GNSS Remote Sensing of the Ionosphere with Machine Learning and Modeling

(CEDAR Early Career Science Highlight)

Kshitija Deshpande[1] (**deshpank@erau.edu**), *Anna-Marie Bals, Chintan Thakrar, Nick Gachancipa, Pralay Vaggu,* Matt Zettergren[1], Leslie Lamarche[3]...

1. Embry-Riddle Aeronautical University (ERAU), Daytona Beach, FL, USA
2. The University of Tromsø, Norway
3. SRI International, Menlo Park, CA, USA.

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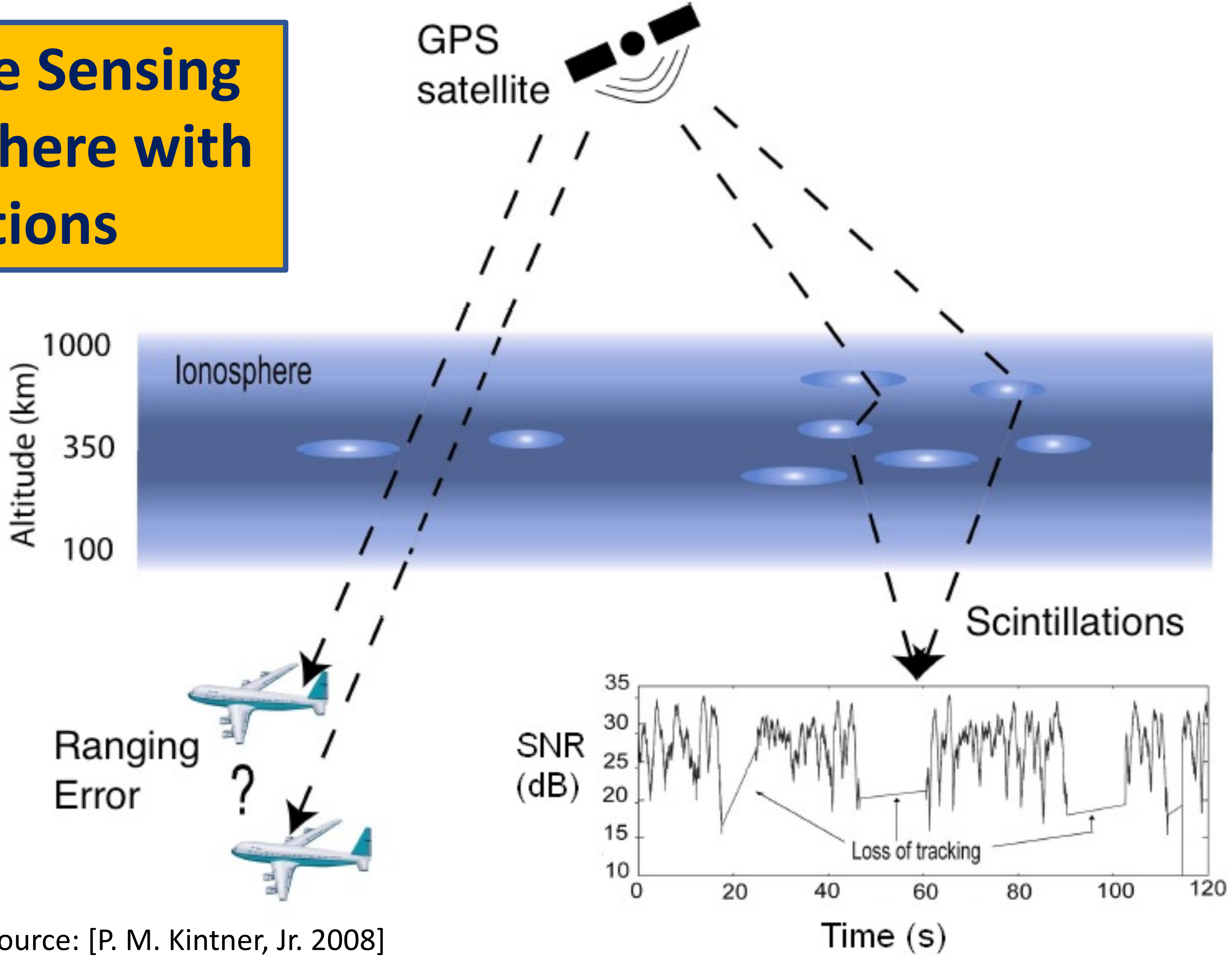
GNSS Remote Sensing of the Ionosphere with Scintillations



GNSS/ GPS Signals are degraded due to ionospheric irregularities

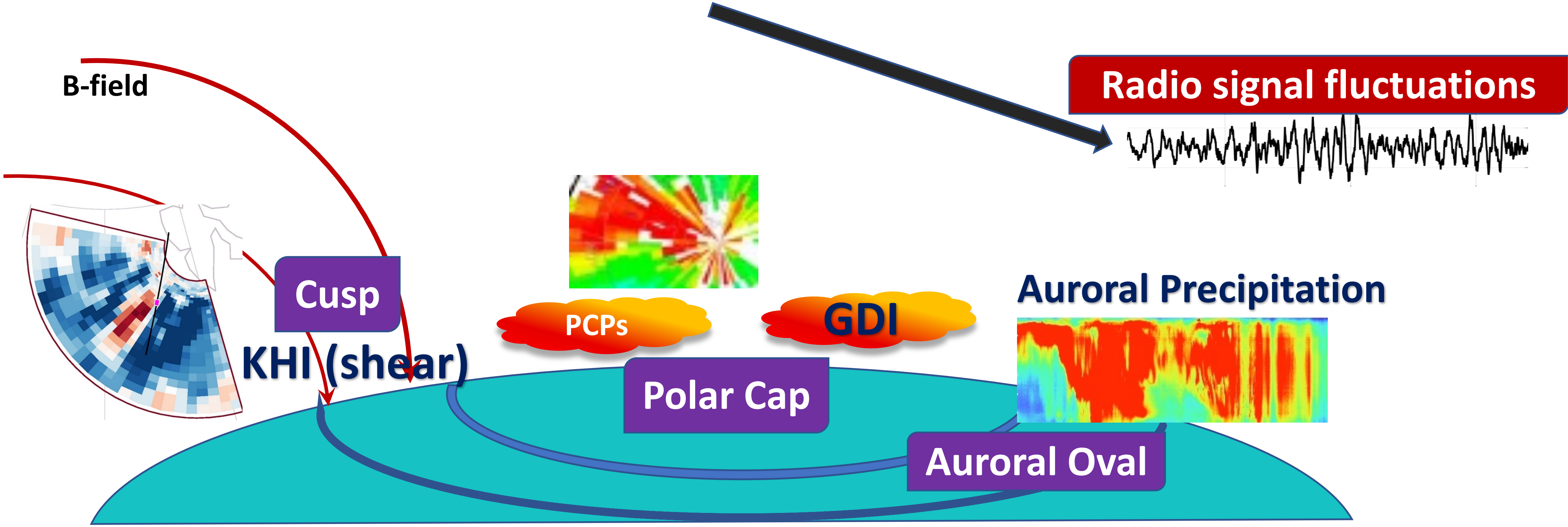
Source: [P. M. Kintner, Jr. 2008]

Hi(gh level)story of scintillations...

- GPS/ GNSS scintillations or **fluctuations in the radio signal** – it is important to understand these to fix errors in PNT solutions.
- However, they are **great for science!** Specifically, for **remotely sensing the ionosphere**. Why?- because scintillation data are **abundant**ly available across the globe.
- Since the 1970s, veterans in our field have been using radio signals to study **irregularities – dynamic electron density structures** in the ionosphere, and in **multi-scale ionospheric studies** to understand **cascading of energy** between large to small scales.
- There are many individual **case** studies, as well as **statistical and climatological** studies of high and low-latitude scintillations.
- **Propagation modeling** is bringing new information when **coupled with ionospheric models** and **auxiliary data**.

Citations: Rino 1973, Yeh Liu 1982, Kintner Seyler 1985, Spogli et al 2009, Jin et al 2015, Review by Deshpande et al in Nishimura et al. 2022 book on Cross-Scale Coupling and more …..

Different Sources of Scintillation Producing Irregularities



The **science questions** we are trying to answer here:

1. **Can we categorize the high latitude irregularities (e.g. auroral oval Vs polar cap latitudes) in terms of temporal and spectral scintillation signatures using analytics and ML?**
2. **What is the relationship between scintillation and the sources of irregularities responsible for the scintillation?**

Figures: KHI: https://doi.org/10.1002/2016JA022999, PCP: https://doi.org/10.1002/2016GL069230, Precipitation: Thanks to Don Hampton

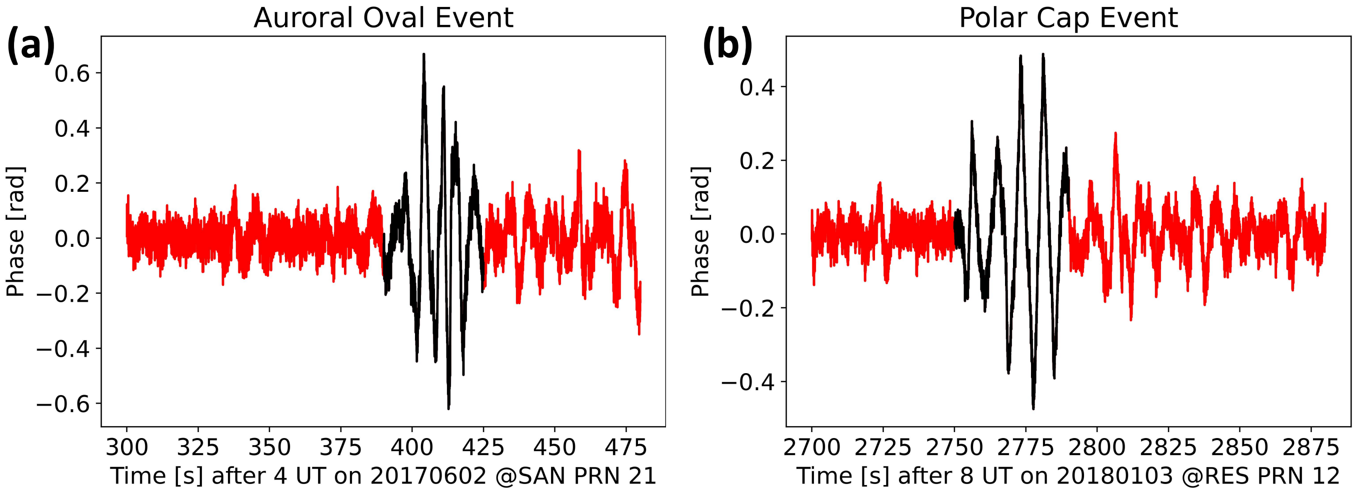
So where does Machine Learning come in?

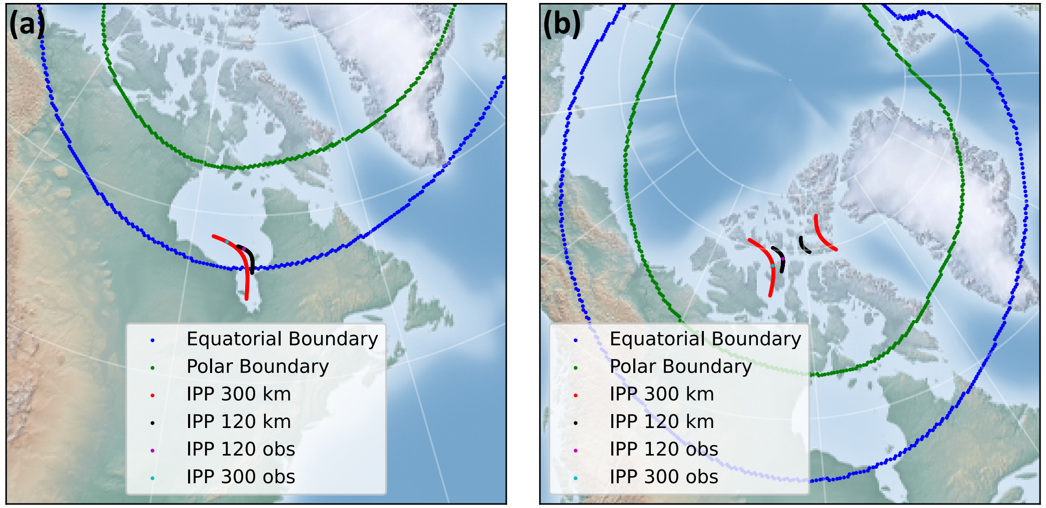
- A typical science-grade GNSS receiver collects **high-rate 50-Hz phase and amplitude data** for **35 satellites at a time** – Big Data.
- Big Data is a collection of high-volume, high-velocity, and/or high-variety information that typically requires processing and analysis before it can be used to improve decision-making and processes. – Research Firm Gartner's definition – **GNSS data = Big Data**!
- Working with **Big Data** – extracting scintillation instances, different features, predicting occurrences, etc. can be done better with **machine learning** (ML) algorithms.
- **ML and deep learning** are fast-growing fields with tons of applications in space weather, however, one needs to **be careful** in their usage. Not to be used as black boxes.
- **Data preprocessing** in terms of collecting, cleaning up the raw data, and labeling it correctly are **critical** for reliable ML usage.

Our quest: Can we categorize the high latitude scintillations based on the source regions (polar cap Vs auroral oval)?

Categorizing Scintillation in terms of Source Regions Using Machine Learning and Deep Learning - Thakrar et al. [in prep]

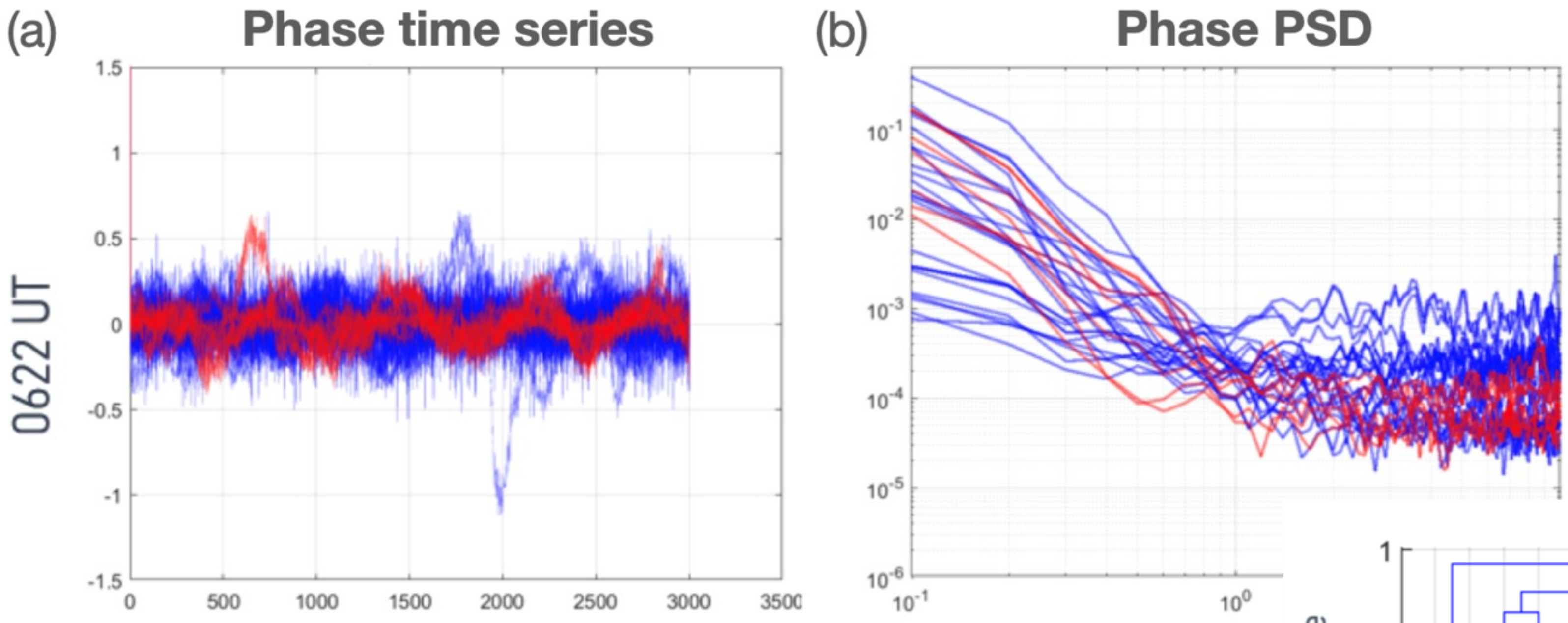
1. 2 years of CHAIN data from 3 Stations (1TB/year/station).
2. For labeling, we use SSUSI-derived auroral oval boundaries
3. We use an Unsupervised Isolation forest machine learning algorithm for the detection of scintillation events with accuracy > 98%.
4. We train a neural network (supervised) model to classify scintillation events based on the locations: auroral and polar regions with 95% training and ~ 80% validation and testing accuracy (for all kp).
5. NN models is extracting patterns from the data, which proves that the model is capable of distinguishing auroral oval/polar cap events.



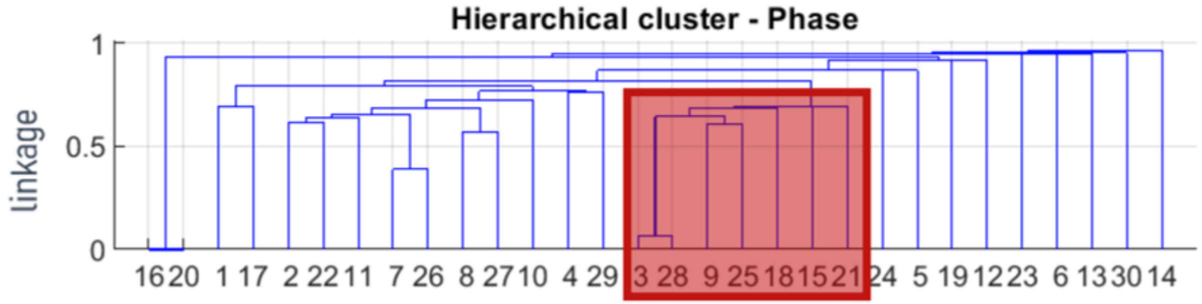


Database to Identify High-Latitude Scintillation Signatures With Unsupervised Machine Learning - Bals et al. 2022 IEEE RFID

- Reports significant scintillation event detection approach that does not require thresholds or training of an ML model
- Unsupervised ML With Agglomerative Hierarchical Clustering for Time Series (phase, power and both)

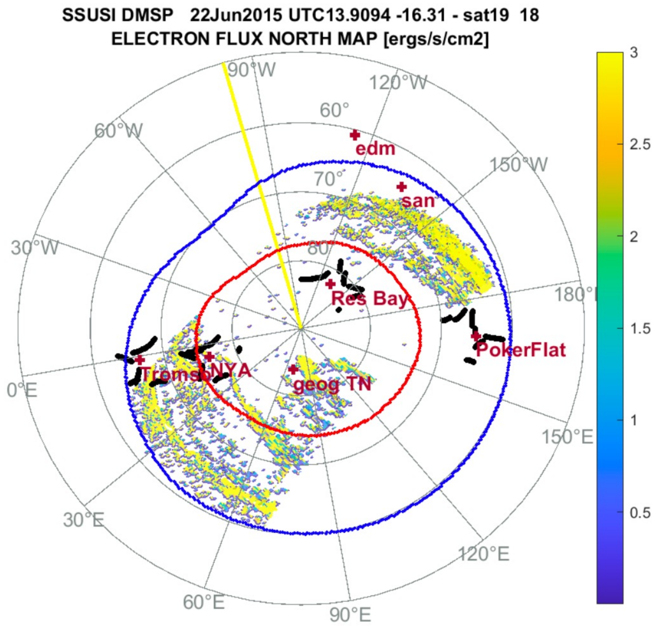


Phase signatures from the clustering analysis for PokerFlat on 22nd of June 2015 after 6:22 UT. Red signatures correspond to the extracted subgroup (possibly related to ionospheric structures different than the rest).

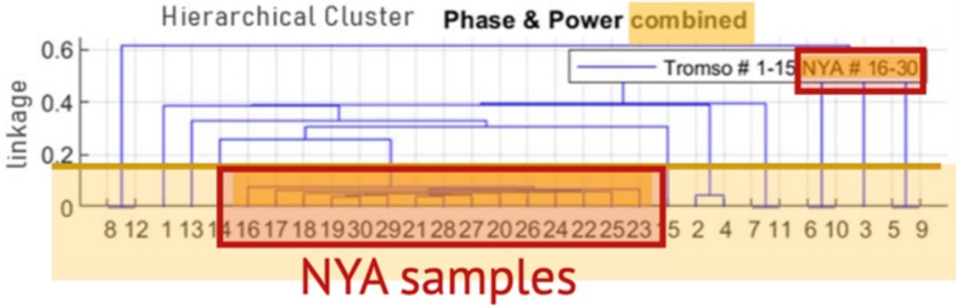


Decision Trees based Classification of scintillation in terms of source regions during Storm Times – Bals and Deshpande [in prep]

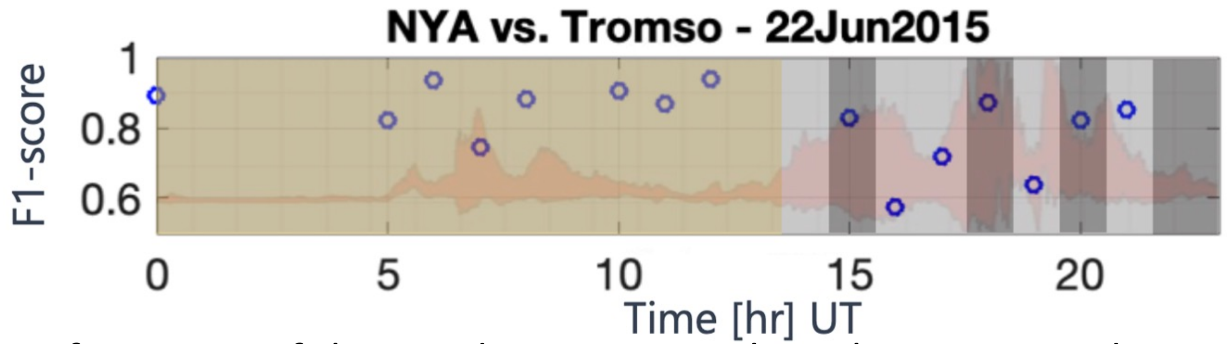
- We explored 5 different storm times and different pairs of stations (between polar cap and auroral oval) in order to classify scintillations based on their signatures.
- We use a combination of hierarchical clustering and decision trees to classify signatures between polar and auroral regions.



Labeling process per hour for scintillation signatures at each station



Hierarchical clustering in power and phase on the 9th of March 2012. The red box marks all samples from the Ny.



Performance of the ML decision tree algorithm expressed as the F1-score (over day and night). Dark gray shading indicates an ambiguous label for the signatures within that hour. Drops in performance seem to correlate with unclear signature labels.

What about modeling?

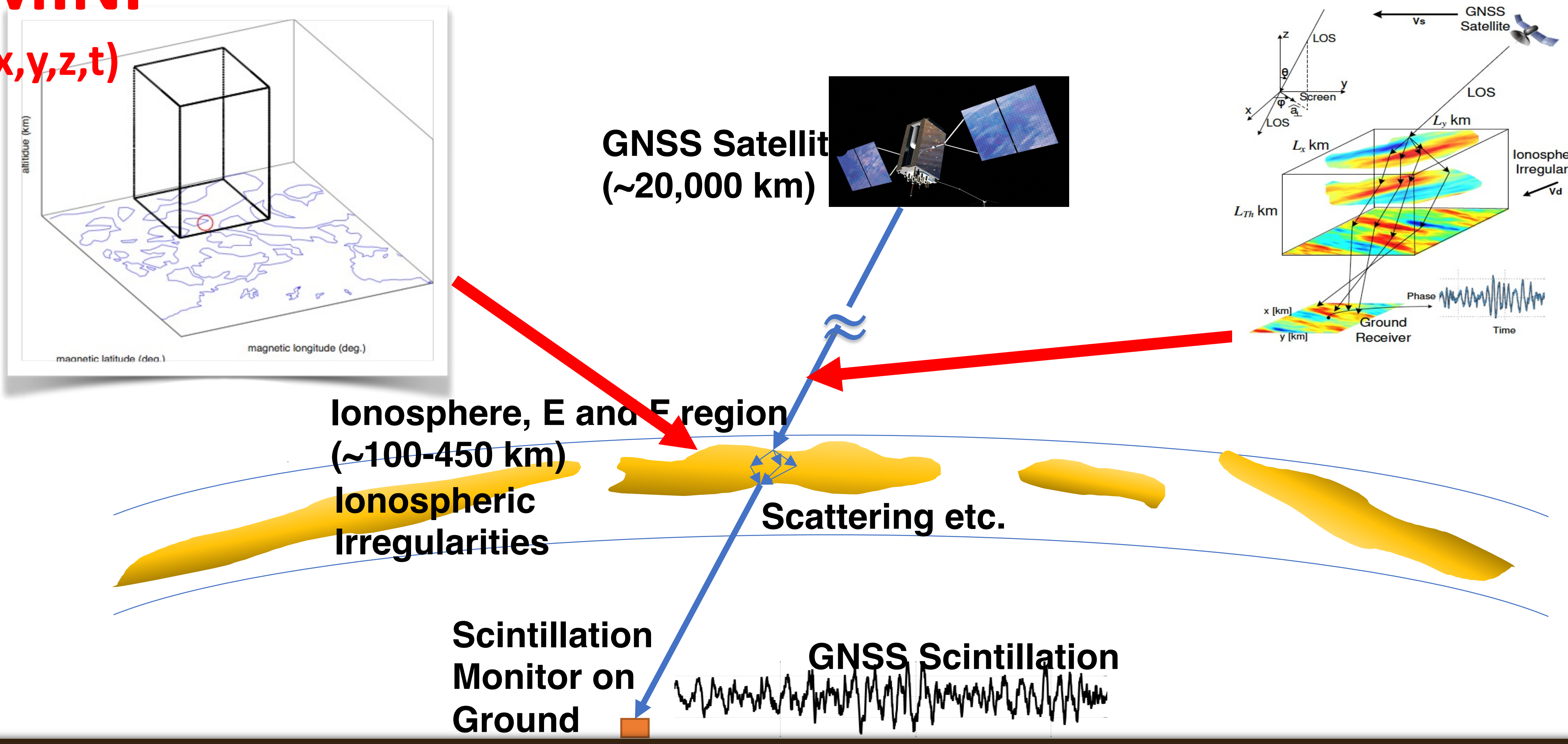
While exploring **ML to categorize** scintillation in terms of source regions, we are separately understanding the physics for individual cases using modeling studies.

Coupled models for scintillation study

GEMINI

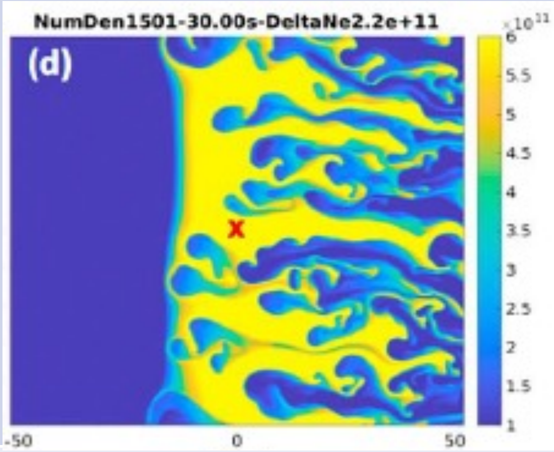
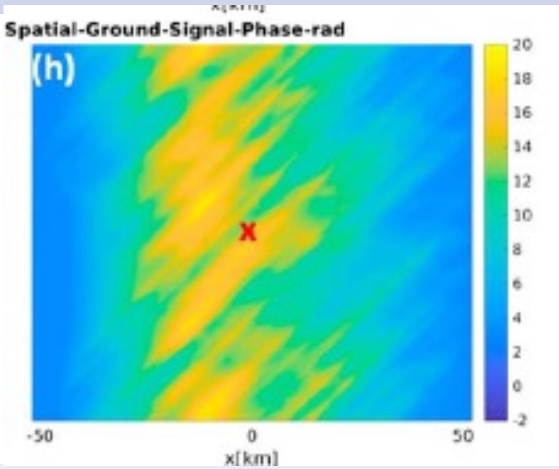
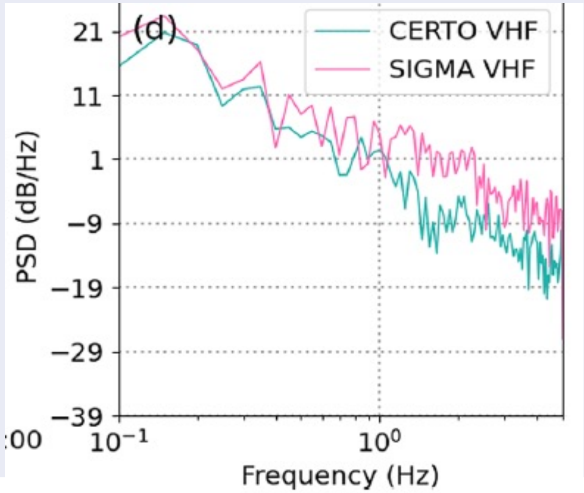
Ne(x,y,z,t)

SIGMA

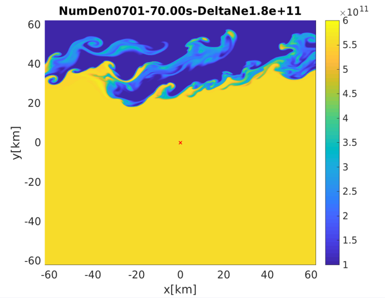
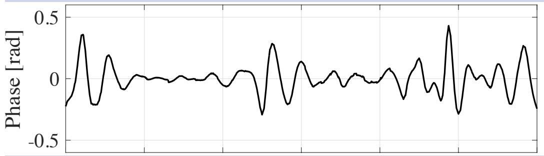
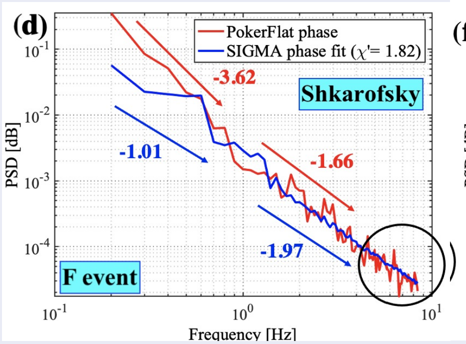
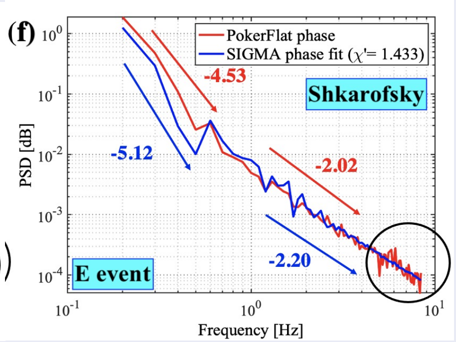
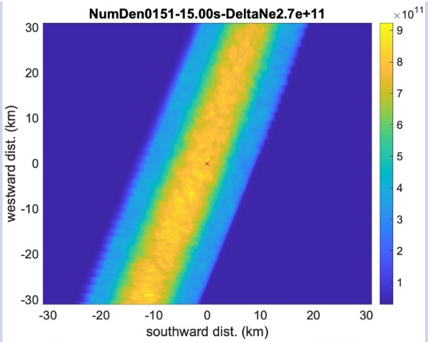
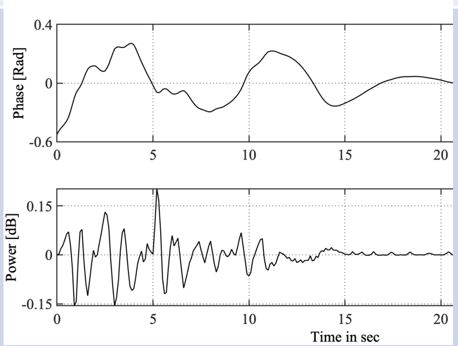


$\mathbf{E}_0, n_e(x, y, z, t_0)$ → **GEMINI** → $n_e(x, y, z, t)$ → **SIGMA** → phase and amplitude scintillation

Modeling Studies of scintillations

Instability/ Source region	Paper	Result	Conclusion
Gradient Drift Instability (GDI)/ Polar Cap	Deshpande and Zettergren 2019	 	GDI in the trailing edges creates scintillations
GDI/ Polar Cap (multifrequency)	Lamarche, Deshpande, Zettergren 2022		GDI turbulent cascade needs to develop to create UHF, VHF and GPS signatures.

Modeling Studies of scintillations

Instability/ Source region	Paper	Result	Conclusion
Kelvin Helmholtz Instability (KHI)/ Cusp	Spicher et al 2020	  120s long time series	Scintillations are related to small-scale structures near KHI vortices.
Precipitation/ Auroral	Vaggu et al 2023	 	E Vs F irregularities show distinctive morphological features [inverse modeling approach]
Precipitation/ Auroral	Vaggu et al [in prep]	 	Precipitation can generate scintillation within the arc.

Summary

- We are exploring different **ML approaches to categorize** scintillation events between source regions using high-latitude datasets.
- We have successfully **used hierarchical clustering, decision tree, isolation forest, and neural network algorithms** to detect, classify and categorize scintillations. We are now exploring SVM [see Marie Bals' poster Wednesday afternoon].
- We investigated **the effects of KHI (in Cusp) and GDI (in Polar cap region) on radio signal fluctuations** using GEMINI-SIGMA modeling, studied **multi-frequency effects on radio signals** (GDI in Polar Cap) by simulating the signal fluctuations at UHF (1.57 GHz, 400 MHz) and VHF (150 MHz), and are looking into **scintillation due to precipitation** or possibly secondary instabilities [see Pralay Vaggu's poster Wednesday afternoon].
- We are also trying to understand **the spectral slope connection** between GDI, KHI, precipitation, and their scintillation signatures on the ground with both modeling and machine learning.
- Our ultimate goal is to explore a **combination of ML algorithms and modeling** for **scintillation prediction problems**.

Challenges?

- What’s the most suitable ML algorithm for each task?
- How can we be sure that the scintillation signatures are different indeed (that’s our hypothesis)?
- How to obtain a trustworthy still large number of samples to train your ML algorithm?
- For modeling, is there really one type of instability causing scintillation or a mix?
- Do we use scintillations from refractive, diffractive sources, or both?
- What size structures generate scintillation? How strong do they have to be?
- Do we have a primary mechanism like precipitation or secondary instabilities or a combination generating scintillation on the ground?

And many more….

Review by Deshpande et al in Nishimura et al. 2022 book on Cross-Scale Coupling – We dedicate a whole large section in this chapter to Challenges in modeling and high latitude irregularity studies!

“In a day, when you don't come across any problems - you can be sure that you are traveling the wrong path.”

— Swami Vivekananda, one of the greatest thinkers of all time