Enhancing GNSS Resilience with AI: Single-Frequency TEC Estimation Using the Portable SDR-Based ÆtherLink System

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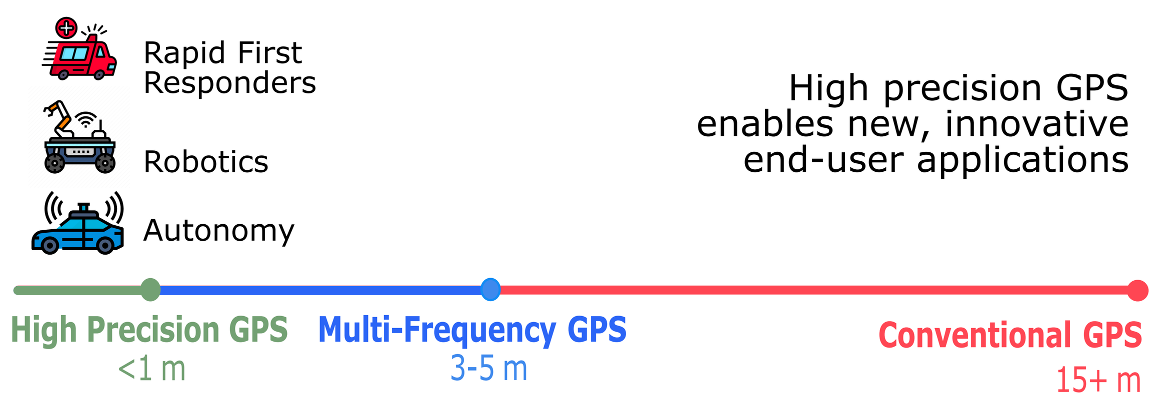
Motivations



Challenges

When Signals travel through Earth's Ionosphere, they get delayed, refracted and attenuated
1-100+ m of errors

Strong signal interference can spoofing and jam GPS
100+ m of errors

Hypothesis

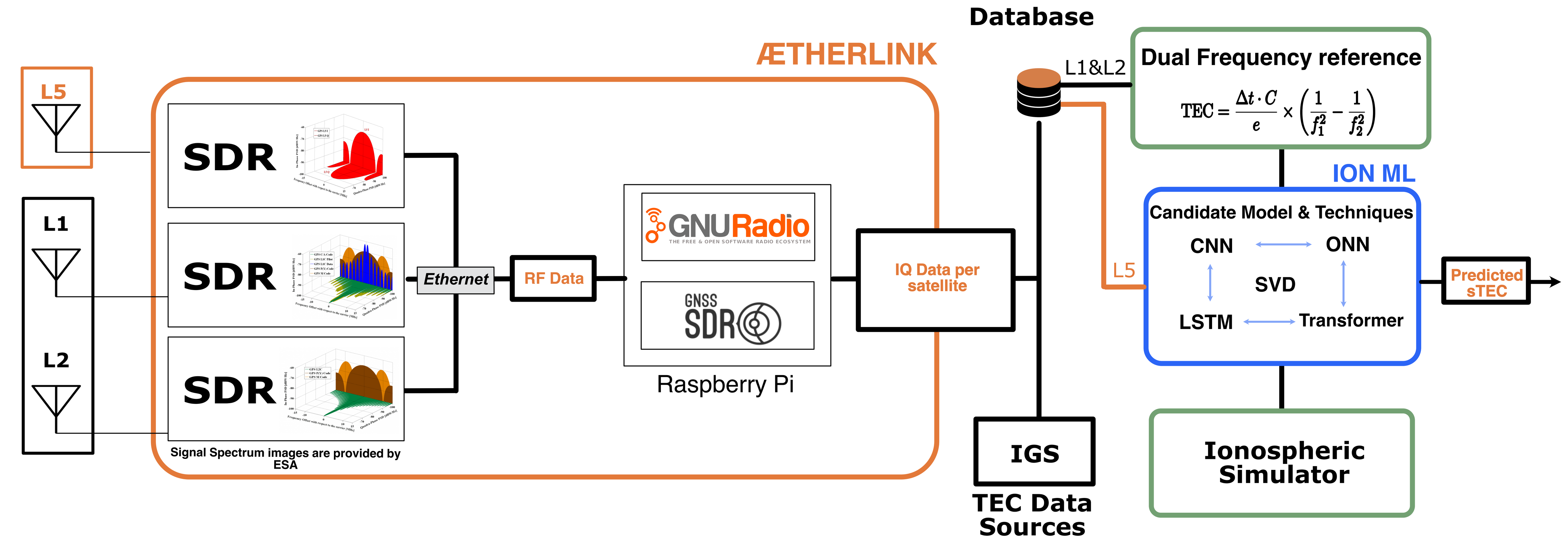
Under moderate to severe **ionospheric dispersion**, a 1 TECU increase in slant TEC yields a measurable change in the differential signal characteristics of **L5 GPS's** In-phase (I) and Quadrature (Q) components—a variation that ÆTHER proposes to exploit via **ML augmented signal processing** to predict **satellite-specific TEC in real time**.

State of the Art

Current Methods	Measurement Type	Strengths	Current Limitations	How ÆTHERLink addresses it
Global vTEC Models [1-3]	Large-scale interpolation	Global coverage	Low spatiotemporal resolution	In-situ measurements
		Low computational demands	Only 50% of RMSE error	Physics-based ML for high precision measurements
		Large-scale monitoring	Expensive and slow	SDRs + Embedded computers
Dual Frequency sTEC [3-5]	Frequency based measurement	High accuracy	Susceptible to cycle slips	Studies single frequency L5 GPS signals
			Highly susceptible to partial outages	
		Real time	Needs specialized equipment	Uses commonly available RF equipment
			High convergence times	Immediate measurements

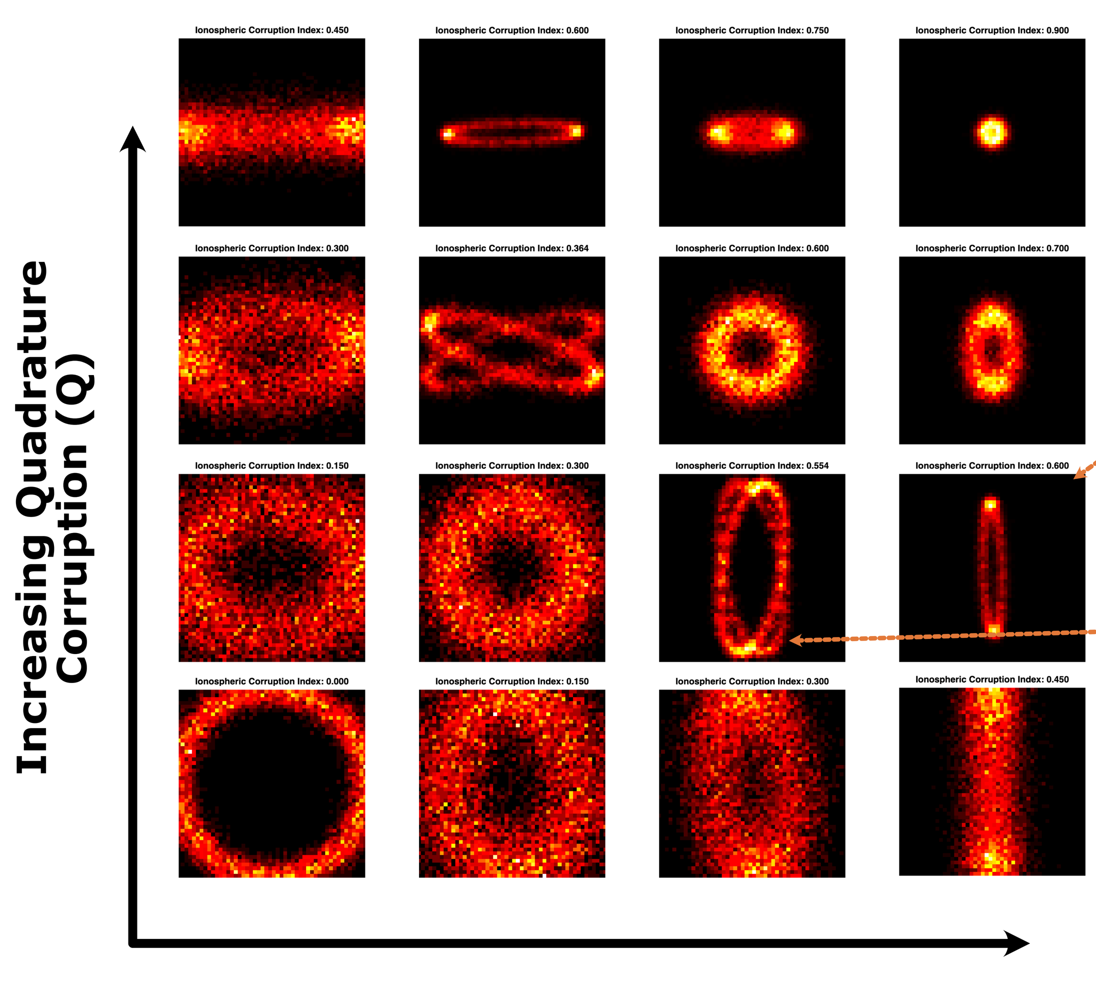
References:
[1] - G. Johnston et al. Springer Handbook of Global Navigation Satellite Systems, 2017
[2] - H. Mahbuby and Y. Amerian. Pure Appl. Geophys., vol. 178, no. 4, Apr. 2021
[3] - P. Chen et al. Advances in Space Research, vol. 65, no. 1, Jan. 2020
[4] - Y. Yin et al. IEEE Transactions on Geoscience and Remote Sensing, vol. 62, 2024
[5] - M. Li et al. Space Weather, vol. 22, no. 7, Jul. 2024

Methods



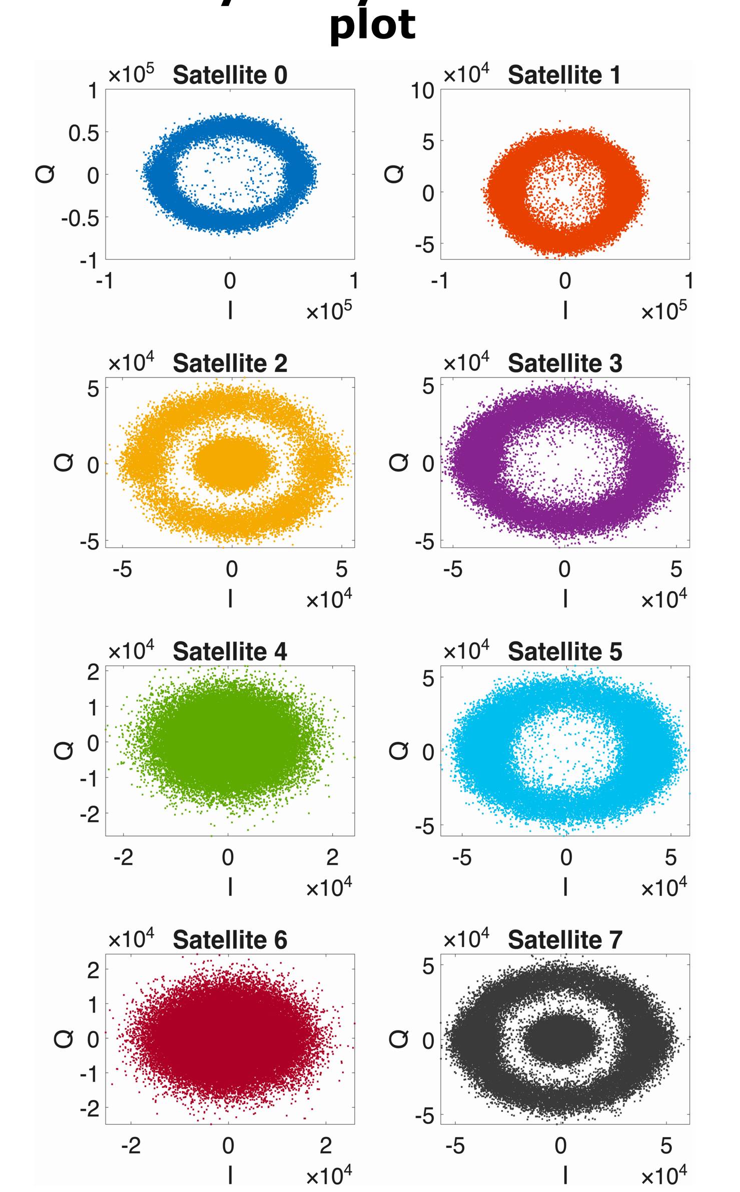
Results

Ionospheric IQ Sampling Simulation BPSK Heat-map



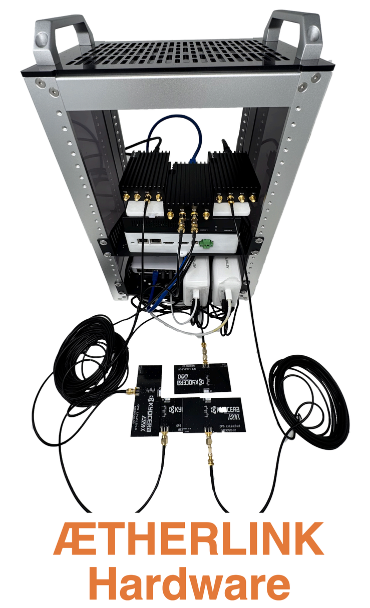
ION ML will train on patterns collected under known TEC conditions to predict per satellite sTEC along the line of sight.

Preliminary analysis of satellite IQ plot



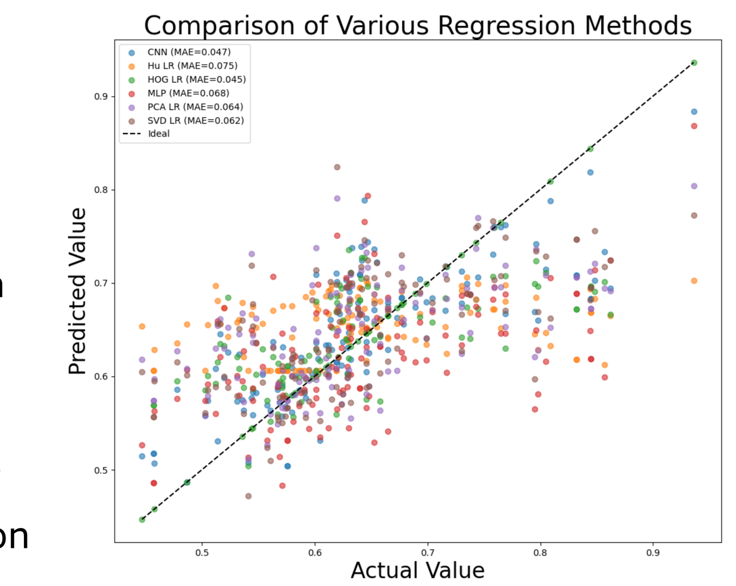
Ellipticity of all plots and pattern support hypothesis that individual satellite's IQ values are affected differently.

Discussion



- Current Studies have highlighted issues with the ÆTHERLink hardware and compatibility issues between SDRs, available software and platforms. Efforts are ongoing to further develop the software components of ÆTHERLink

- Preliminary data suggest a combination algorithms with both conventional and ML components is good candidate for ION ML, though further studies need to conducted to validate this proposition



Future Works

Limitations	Future Works addressing Limitations
• Preliminary Findings This study is in its early stages, and further investigations are needed to validate and refine the results.	We are currently conducting more studies in the field to verify and develop our methods
• Hardware Constraints The existing hardware has limited capabilities in terms of operation across different platforms, leading to potential incompatibility issues and performance bottlenecks. • Software Compatibility Issues Although software solutions are available, they do not always integrate seamlessly with diverse hardware platforms, complicating deployment and scaling.	We are currently focusing on improving the compatibility between software and hardware to ensure smoother integration across different systems using a more generic python and MATLAB based method
• Algorithm Limitations Existing algorithms, such as Phase-Locked Loop (PLL), heavily rely on extensive filtering techniques. While this is useful for certain applications, it can inadvertently eliminate important signal characteristics that may be critical for more precise tracking and analysis.	We are currently exploring alternative algorithms that minimize filtering to retain key signal features while maintaining tracking accuracy

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