Modelling and forecasting ionospheric scintillation at high latitudes

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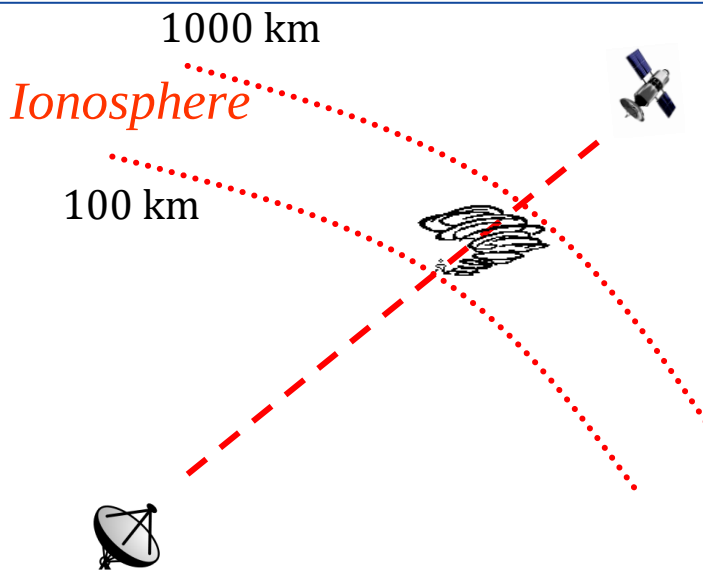
May 19th , 2022

Introduction : Context of this research activity

Increasing operational needs
for ionospheric scintillation characterization,
in particular for GNSS systems
(log-amplitude and phase variance, and associated spectra).

Scintillation activity influenced by Space Weather events,
especially at high latitudes.



So requests for :

- Direct problem modeling (for system design)
- Inverse problem modeling (for ionosphere conditions probing)
- Scintillation events forecasting (for system operational planning)

Presentation outline

- Modeling efforts on ionospheric scintillation
  - STIPEE code
  - Inversion of ionosphere characteristics from GNSS signals

- Forecasting ionospheric scintillation in Arctic area
  - Statistical approach: HAPEE model
  - Machine Learning approach: LSTM

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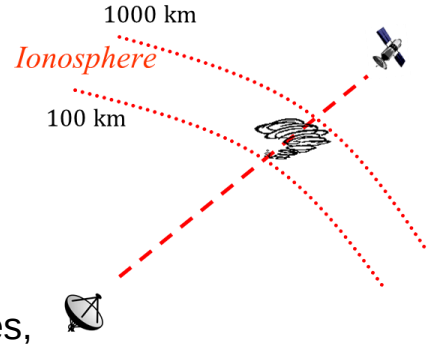
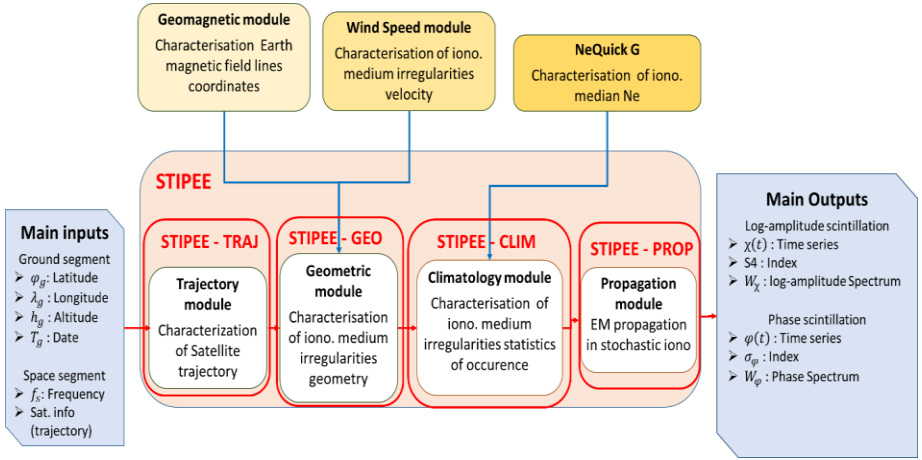
Modeling ionospheric scintillation : STIPEE code



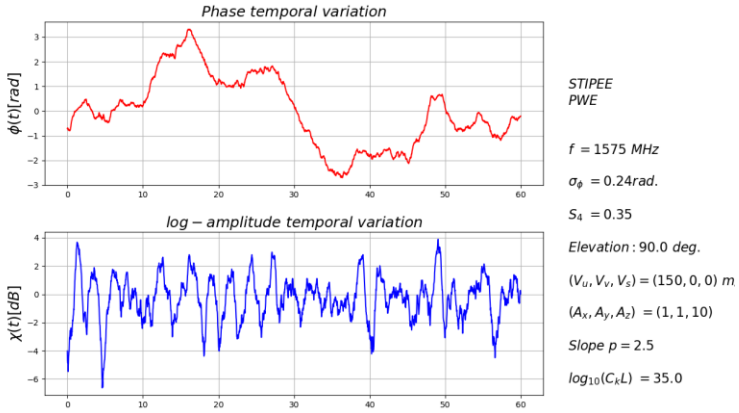
STIPEE = Software Tool for Ionosphere Propagation Effects Evaluation

Objective

Developing a climatological model of ionospheric irregularities, compatible with an EM propagation scintillation tool (PWE-MPS) and valid at all latitudes, so that the model is able to consider any type of Earth-satellite link.



BLOCK DIAGRAM OF STIPEE MODEL FOR SCINTILLATION MODELING



Example of phase $\varphi(t)$ (top graph) and log-amplitude $\chi(t)$ (bottom graph) time series generated by STIPEE model at L1 frequency.

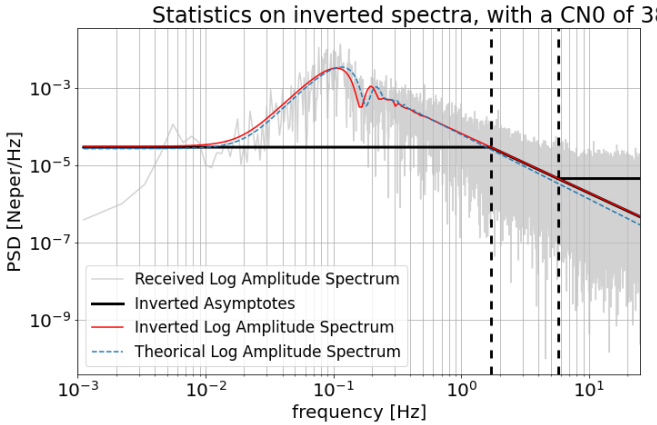
Modeling ionospheric scintillation : Inversion of ionosphere characteristics from GNSS signals

Objective
Retrieve turbulent ionosphere characteristics from GNSS signals,
in order to feed / cross validate STIPEE model.

Aurelien Galmiche PhD (2018) :
first algorithm was developed (for low latitudes)

Probing of medium **anisotropy, strength of irregularities, PSD-slope, medium drift velocity**

Current R&T study with TAS for model improvement.



Parameter	Inverted	Theorical
Plateau [Neper/Hz]	2.93e-05	2.54e-05
Medium slope [\]	2.54	2.68
Cutoff freq. [Hz]	1.70e+00	1.71e+00
Az [-]	28.00	28.47
Ay [-]	1.00	1.00
log10(CkL) [\]	32.77	32.90
Vdrift [m/s]	30.77	26.84

Example of log-amplitude χ PSD inversion.

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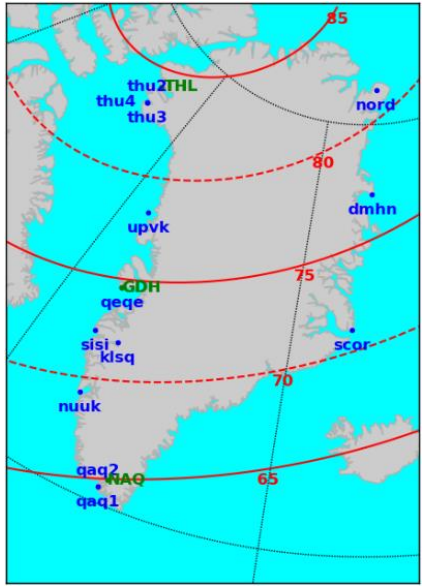
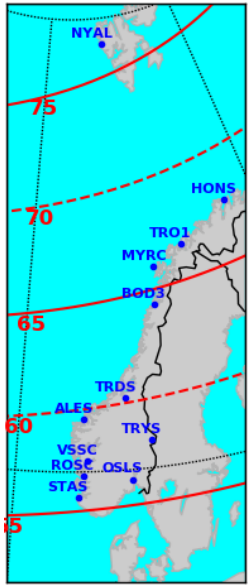
Forecasting ionospheric scintillation in Arctic area

Data sources:

Locations of:

- NMA GNSS receivers in **Norway**
- GNET GNSS receivers in **Greenland**





ROTI = Rate of Change of TEC Index
→ proxy of scintillation activity

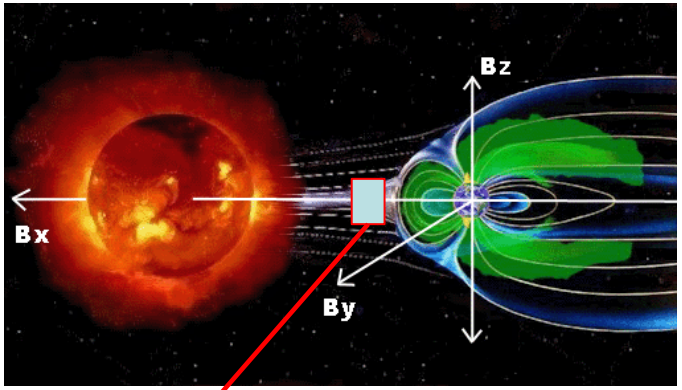
The final ROTI database used as baseline for the forecasting service development validation and test contained more than **95 million ROTI data** samples from **2013-2021**

Solar wind parameters are extracted from the 5-min resolution solar wind and geomagnetic activity data NASA's OMNI database
from Space Physics Data Facility (SPDF, https://spdf.gsfc.nasa.gov/).

Forecasting ionospheric scintillation in Arctic area
Statistical approach: HAPEE model

From NMA and GNET databases of ROTI index, regressions of statistics conditioned by solar wind data measured at L1 Lagrange point to develop a scintillation forecasting model

- Input

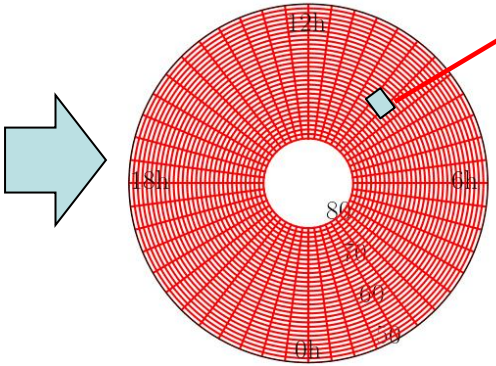


Newel coupling function

$$\frac{d\Phi_{MP}}{dt} = v^{\frac{4}{3}} B_T^{2/3} sin^{8/3}\left(\theta/_2\right)$$

- Output

Mlat, MLT position

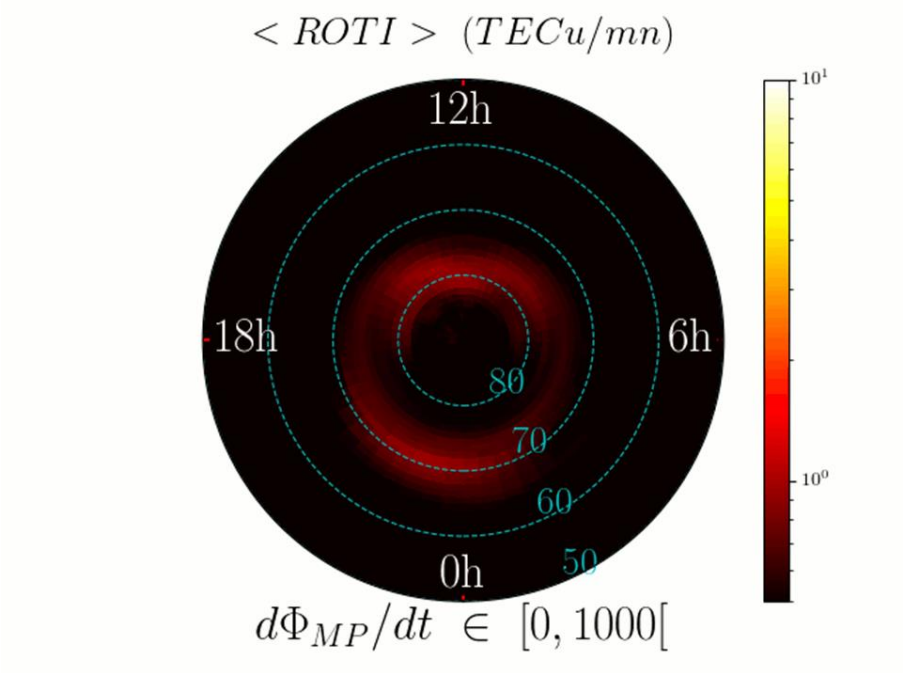


Forecasting ionospheric scintillation in Arctic area
Statistical approach

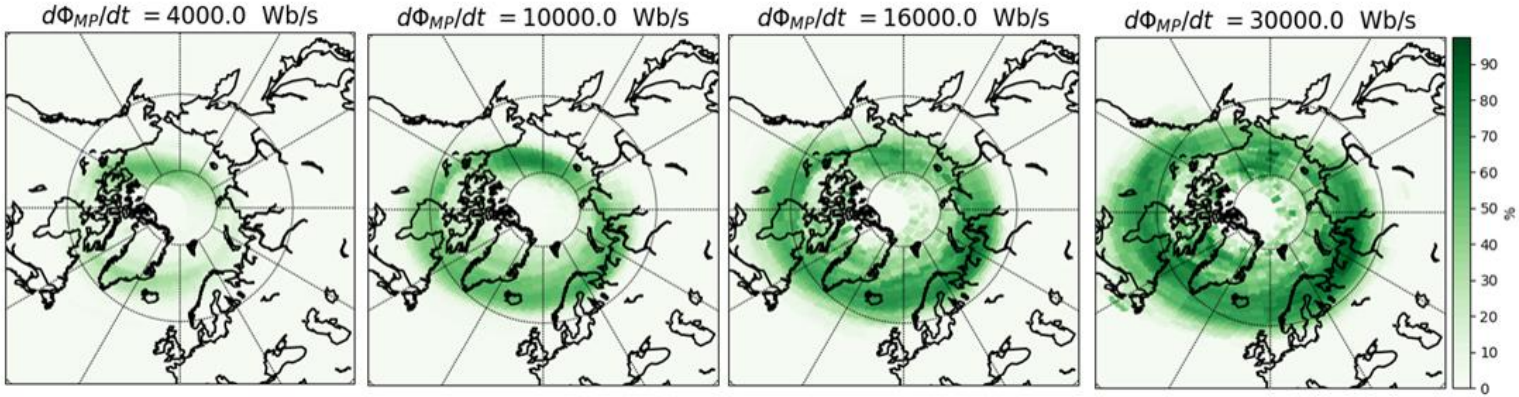
Examples of HAPEE modeling

forecasting of $\langle ROTI \rangle$
between $t_0 + 2$ and $t_0 + 3$h

versus Newel coupling function level at t_0



Forecasting ionospheric scintillation in Arctic area
Statistical approach



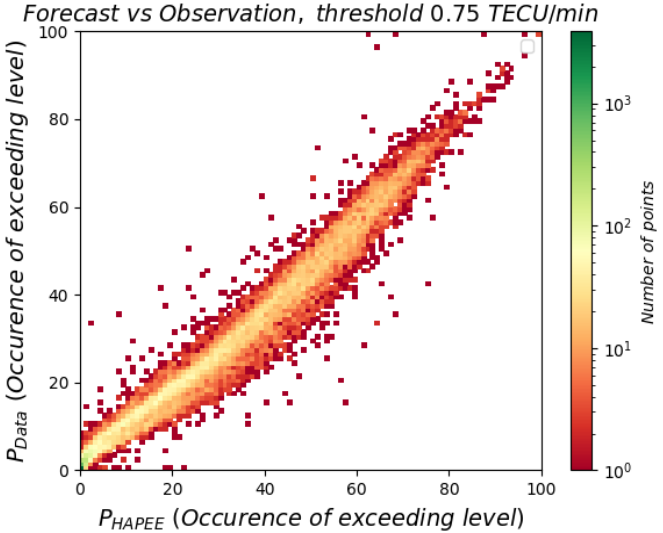
Probability of occurrence for a ROTI value to exceed a threshold of 1 TECu/mn between t_0 and $t_0 + 1$h for different coupling function values, at 0h, UTC.

Forecasting ionospheric scintillation in Arctic area
Statistical approach : HAPEE Validation

The results of correspondence between modeled and measured $P(ROTI > T_{ROTI})$ are presented in the adjacent figure for threshold 0.75 TECU/mn.

To get this representation, the percentages computed by HAPEE model have been binned every percent. Then, for each interval of 1% of the forecasted percentile, the measured value is represented in ordinate axis by a histogram.

The colors represent the number of points.
This representation allows to illustrate the spreading between modeled and data percentages.



Comparison of forecasted (abscissa axis, from HAPEE model) and measured (ordinate axis, from test dataset) probability $P(ROTI > T_{ROTI})$.

$P(ROTI > T_{ROTI})$ is the % of occurrence to exceed a ROTI threshold for low level of disturbance, i.e. T_{ROTI}= 0.75 TECU/mn.

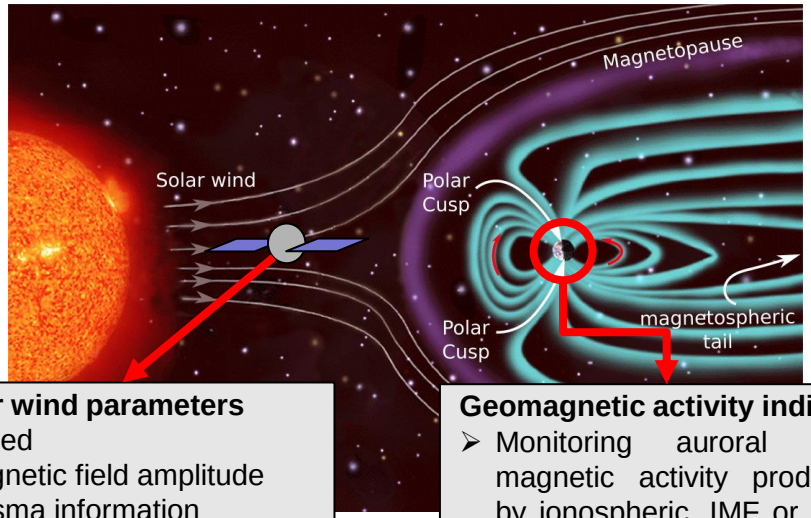
Forecasting ionospheric scintillation in Arctic area
Machine Learning approach

- Obj. : Use Neural Networks to make regional forecasting of **ROTI time series** using **GNET and NMA ROTI** databases as **training** and **evaluation** databases, respectively.

- Motivation to perform this work:

➢ To what extent can **data-driven modeling predict high latitude ionospheric scintillation**?

➢ Is the neural network able to provide **new information** (complementary to HAPEE model) about Space Weather phenomena?



Solar wind parameters
- Speed
- Magnetic field amplitude
- Plasma information

etc ...

Geomagnetic activity indices
➢ Monitoring auroral zone magnetic activity produced by ionospheric, IMF or solar wind conditions.

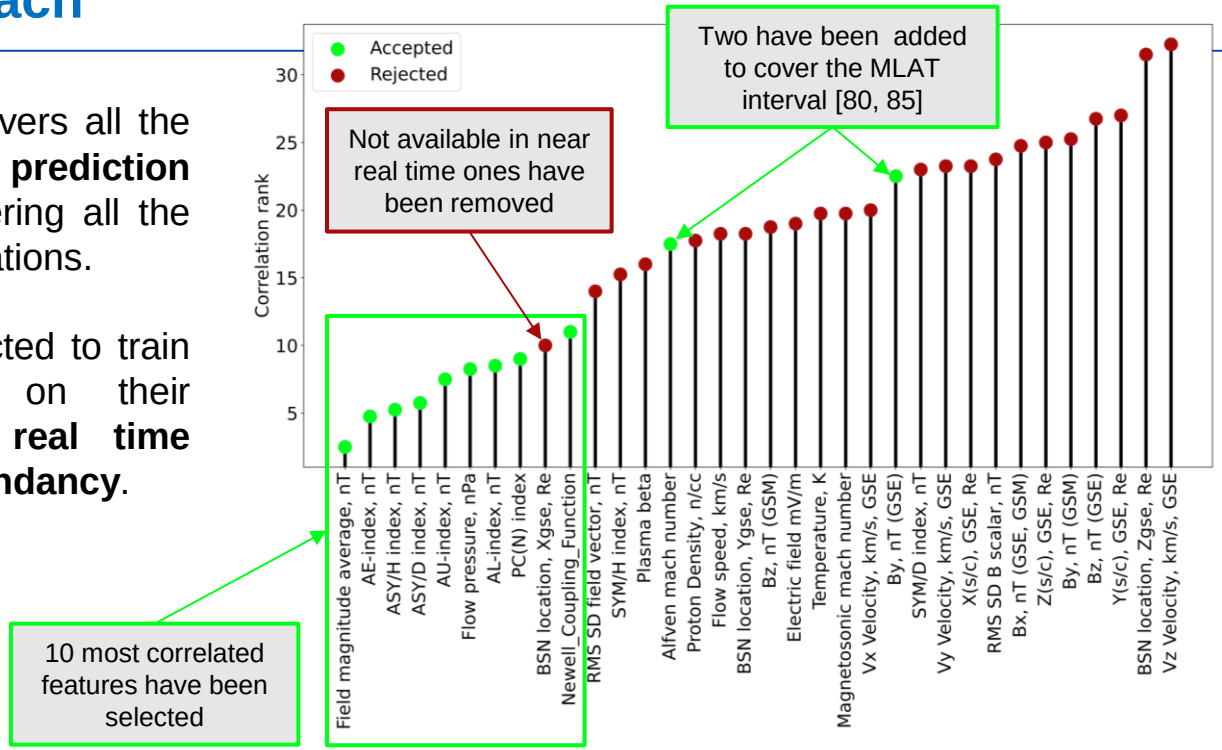
Two different categories of input data, from NASA's OMNI database SPDF, (https://spdf.gsfc.nasa.gov/), available since 1995

Forecasting ionospheric scintillation in Arctic area
Machine Learning approach

- Input global classification: Covers all the **MLAT/MLT intervals** for a given **prediction horizon** (**1h** and **3h**) by considering all the **mean** rank of the unitary classifications.

➢ **11 OMNI** inputs have been selected to train neural networks, depending on their **correlation with ROTI**, their **real time availability** and considering **redundancy**.

➢ **MLT** has been added as inputs to the Neural Networks.



Representation of the global classification of each OMNI inputs. Selected features are in green, rejected ones are in red. Correlation rank corresponds to the average of different Kendall correlation rankings on each ROTI dataset.

Forecasting ionospheric scintillation in Arctic area
Machine Learning approach

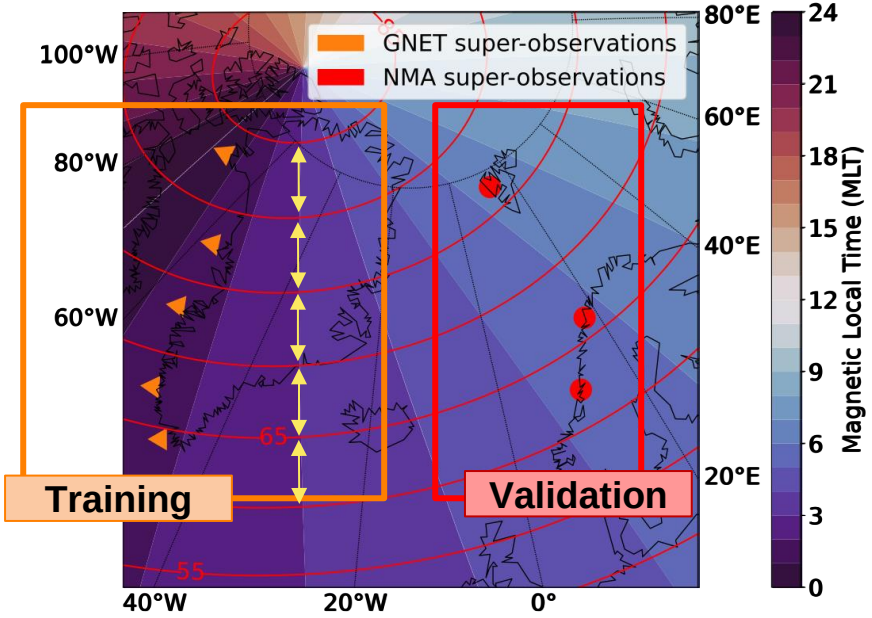
- Predicted super-observations: Statistical **combination** of **simultaneous observations** from several GNSS satellites.

➢ Combine observations from multiple GNSS satellites to obtain **single super observation.** (Deep Learning requirement)

➢ **Represent current scintillation conditions** in the ionosphere with **a robust sensitivity to outliers.**

- Regional forecasting: 5 **M**agnetic **Lat**itude (MLAT) intervals have been defined.

ROTI at T_0 → ROTI in [T_0 - 30 mins, T_0 + 30 mins]
→ Mean of ROTI, MLT and MLAT



From ROTI measurements available on 2014/01/22 at 11h20 to associated super-observations. GNET database (training) values are in orange, NMA (validation) ones are in red. MLT is indicated in color scale.

Forecasting ionospheric scintillation in Arctic area
Machine Learning approach

- **Long Short-Term Memory NN:**

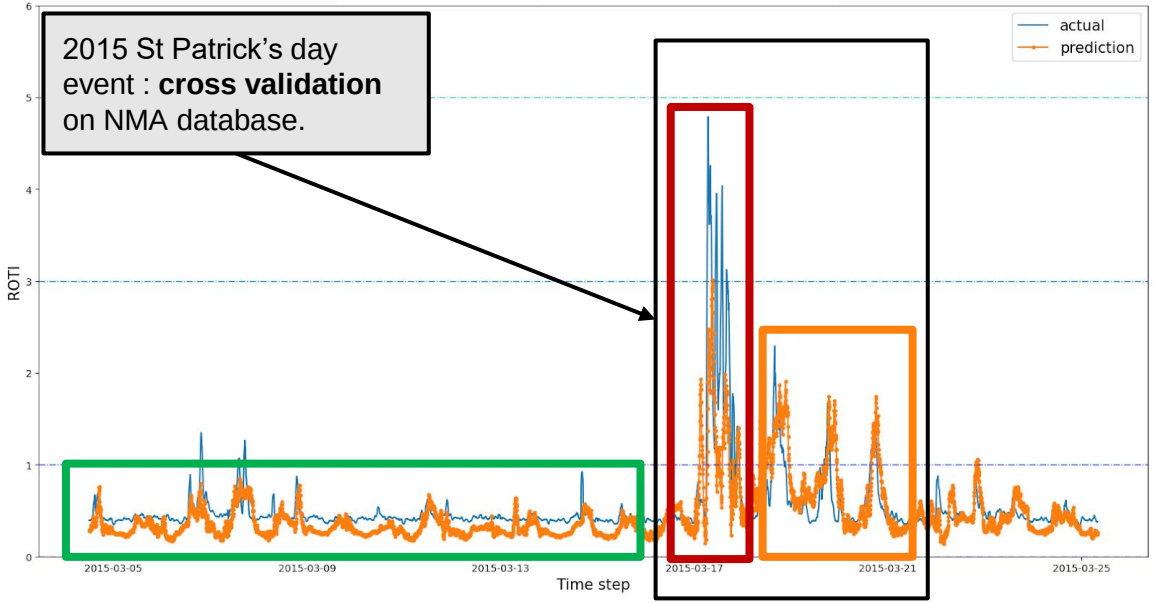
➢ Capture the **long-term dependencies** and global trends.

➢ **Recognize** data **sequential characteristics** and use patterns to **predict** the **next likely scenario**.

- **Results:**

➢ ROTI ∈ [0,1] : able to predict the noise floor.
ROTI ∈ [1,3] : more or less able to predict medium intensity event.
ROTI ∈ [3,5] : difficulty in predicting major events (often underestimated).

➢ Performances evaluated with dedicated metrics like **Probability of Detection, False Alarm Rate** and **True Skill Score** (not presented here)**.**



2015 St Patrick's day prediction plot.
Model trained with [60-65] GNET dataset and evaluated on [60-65] NMA dataset.
Horizontal dotted lines are ROTI thresholds,
defined according to the criticality of the ionospheric scintillation.

Modelling and forecasting ionospheric scintillation at high latitudes
Conclusions

- ONERA has developed tools for:
  - direct modeling of scintillation (physical approach to solve EM wave propagation)
  - statistical characterization of events occurrence (all latitudes) STIPEE model
  - empirical forecasting of events (statistical and ML approaches) HAPEE model

- Prospects:
  - Models improvements (and merging) and further validations (with additional data - CHAIN)
    → *All additional data related to ionosphere are welcome !*
  - STIPEE to be adopted by ITU-R, HAPEE tested for ESA SSA web site
  - Extend the forecasting horizon from solar imagery features analysis
  - Complete direct modeling with a more physical approach, at least for specific events and physical understanding (IRAP - IPIM model ?)

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