On the 2015 St. Patrick's Storm Turbulent State of the Ionosphere: Hints from the Swarm Mission

P. De Michelis, A. Pignalberi, G. Consolini, I. Coco, R. Tozzi,
M. Pezzopane, F. Giannattasio

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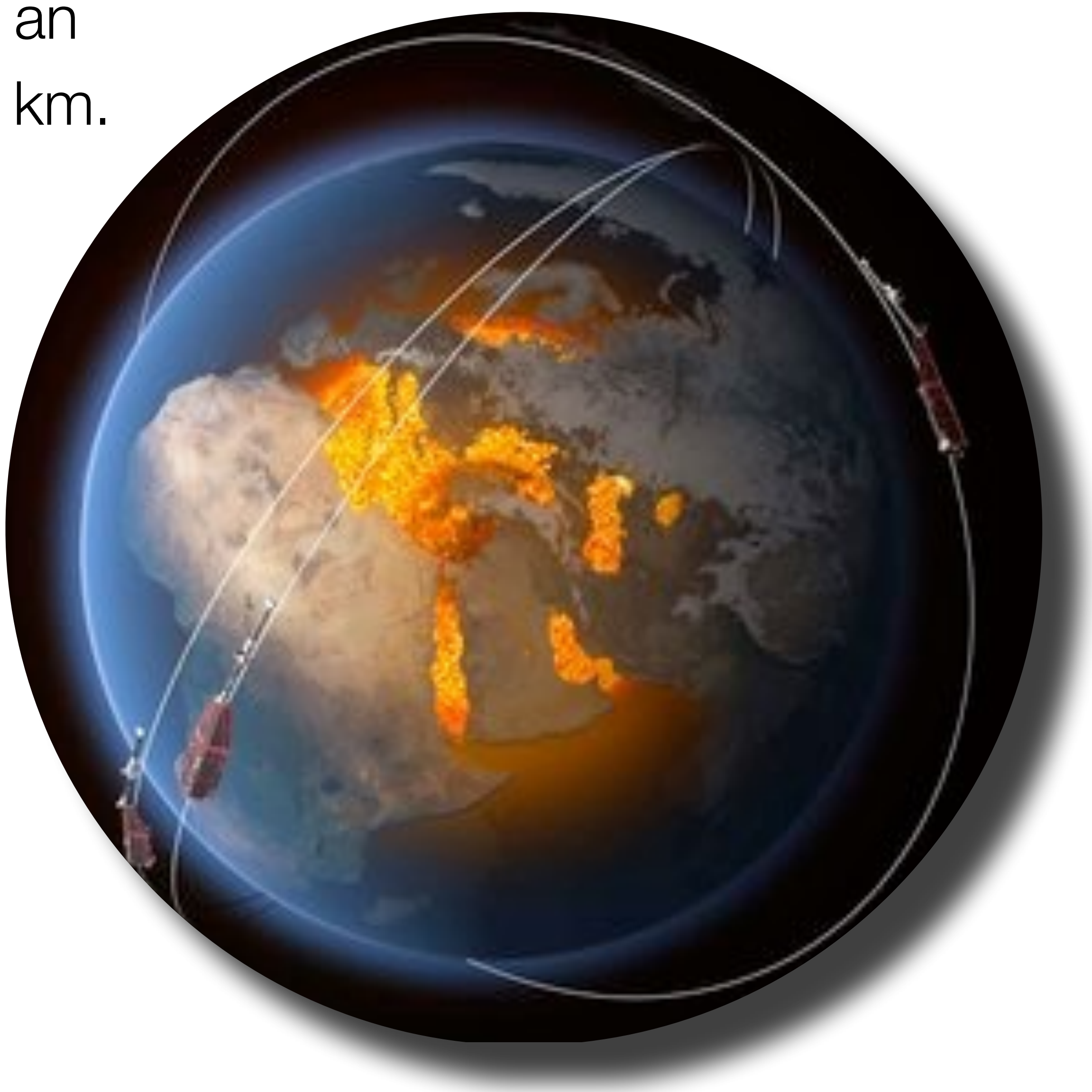
Swarm Constellation

Swarm is an ESA minisatellites constellation that consists of 3 satellites (Alpha, Bravo & Charlie) placed in two different polar orbits, two flying side by side at an altitude of 450 km and a third at an altitude of 530 km.



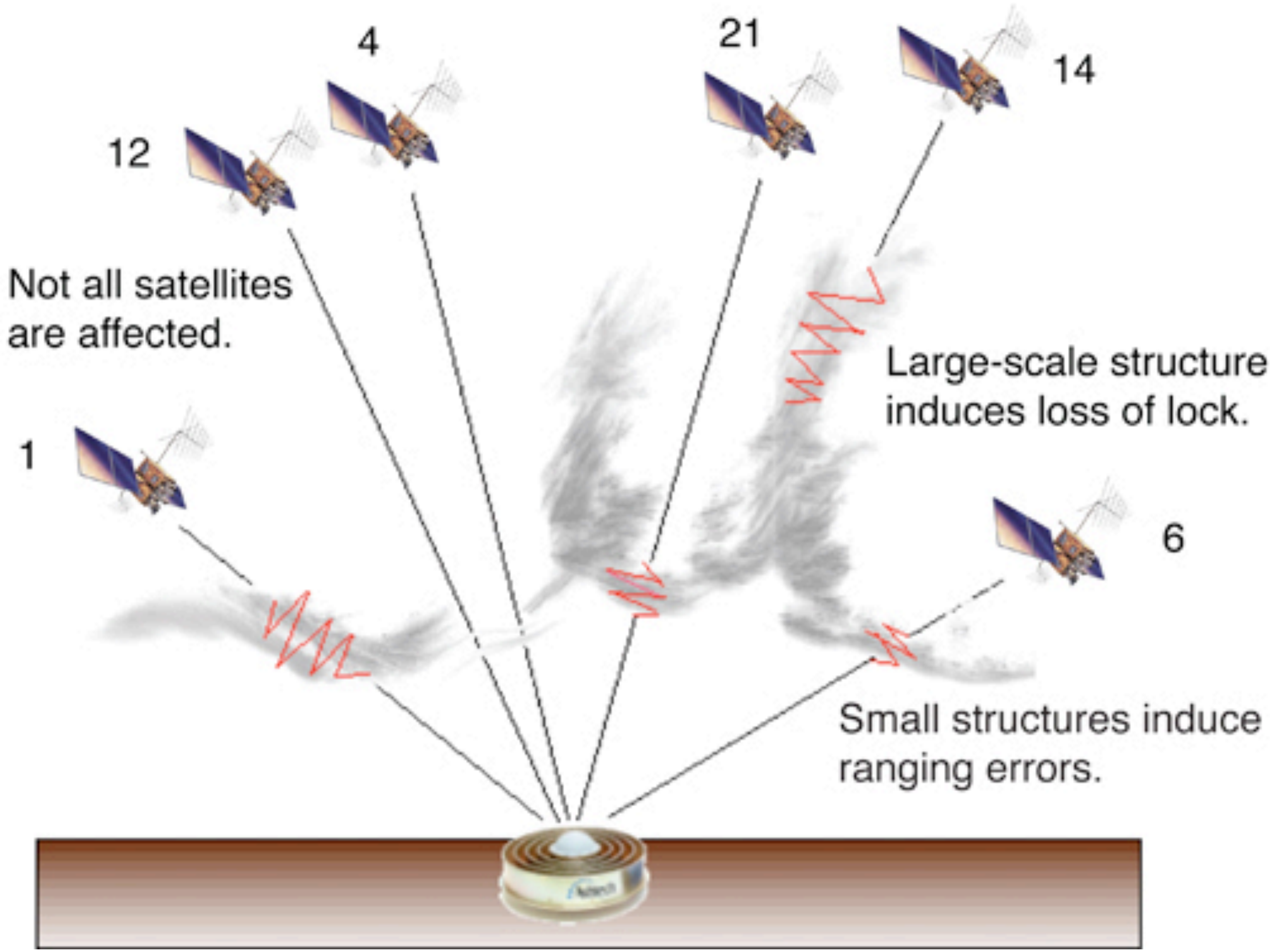
All the three Swarm satellite are equipped with the following set of identical instruments:

- Absolute Scalar Magnetometer
- Vector Field Magnetometer
- Star Tracker
- Electric Field Instrument
- GPS Receiver
- Laser Retro-Reflector
- Accelerometer.

Why is it important to study the occurrence of turbulence processes in the ionosphere

The ionospheric turbulence can disturb the propagation of a signal passing through it.

Signals can be delayed, distorted or lost while passing through the ionosphere.

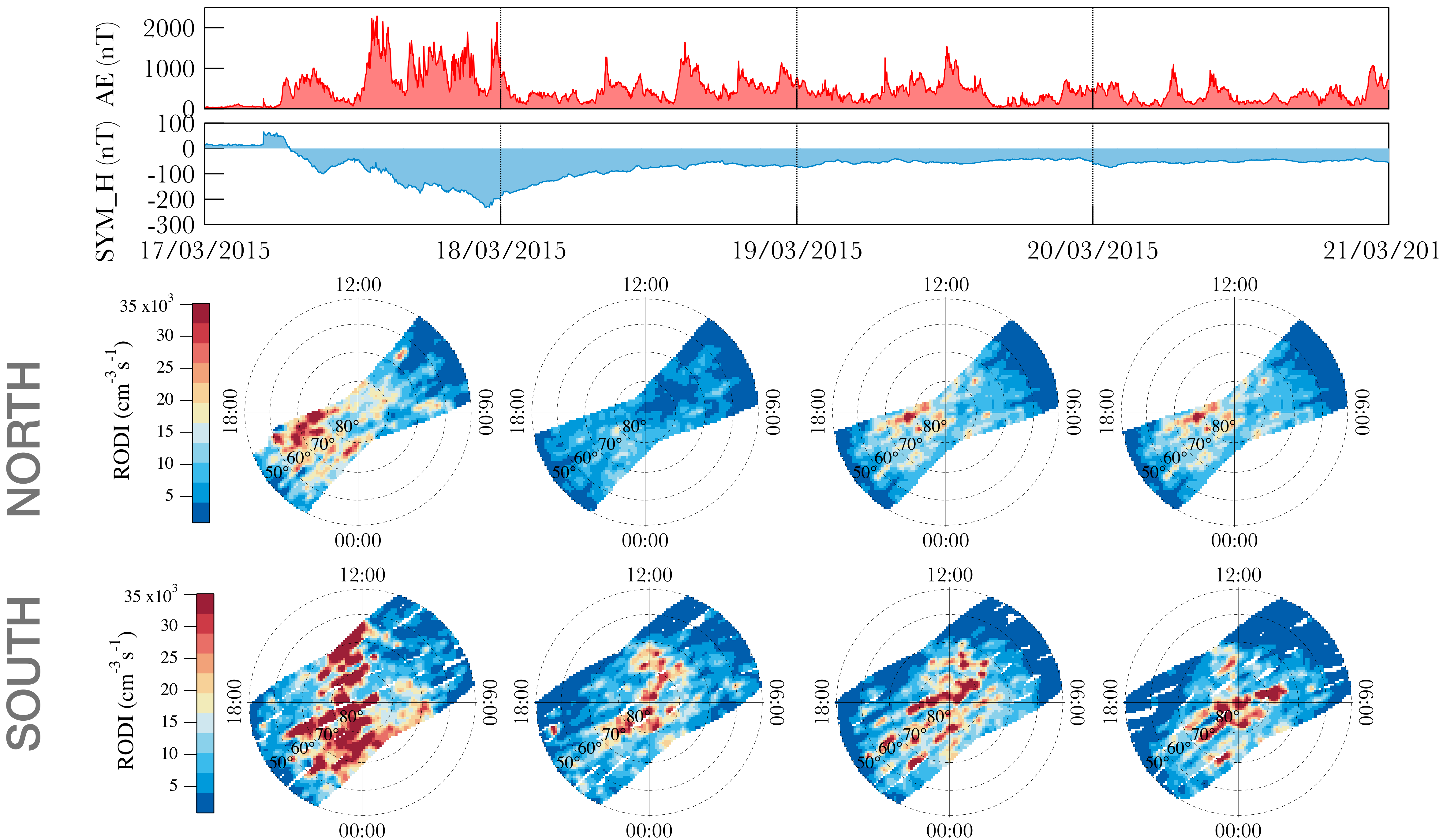


In the last years the dependence of our society on the Global Navigation Satellite System (GNSS) has increased substantially.

Critical applications (railway control, highway traffic management, precision agriculture, commercial aviation, and marine navigation) require and depend on GNSS services.

This means that our critical infrastructures and economy are dependent on positioning, navigation, and timing services.
Our society is vulnerable to damages due to the malfunction of these systems.

DATASET: Electron Density and RODI (Rate Of change of Density Index) from Swarm constellation



Is there a relation between the occurrence of plasma density irregularities as described by the **Rate Of change of electron Density Index** and the **scaling properties of electron density fluctuations/increments** during the development of the geomagnetic storm?

If the **origin of plasma density irregularities is due to a turbulence process** the plasma density increments are expected to show **self-affinity**.

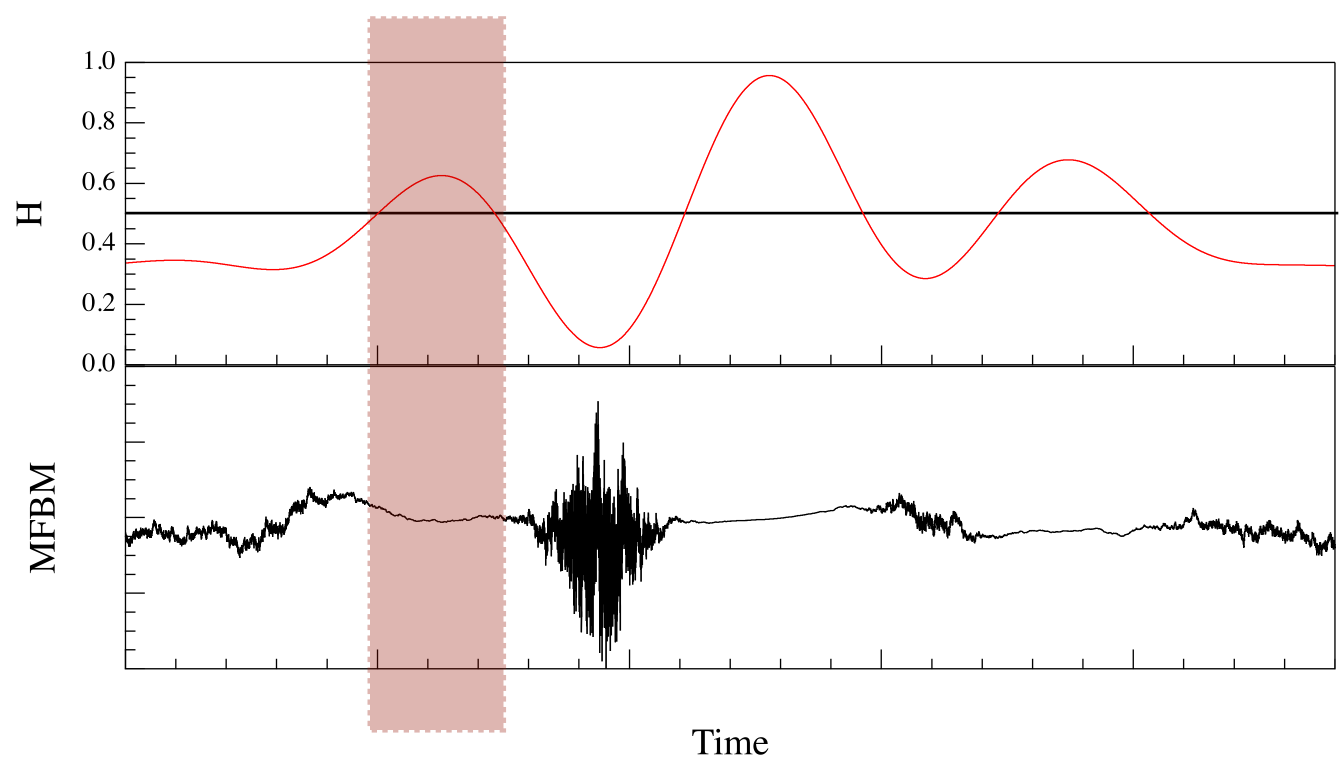
The study of the scaling properties of electron density fluctuations can be, indeed, important to understand if the **turbulence is the main source of the irregularities and to understand the type of turbulence**.

Results:
1st-order Structure Function

$$S_1(\tau) =< |N_e(t+\tau) - N_e(t)| >_T \sim \tau^{\gamma(1)}$$

The **Hurst exponent** quantifies the relative tendency of a time series:

- to cluster in a direction (H>0.5). It has a **persistent** behavior. Long-range correlated signals are characterized by a sign-persistence of their increments.
- to regress strongly to the mean (H<0.5). It has an antipersistent behavior. That happens in short correlated signals.



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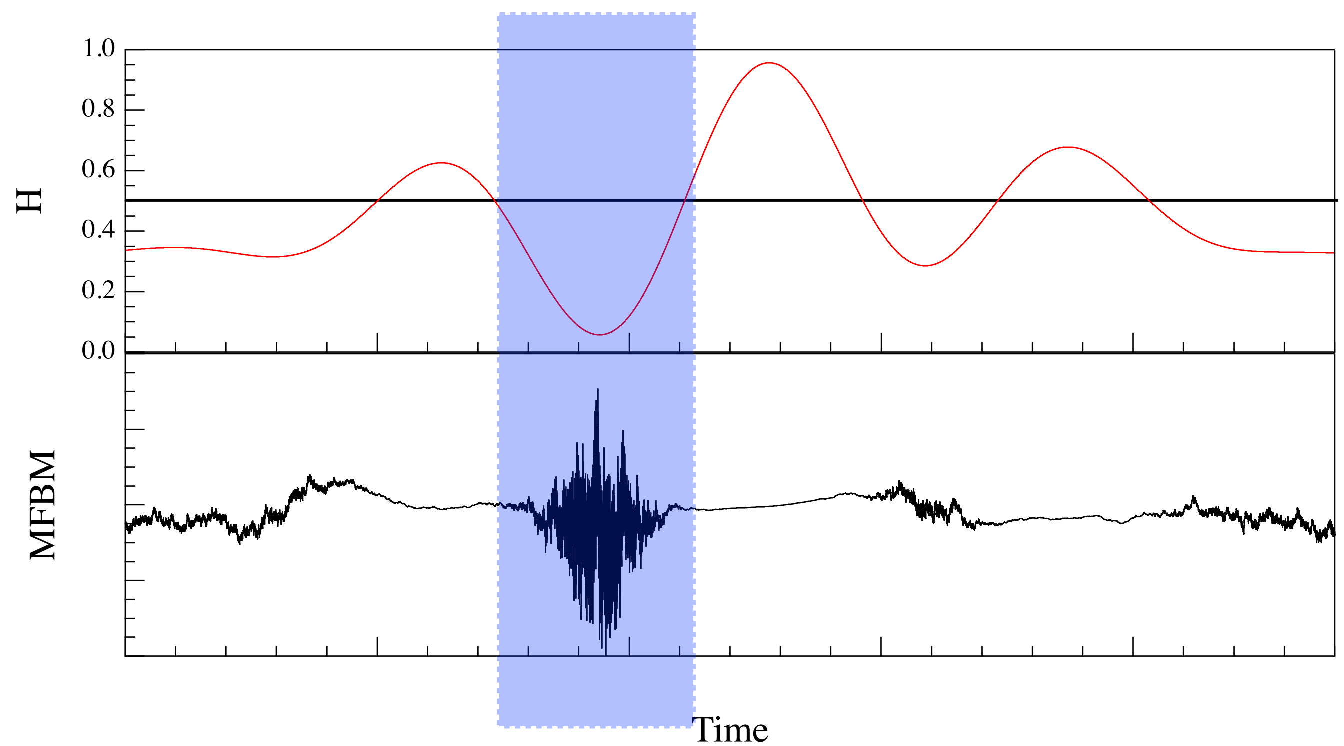
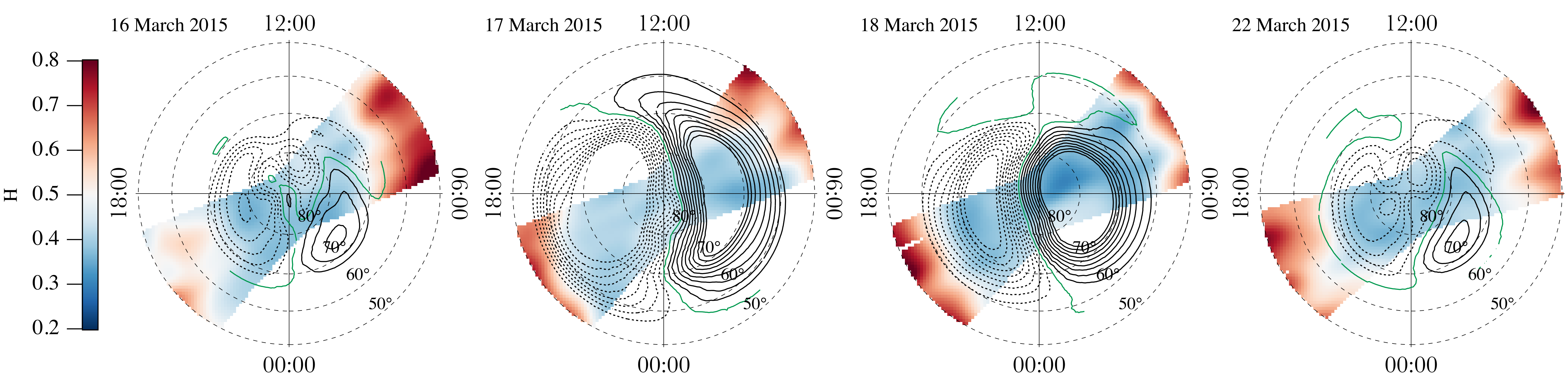


Results:
1st-order Structure Function

$$S_1(\tau) =< |N_e(t+\tau) - N_e(t)| >_T \sim \tau^{\gamma(1)}$$

- The **anti persistent character** seems to be a typical features of high-latitudes.
- The **persistent character** appears to be a typical features of mid-latitudes.

- The position of the profile of the local Hurst values with respect to H = 0.5 seems to follow the spatial and temporal evolution of the auroral zone during the selected period.



Spectral Features: Spectral Density Exponent

To better characterize the scaling properties of the geomagnetic field fluctuations we evaluate the **2th-order structure function:**

$$S_2(\tau) =< |x(t+\tau) - x(t)|^2 >_T$$

$$S_2(\tau) \sim \tau^{\gamma(2)}$$

The values of $\gamma(2)$ permit us to describe the spectral properties of the analyzed signal. According to Wiener-Khinchin theorem, the Fourier power spectral density (PSD) exponent β of a signal is related to $\gamma(2)$ according to the following relation:

$$PSD(f) \sim f^{-\beta} \quad \rightarrow \quad \beta = \gamma(2) + 1$$

Thus, from $\gamma(2)$ it is possible to infer the scaling exponents β of the power spectrum of the original signal, which **can provide information on the different turbulence regime and processes.**

Results
Spectral Features: Spectral Density Exponent

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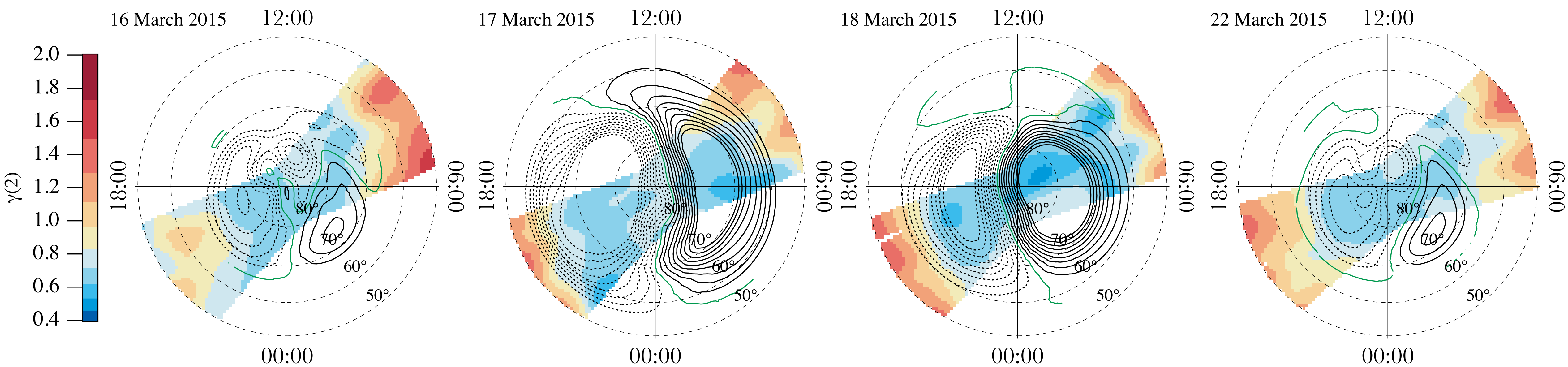
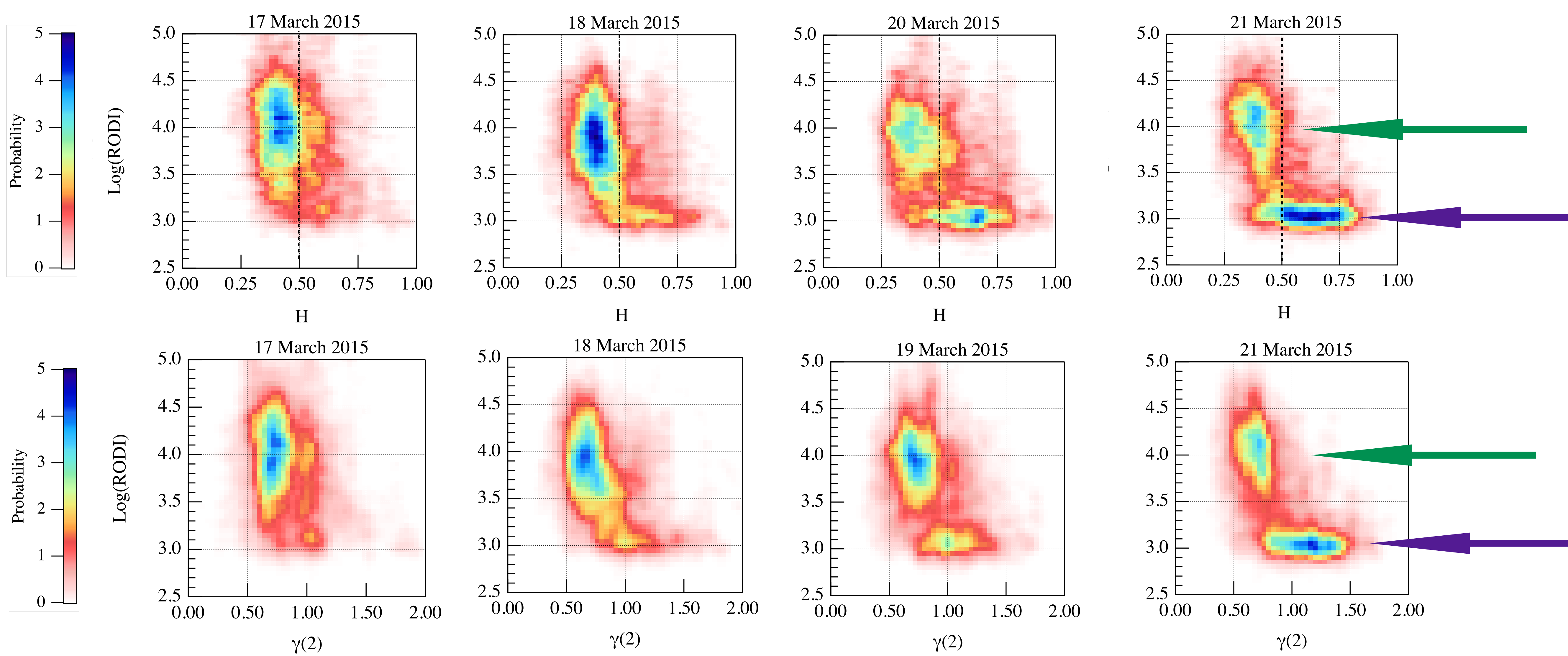


Different scaling (turbulence) regimes and processes may characterize the regions where the convection patterns are localized. The values in the range 0.6 to 0.8 support the idea of a fluid and/or MHD turbulence as a source of these perturbations.

Results:
RODI vs Structure Function Exponents of Electron Density

To investigate the possible relationship between RODI parameter and the scaling features of the Ne fluctuations we evaluate the **joint probability distributions** between RODI and first and second-order scaling exponents.



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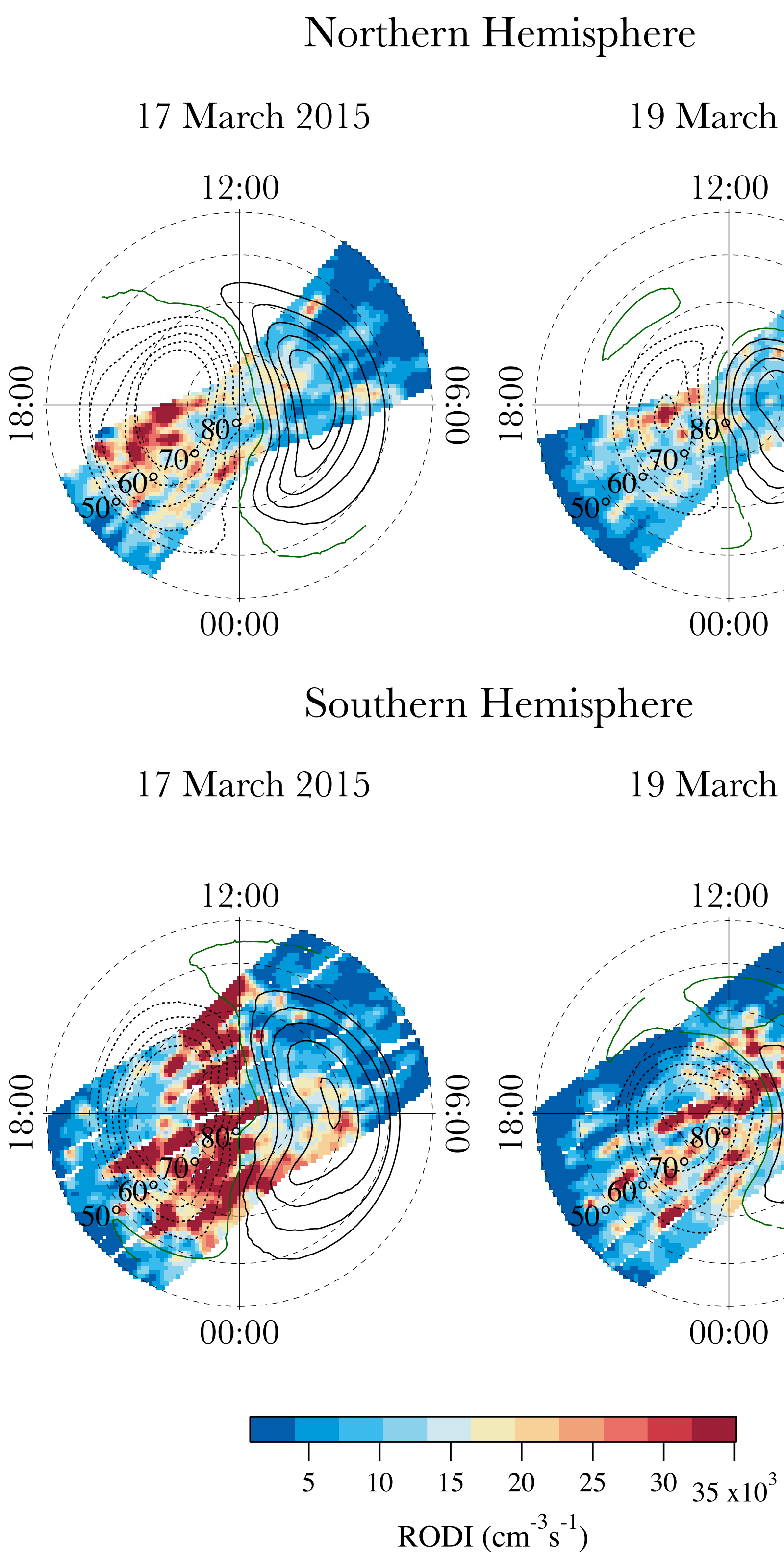
RODI vs Structure Function Exponents of Electron Density



They are mainly localized along the convection patterns that travel across the polar cap from the dayside to the nightside. This result seems to support the hypothesis according to which the physical mechanisms responsible for the formation of high-latitude ionospheric irregularities characterized by high values of RODI can be both the **gradient-drift** and the **Kelvin-Helmholtz instability**, while perhaps the low RODI values' family could be due to a different kind of turbulent/stochastic process.

Summarizing ...

- The plasma density variations may be due to different processes not necessarily linked to turbulence phenomena.

- The RODI parameter cannot be generically considered as a proxy of the occurrence of ionospheric turbulence.

- The scaling features of electron density fluctuations permitted us to find two families of plasma irregularities which seem to be associated with different physical properties.

- Only **plasma density variations associated with high values of RODI are characterized by scaling properties which support the idea of a fluid and/or MHD turbulence as a source of these perturbations**.