Ionospheric Turbulence: Impact on the Global Navigation Satellite Systems Functioning

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AIM

- To investigate the possible turbulent nature of plasma density irregularities
- To assess the possible dependence of the GPS signals loss of lock on the presence of a specific kind of ionospheric irregularities and thereby appraise the origin of one of the largest space weather effects on the GNSS systems and users.

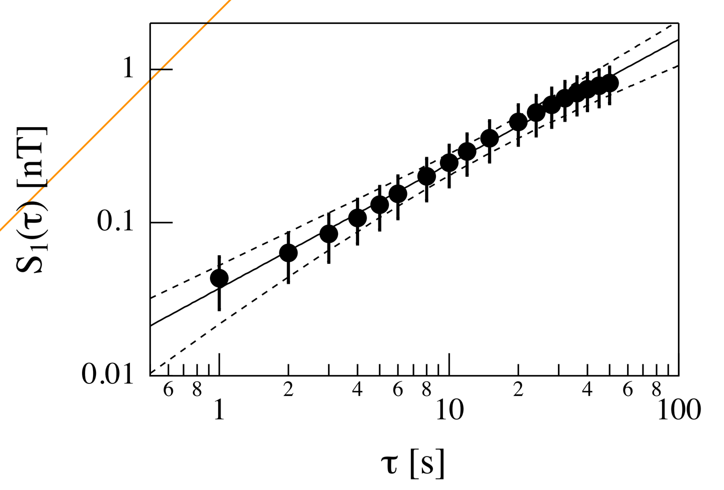
METHOD OF ANALYSIS

We consider q[th]-order structure function $S_q(\tau)$, which for a signal Ne(t) defined over an interval T is given by:

$$S_q(\tau) = < |N_e(t+\tau) - N_e(t)|^q >_T$$

when we deal with a scale-invariant signal, the $S_q(\tau)$ exhibits a power law behavior:

$$S_q(\tau) \sim \tau^{\gamma(q)}$$



The estimation of the scaling features is done for Ne fluctuations at timescales smaller than 40 s, using a moving window of T=400 s. The Ne fluctuations in the range from 1 s to 40 s correspond to investigation of **spatial fluctuations from 7.6 km up to 300 km**. The choice of a moving window of 400 s, which is 10 times larger than the maximum scale which we want to investigate (40 s), permits us to have a reliable estimation of 40 s fluctuation statistics.

$\gamma(1)$ — Provides information on the range of correlation of the investigated quantity: values of $\gamma(1) < 0.5$ are the evidence of the **anti-persistent character of its increments** so that we can talk of short correlated signals, values of $\gamma(1) > 0.5$ are the evidence of the **persistent character** of its increments so that we can talk of long-range correlated signals.

$\gamma(2)$ — Through $\beta = \gamma(2) + 1$ provides information on the **spectral features** of the quantity under investigation, representing the slope of a power law PSD can provide information on the presence of turbulence.

DATASET

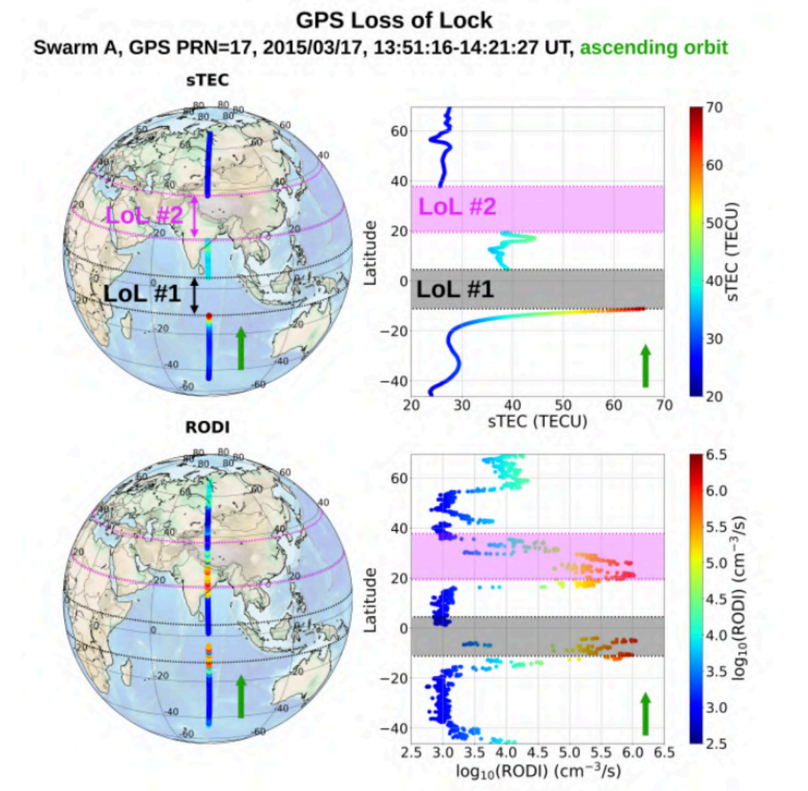
Swarm A & Swarm B
15 July 2014 - 31 December 202

★ **Electron density** (Ne) time series

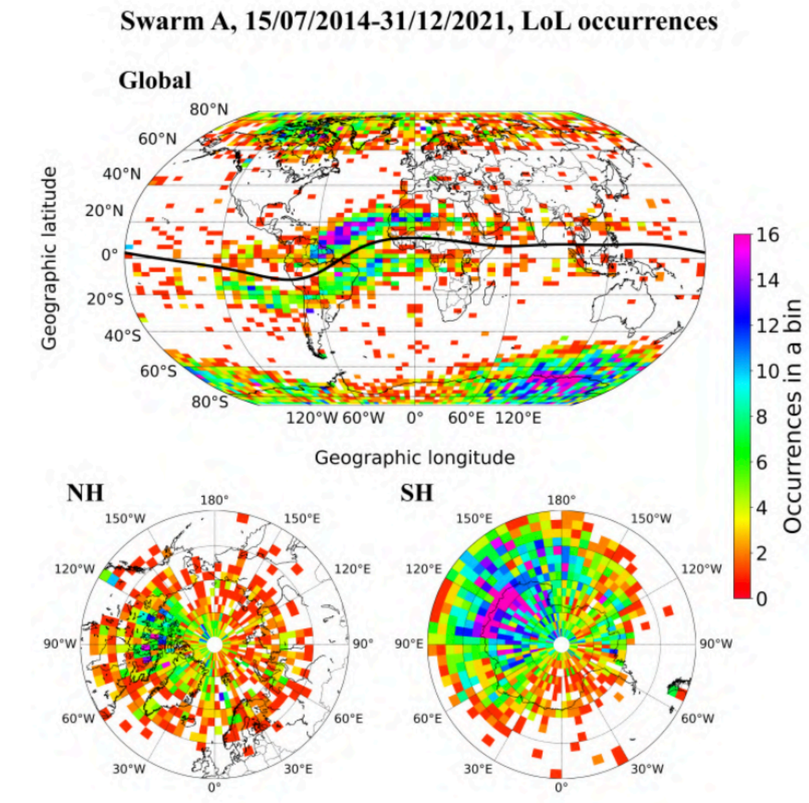
★ **RODI** (Rate of Change of electron density index). RODI is the standard deviation of Ne time derivative calculated on a window of fixed width ($\Delta t = 10s$) sliding along Ne time series.

★ **Loss of Lock** (LoL) time series. The LoL events are identified by looking for interruptions in the sTEC time series for a specific GPS satellite, which is identified by the corresponding Pseudo Random Noise number (PRN).

★ **IBI.** Swarm Level-2 Ionospheric Bubble Index product which identifies the occurrence of plasma bubbles analyzing the magnetic field variations associated with electron density depletions



Example of GPS LoL events as identified in the sTEC time series measured by Swarm A during an orbit and corresponding RODI values calculated from Ne measurements. The magenta and grey belts identify the GPS LoL duration. Left panels represent the satellite track in a geographic coordinates map, while the right panels show the corresponding plot latitude vs value (sTEC or RODI).



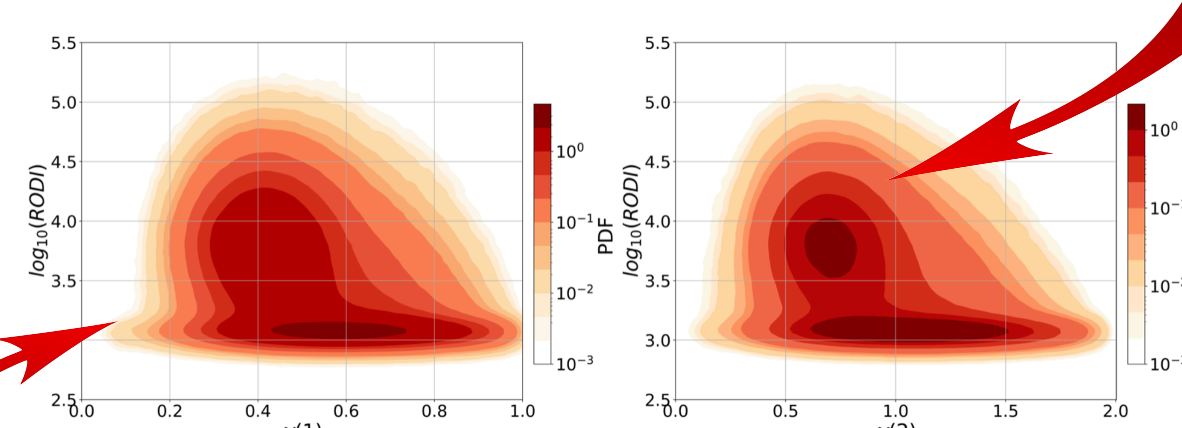
Geographic distribution of GPS LoL occurrence for Swarm A during the selected period as global projection and as Northern hemisphere (from 50° N to the North pole) and Southern hemisphere (from 50° S to the South pole) polar projections, respectively. Bins are 2.5° wide in latitude, and 5° wide in longitude.

RESULTS

Mid and High Latitude

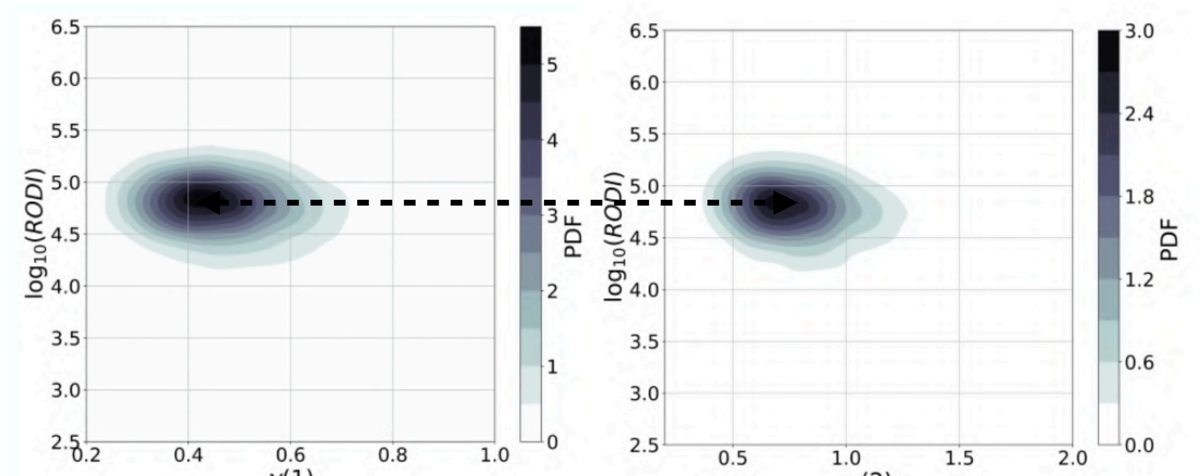
Analyzing the scaling properties of Ne fluctuations at mid and high latitudes we identify two distinct classes of plasma density fluctuations in the ionosphere which are characterized by different values of both the scaling exponents and RODI.

High values of RODI are generally associated with Ne fluctuations characterized by an antipersistent ($\gamma(1) < 0.5$) behavior and a second-order scaling exponent $\gamma(2)$< 1.



Low values of RODI are mainly associated with Ne fluctuations characterized by a persistent ($\gamma(1) > 0.5$) behavior and a second-order scaling exponent $\gamma(2)$>1.

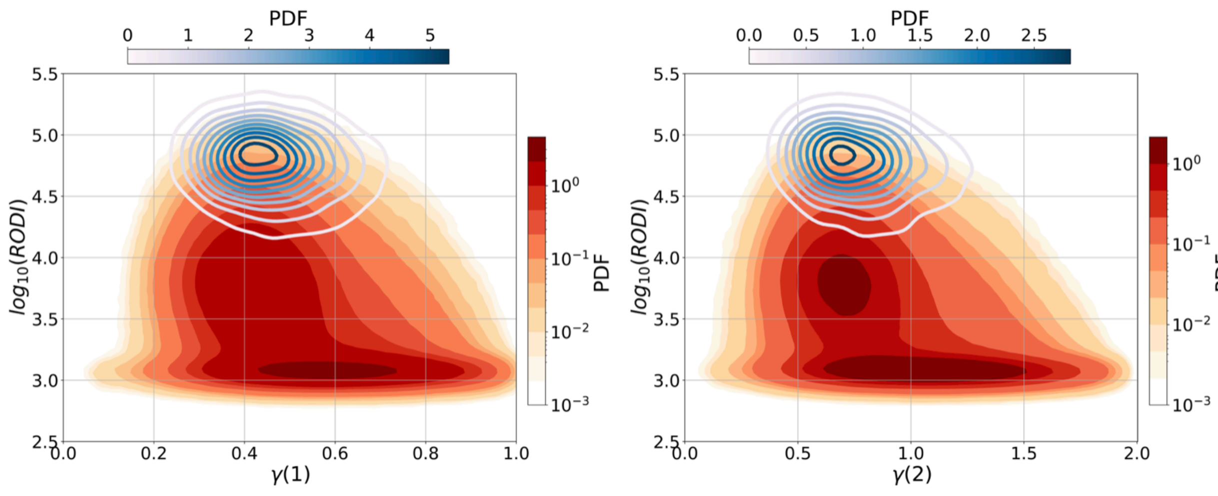
We consider the LoL events and analyze the corresponding local fluctuation scaling properties of the Ne measurements.



GPS LoL events are mainly associated with $\gamma(1) = (0.47 \pm 0.12)$. Ne fluctuations during LoL events have an anti-persistent character, i.e., there is not a long-term memory effects on the fluctuations sign.

GPS LoL events are mainly associated with $\gamma(2) = (0.8 \pm 0.2)$ that means a power spectral exponent $\beta = \gamma(2) + 1 = (1.8 \pm 0.2)$

The occurrence of **GPS LoL events** is associated with the specific class of Ne fluctuations. When a GPS LoL event is ongoing, Ne fluctuations are in a **turbulent state** characterized by **intermittent structures** and generally accompanied by extremely **high values of RODI**.



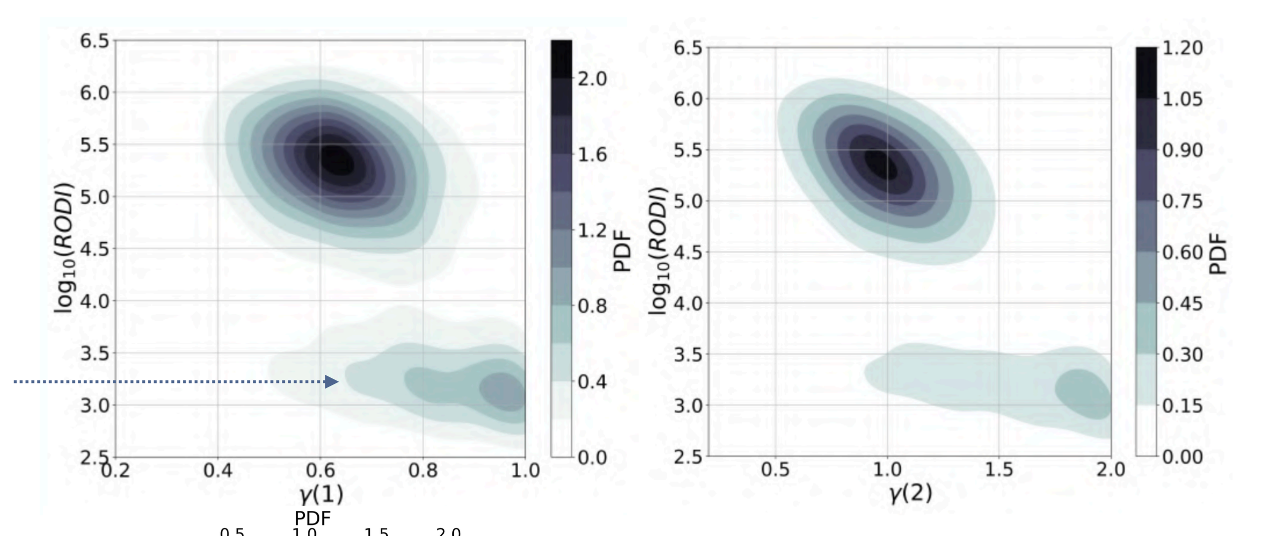
Comparison between the features of Ne fluctuations corresponding to the GPS LoL events and those obtained by considering all the available Ne data recorded in the same regions and for the same period.

Low Latitude

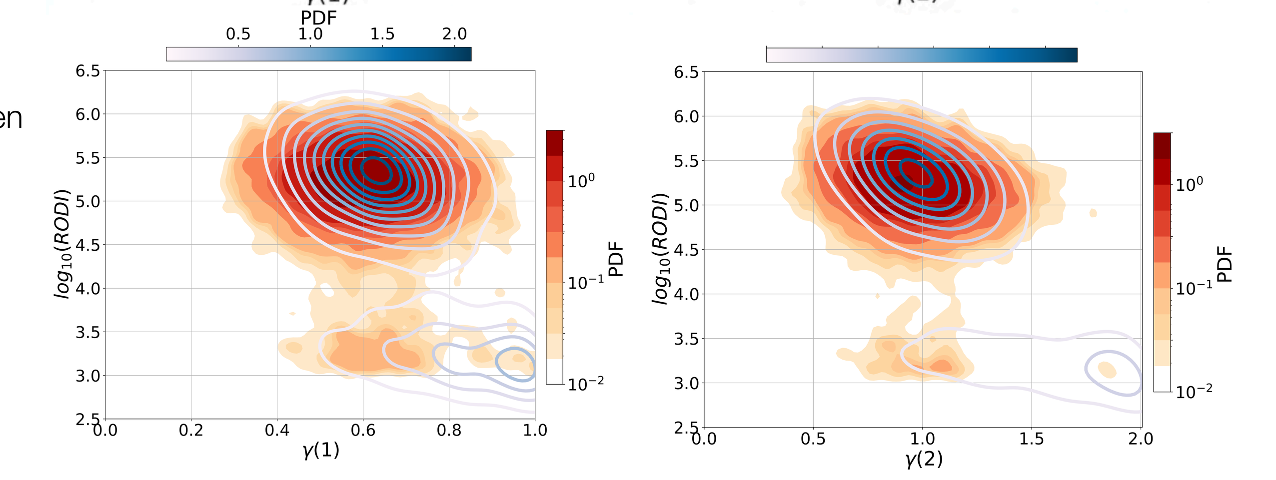
Ne fluctuations associated with LoL events in the equatorial belt are mainly characterized by a mean value of $\gamma(1) = (0.64 \pm 0.13)$, suggesting a more persistent character of the fluctuations, and a mean value $\gamma(2) = (1.0 \pm 0.2)$. RODI values are extremely high, even higher than those obtained for mid- and high-latitude regions.

There is an additional class of events for which the Ne fluctuations show completely different properties: RODI<10[3.5] , $\gamma(1) > 0.6$, and $\gamma(2) > 1$.

This class consists of nearly 25% of all recorded events and the values of the scaling exponents suggest a different origin for the LoL of the GPS signals.



A good agreement exists between Ne fluctuation scaling properties associated with GPS LoL events and those obtained in correspondence of plasma bubbles.



This suggests that in the equatorial ionosphere most of GPS LoL events are triggered by the plasma bubbles development. However, about 25 % of the LoL events recorded in the equatorial belt do not seem to be related to the presence of plasma bubbles. They could be triggered by plasma blobs, that are mesoscale plasma density enhancements relative to the ambient plasma with longitudinal widths comparable to those of equatorial bubbles but with a different origin.

CONCLUSIONS

Our findings show that both the scaling exponent values corresponding with GPS LoL events in the two analyzed regions and the corresponding values of RODI depend on latitude:

- The values of the second-order scaling exponents are slightly different moving from high to low latitudes.
- The persistence character of the high/low-latitude fluctuations is different, being the first-order scaling exponent below 0.5 at high latitudes (anti-persistent fluctuations) and above 0.5 at low latitudes (persistent fluctuations).

The different values of $\gamma(1)$ and $\gamma(2)$ at high/low latitudes suggest that different instability/turbulence processes can be at the origin of the ionospheric irregularities' generation which are at the base of a GPS LoL event.

The main result is that when a **GPS LoL event is ongoing, Ne fluctuations are in a turbulent state characterized by intermittent structures and generally accompanied by extremely high values of RODI. This is always the case at mid- and high- latitudes (|QDLat|>50°), while in the equatorial belt this happens in at least 75% of GPS LOL events.**

References

- **De Michelis et al.**, *J.G.R.*, 125, 2020. https://doi.org/10.1029/2020JA027934
- **Consolini et al.**, *JASTP*, 105531, 2021. doi: 10.1016/j.jastp.2020.105531
- **De Michelis et al.**, *Remote Sensing*, 13, 759, 2021. https://doi.org/10.3390/rs13040759
- **De Michelis et al.**, *Scientific Reports*, 11, 2021. https://doi.org/10.1038/s41598-021-84985-1.
- **Pezzopane et al.**, *Remote Sensing*,13, 2209, 2021. https://doi.org/10.3390/rs13112209
- **De Michelis et al.**, *Remote Sensing*,14, 918, 2022. https://doi.org/10.3390/rs14040918