

# Automatic detection of the electron density from the WHISPER instrument onboard CLUSTER II

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## CONTEXT

The ESA CLUSTER-II mission has been successfully monitoring the plasma bulk properties of the Earth magnetosphere for more than 20 years. The payload is identical for each of the four spacecraft, consisting of 11 experiments dedicated to the measurements of the surrounding plasma, including five instruments from the Wave Experiment Consortium (WEC). As part of the WEC the WHISPER instrument is a relaxation sounder that monitors the in situ space plasma bulk properties such as the thermal **electron density**. It can be operated in two modes:

- **Active** (sounding) mode : an active spectrum is built on-board after local excitation of the surrounding plasma over the 3.5–82 kHz frequency range.
- **Natural** mode: the transmitter is switched off and the (electric) antennas are left at floating potential. The instrument becomes a natural wave receiver delivering spectrograms over the 2–80 kHz frequency range.

The plasma bulk properties can be extracted, under certain conditions, from the active and natural electric field spectrogram. In particular, the thermal electron density, one of the key datasets provided by WHISPER experiment, routinely delivered to the Cluster Science Archive, is used for scientific studies and is the main driver of the calibration of particle instruments.

The extraction of the electron density, directly related to the frequency of plasma signatures (**Fpe**), requires a careful analysis of active and/or natural spectra and can be tricky in some plasma **regions**. Indeed, the location of plasma resonances in the electric field spectrograms, related to the plasma parameters, strongly depends on the plasma conditions such as the magnetic field or spacecraft position. In the case, the thermal electron density has been extracted by various ad-hoc algorithms developed throughout the mission lifetime, from fully manual to semi-automatic, but always requiring time-consuming manual intervention.

## OBJECTIVES

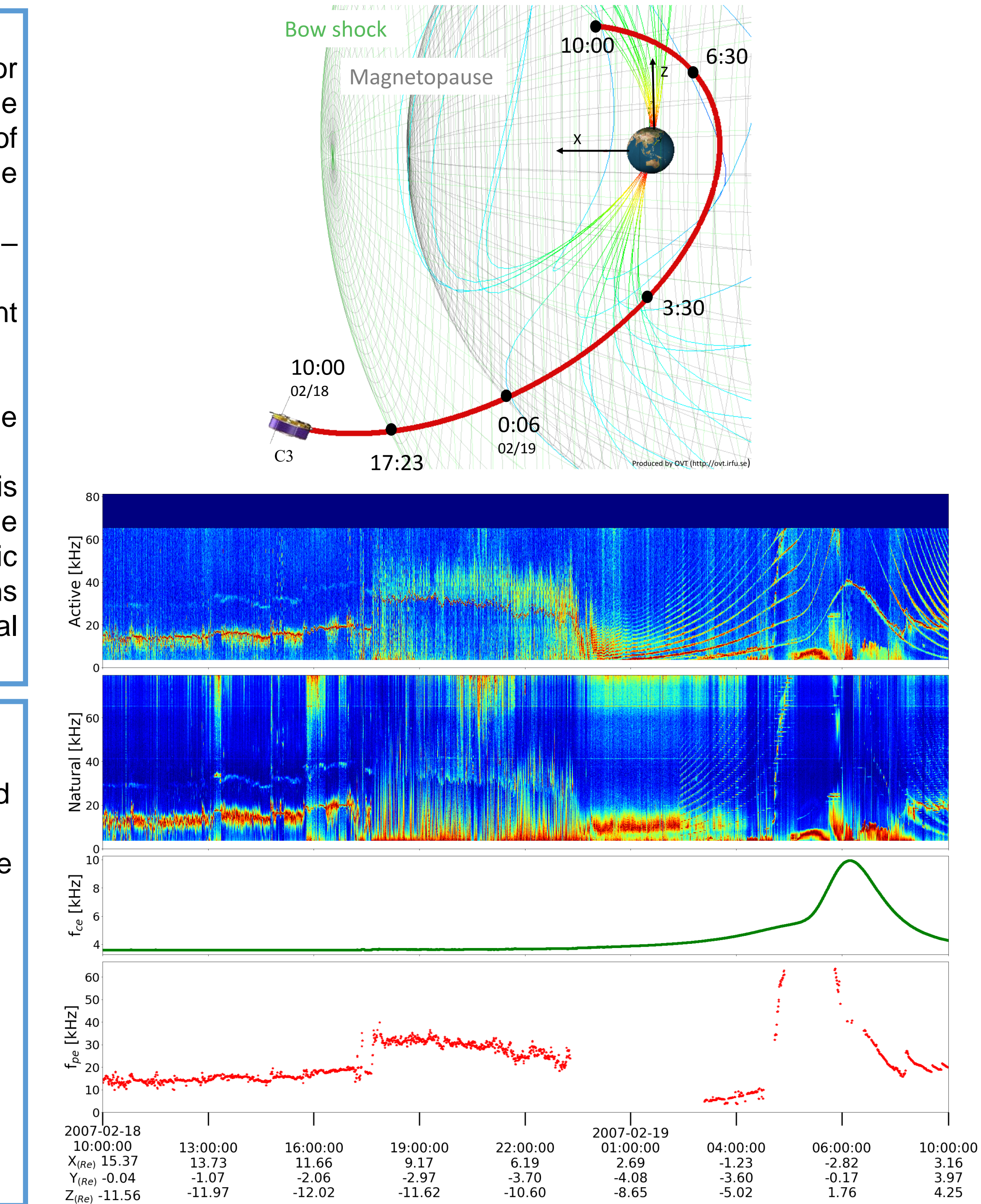
In order to improve data analysis, we developed a tool to automatically analyze the WHISPER spectra without need of manual inputs. Our final objective is a fully automatic electron density production on a subset of magnetospheric regions, i.e., solarwind (SW) and magnetosheath (MS). This will allow to deliver data faster, reduce manpower and subjectivity due to manual intervention. For this purpose, we have implemented automatic routines based on neural networks. The main constraint is to be able to determine the plasma frequency only with the WHISPER instrument data. The priority is to derive electron density in active mode.

1. The automatic electron density determination in active mode, performed in two steps :
  - Identify the magnetosphere regions with neuronal networks classification (Artificial Neuronal Network (ANN), Multi-Layer Perceptron)
  - Determine the electron density with a Neuronal Network adapted to the region (GRU, Recurrent Neuronal Network)
2. The development of **operational pipeline** using these methods to reduce human intervention
3. Improve and extend the thermal electron density determination coverage by applying the neuronal networks only to the natural spectra.

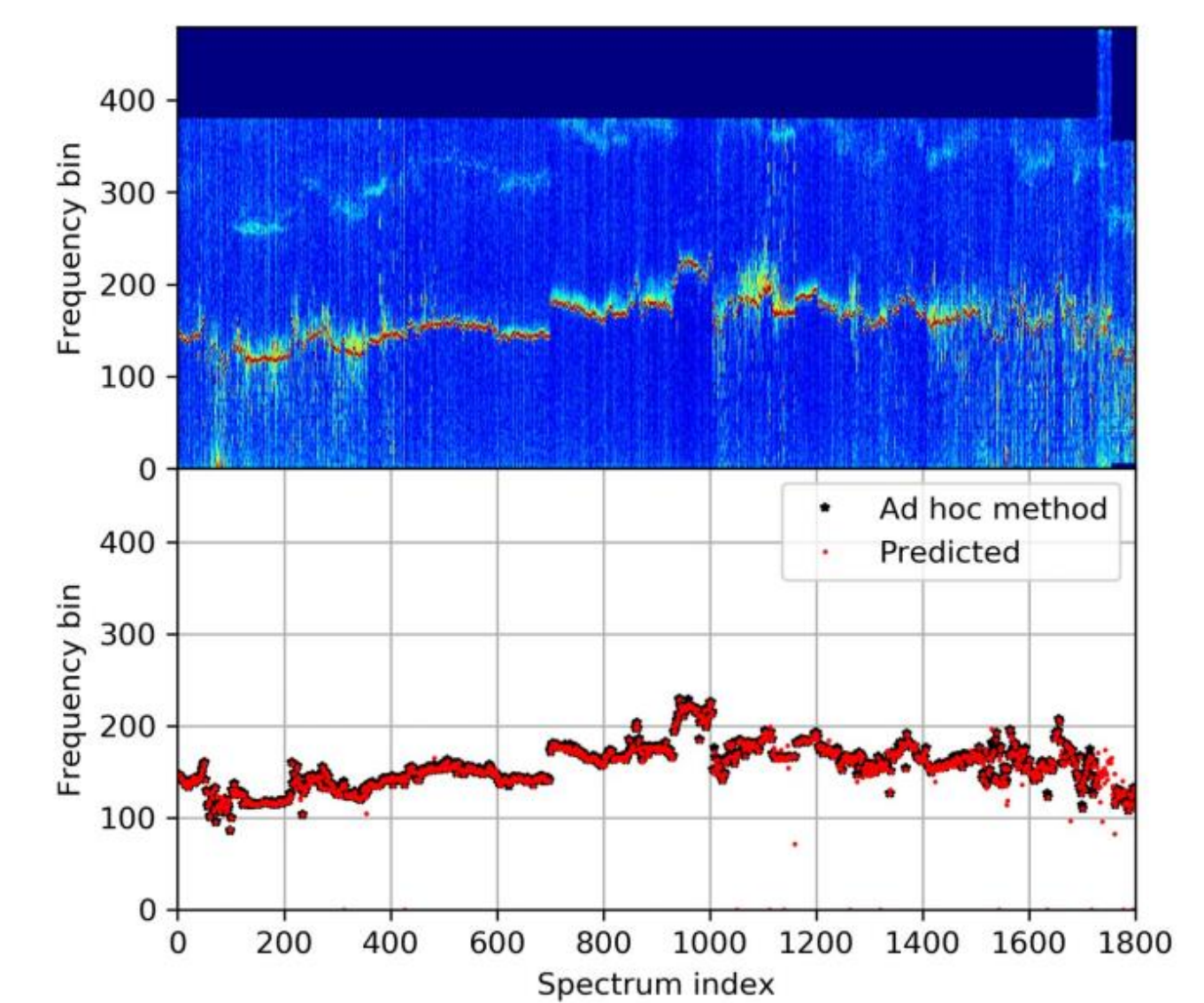
## 1. Automatic electron density determination with Neuronal Networks

Inputs for training are Active and Natural normalized spectrograms (in dB) for a substantial set of data randomly chosen during the mission lifetime, with :

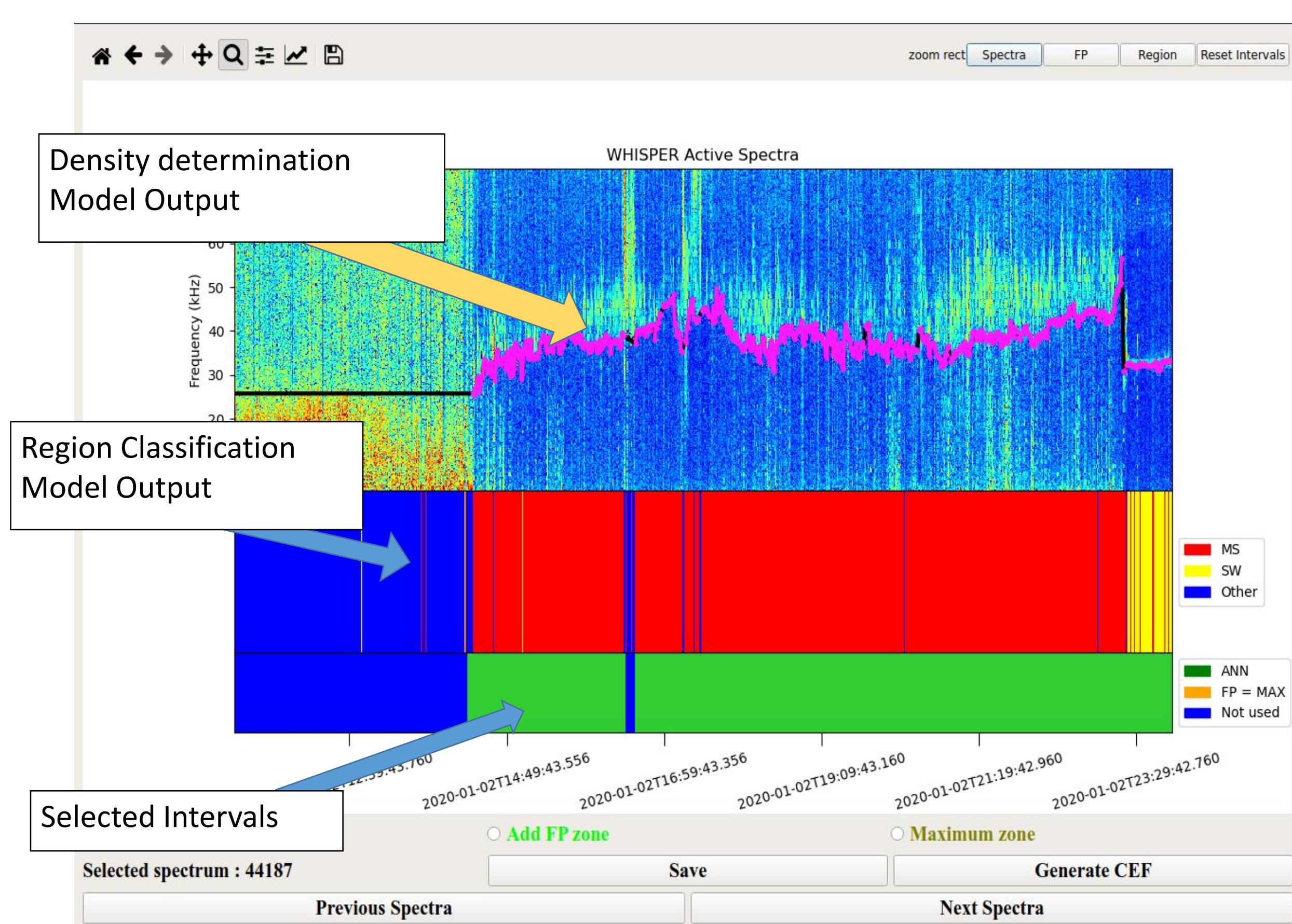
- Corresponding region labels derived manually and with other data products from CLUSTER)
- Electron density values (obtained from ad-hoc and manual determination).
- **Region Classification**  
The output for region determination is the plasma region (MS, SW or Other ). The models were trained with ~400K spectra and tested on ~30K spectra. The best results were obtained using a 4 Layer Multi-Layer Perceptron with up to **97.5%** accuracy
- **Electron density determination from Active spectra**  
The output of these models is the Fpe index inside the spectrogram. The models were trained with ~150k spectra and tested on ~16K spectra. The best model is a GRU (recurrent neuronal network) , it has an accuracy going up to **97%** for the MS and SW region, with 1 frequency bin (+/- 0.165kHz) bin tolerance.



## Fpe Determination in the Solar Wind



## Fp JedAI validation interface



## 2. Operational Pipeline : The JedAI

The « Judging Electron Density by Artificial Intelligence » pipeline allows to plot, visualize and validate the model outputs. It is developed with the main objective of reducing the tedious and time-consuming electron density manual determination or ad-hoc methods selection.

JedAI pipeline takes as input : Whisper Active Spectra and the closest Natural measurement to each Active spectra. First, the region model used in the tool predicts the plasma region for each spectrum. Second, the electron plasma frequency is extracted from the selected spectra. The pipeline works on successive time intervals based on the region classification output, where severe constraints have been imposed to ensure data quality and avoid ambiguous detection :

- A Threshold on the predicted region probability
- A Threshold density estimate probability
- Time continuity

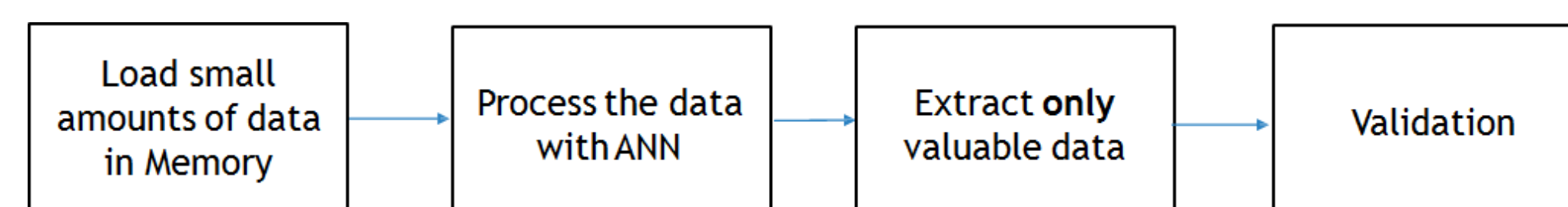
The results are then validated by an operator based on the ANN algorithm optimisation for the selected region. The operator is able to visualise the whisper spectra as a spectrogram with the ANN predictions, in order to quickly validate the electron density derivation.

This can lead up to a maximum of 25% loss in the number of electron densities given by neural networks as compared to ad hoc methods. On the other hand, the processing of one month of data for the four spacecraft now requires approximately 4 h of manual validation whereas the ad hoc methods required around 40 h.

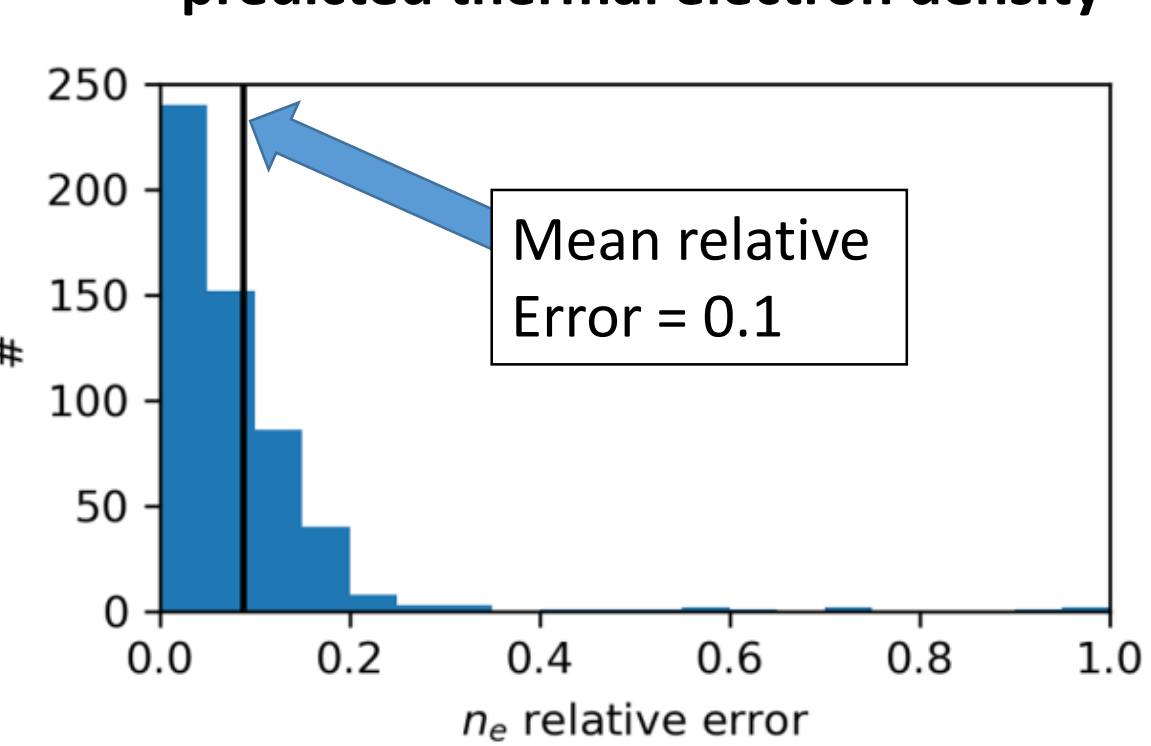
The pipeline is operational in the **solar wind** and the **magnetosheath** regions. It has been designed as a modular tool capable of adding new models for other regions and updating current models. The output of JedAI is the electron density which is ready to deliver to the Cluster Science Archive (CSA) as a high level WHISPER data product.

## 3. Electron density determination from Natural spectra (first studies)

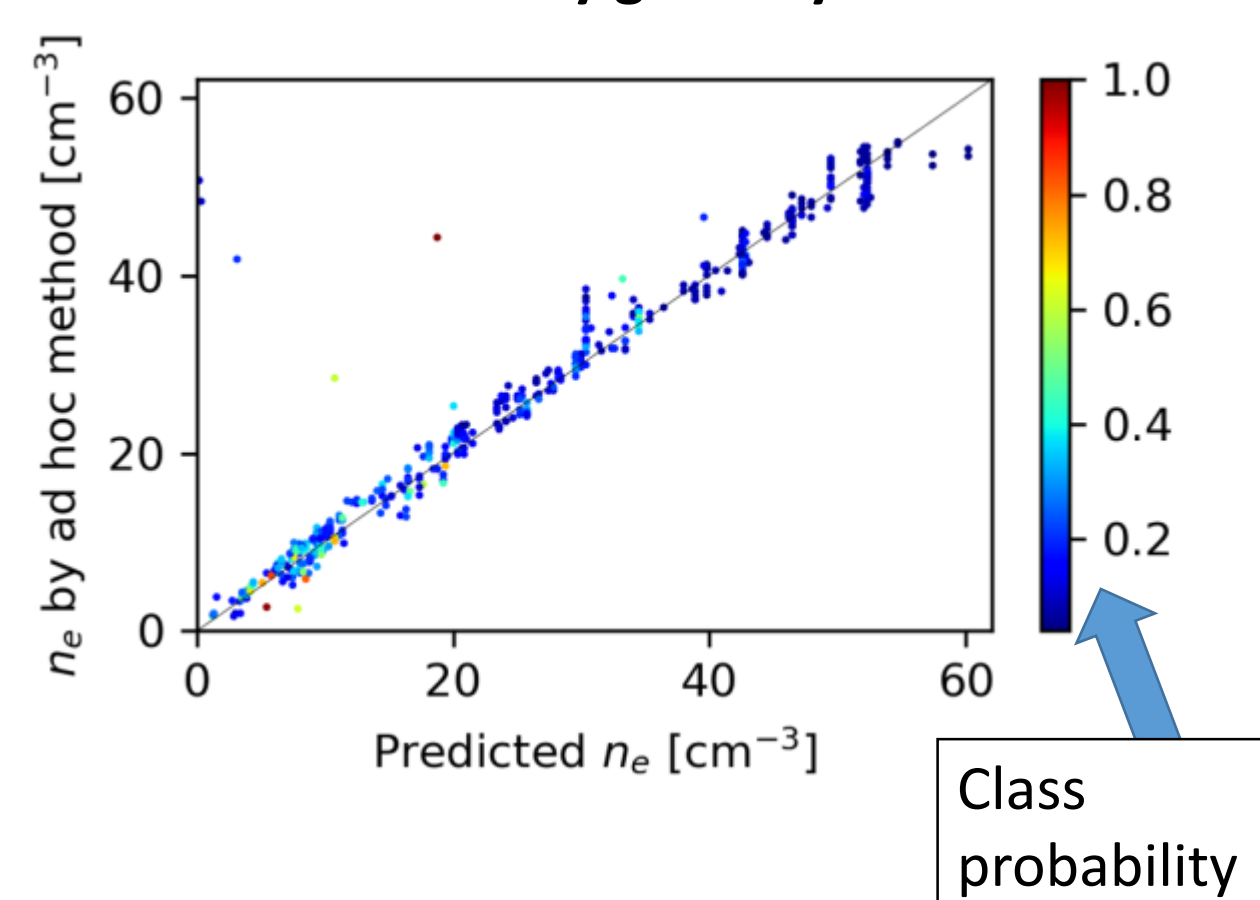
The output of these models is the plasma region, using only natural measurements as an input. In this case we validate only the output data and a full automatic ad-hoc algorithm is applied to determine the electron density. A specific model is created for each region. Each model is trained with ~600K spectra. The accuracy scores are promising in some regions (up to ~97% in MS/SW, ~80% in Cusp/Tail and ~70% in Plasmasphere).



## Relative error distribution of the predicted thermal electron density



## The predicted thermal density vs the density given by ad hoc



## CONCLUSION AND FUTURE WORK

- We have developed a new density determination pipeline which is capable of reducing human intervention, now limited to validation, up to 10 times compared to the previous methods. This pipeline is now operational and is routinely used to produce the Whisper densities delivered to CSA.
- Current work is focused on improving the natural spectra analysis and on improving usability, ergonomics and validation process of the pipeline.
- The long term goal is to study if the automatic determination methods could be applied for future data processing of electric field experiments on-board BepiColombo (Hermean environment) and JUICE (Jovian environment). Indeed, this study is a proof of concept for an operational automatic analysis of massive datasets potentially provided by future missions or constellations.