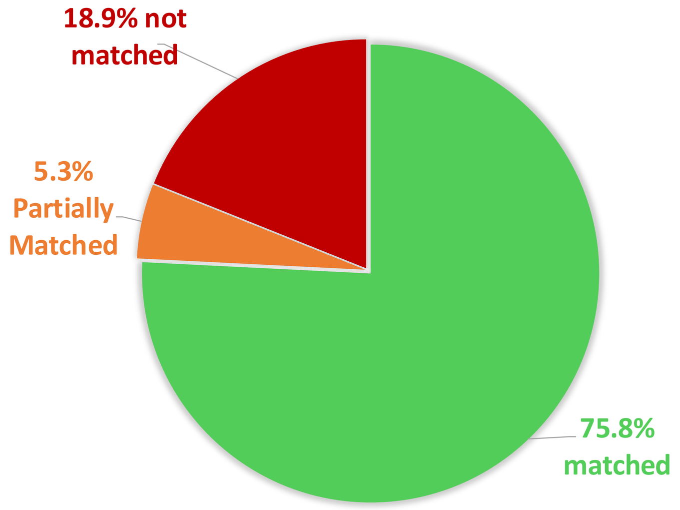
Lightning.
Credit: Mathias Krumbholz



Lighting Signals Signature

For 95 events randomly selected from the AMS database [3] from 2024 Jul 27th to 2024 Aug 10th (Perseids):

Events	Matching Status	Signals Detected	Timeframe
72	Matched	Clear and decent	Within 2 minutes
5	Partially Matched / Not sure	Clear	Within 5 minutes
18	Not Matched	None or Weak	/



References and Acknowledgments

[1] Scales, W. A.; Mahmoudian, A., Charged dust phenomena in the near-Earth space environment. Reports on Progress in Physics 2016, 79 (10), 106802.

[2] Wang, H.; Ridley, A. J.; Lühr, H.; Liemohn, M. W.; Ma, S. Y., Statistical study of the subauroral polarization stream: Its dependence on the cross-polar cap potential and subauroral conductance. Journal of Geophysical Research: Space Physics 2008, 113 (A12).

[3] A. M. Society. "AMS Fireball Reports." https://fireball.amsmeteors.org/members/imo_view/browse_reports (accessed Jan 31, 2025).

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