characterization of IoNospheric TurbulENce level by Swarm constellation

ESA/Contract No.4000125663/18/I-NB CCN1

Occurrence of GPS Loss of Lock Based on a Swarm Half-Solar Cycle Dataset and Its Relation to the Background Ionosphere

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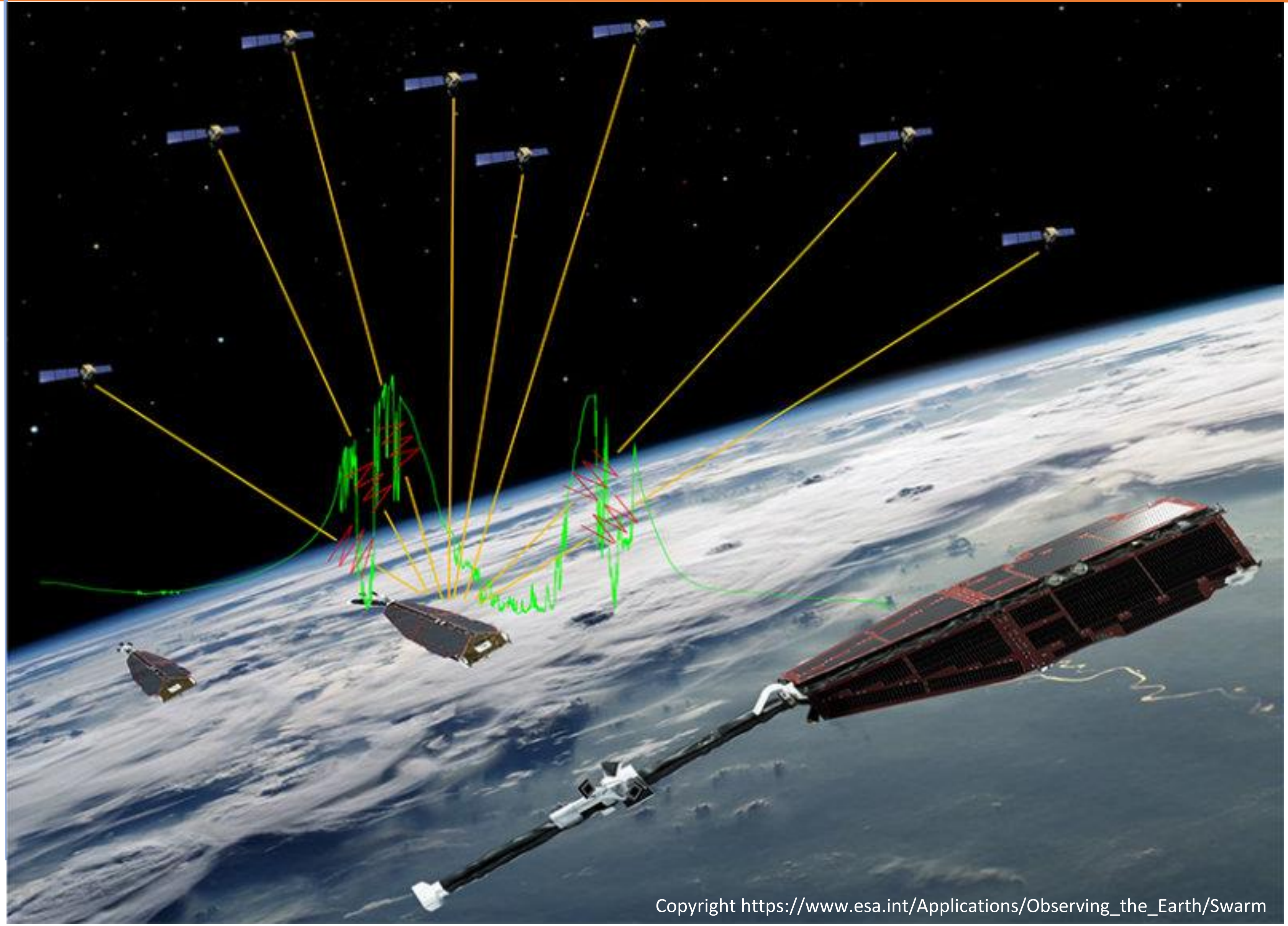
DQW Workshop
14 10 2021

Definition of Loss of Lock event



The **GPS signal is affected by ionospheric irregularities** potentially present along the signal path between the GPS satellite and the receiver.

We are talking about ionospheric structures, such as equatorial plasma irregularities, polar patches, and auroral blobs, that can deeply influence the GPS signal propagation.

These structures set up **intense electron density gradients** that may cause **rapid fluctuations of the received signal phase and amplitude**.

Under these conditions it can happen that the GPS receiver can no longer tracks the signal sent by the satellite, so there is an **interruption of the received signal**.

This is when we talk about a **Loss of Lock (LoL) event**.

GPS Loss of Lock identification method

Swarm Level 2 slant TEC (sTEC) time series calculated from L_1 and L_2 from POD antennas (Swarm L2 TEC Product Description, 2017) are considered.

LoL events are identified by looking for interruptions in the sTEC time series for each specific GPS satellite following a **4-step procedure**:

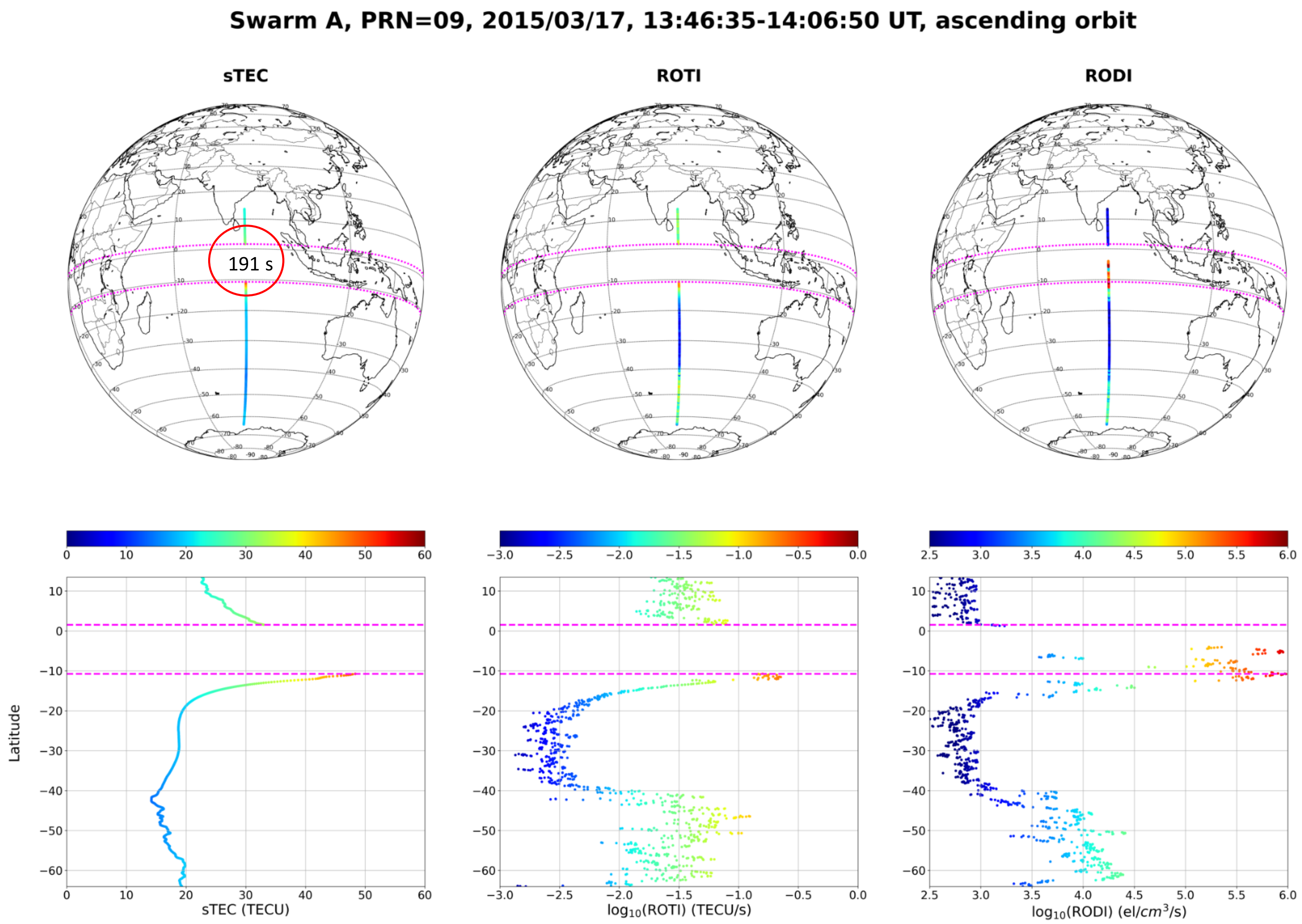
1) To extract the sTEC time series of each specific GPS satellite (then, for each specific PRN) from the Level 2 data files (which contain data of all the 32 GPS satellites);

2) To identify the different orbits for which each GPS satellite is in the field of view;

3) For each of these orbits, **interruptions** in the sTEC time series **ranging from 1 to 1200 s** are identified. The choice of this range guarantees that the identified interruptions are actually LoL and not due to the fact that the satellite has gone out of the field of view.
This means that if for instance a LoL begins just before the satellite is going outside the POD field of view, this event will not be considered in our dataset;

4) Steps 1-3 are repeated for each of the 32 GPS satellites (then, for each PRN).

Example of GPS Loss of Lock event



$$ROD_k = \frac{Ne_{k+1} - Ne_k}{t_{k+1} - t_k}$$

$$RODI_k = \sqrt{\frac{1}{N-1} \sum_{i=-j}^{j} \left| ROD_{k+i} - \overline{ROD}_k \right|^2}$$

$$ROT_k^s = \frac{TEC_{k+1}^s - TEC_k^s}{t_{k+1} - t_k}$$

$$ROTI_k^s = \sqrt{\frac{1}{N-1} \sum_{i=-j}^{j} \left| ROT_{k+i}^s - \overline{ROT}_k^s \right|^2}$$

In the next analyses, RODI and ROTI values associated to each LoL will be the maximum value in a 10 seconds wide window centered at the LoL start timestamp (the lower magenta curve in the Figure).

Duration of GPS Loss of Lock events

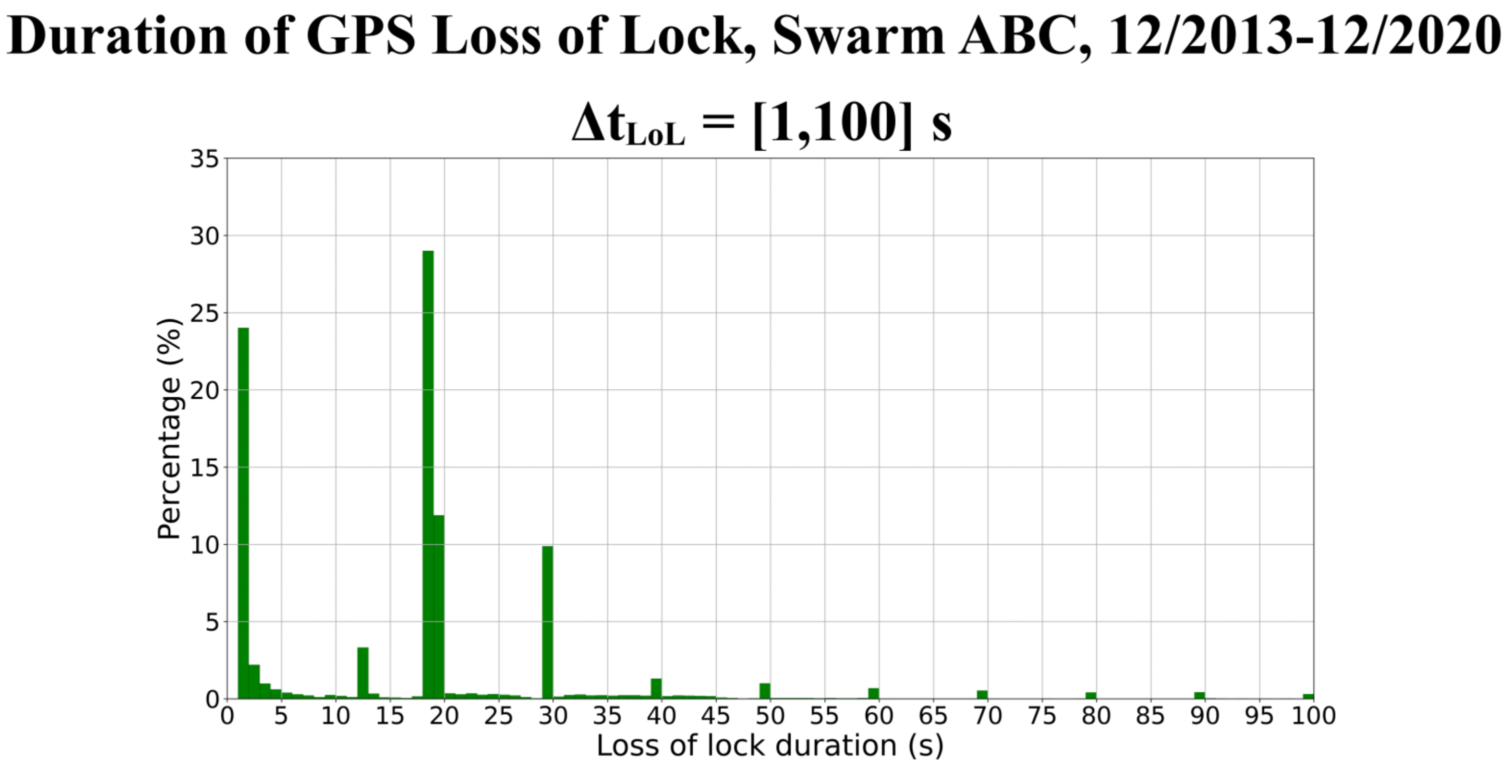
The method has been applied to data recorded from **December 2013 to December 2020** by **Swarm A, B and C**. In this way, it has been possible to identify **44731 GPS LoL events** with corresponding associated RODI and ROTI values.

The largest fraction of LoL is made up of events whose duration is 18 s (about 29% of the total) and 1 s (about 24% of the total).

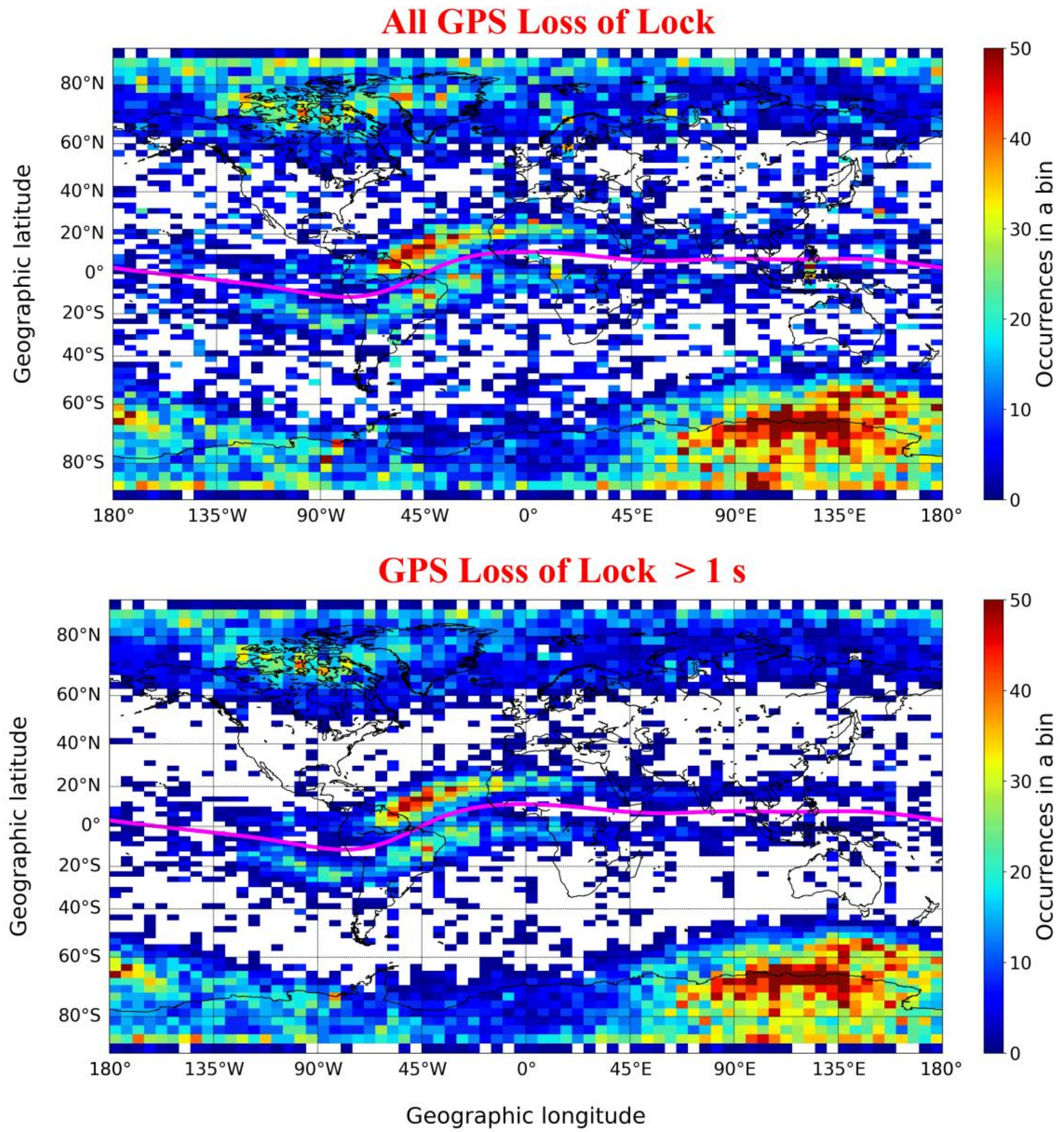
The percentage of events whose duration is greater than 100 s is less than 5.5%.

This distribution of LoL is consistent with that found by *Xiong et al.* (2018, 2019) who analyzed data from December 2013 to November 2016.

We investigated the reliability of very short LoL events. Specifically, we tried to understand whether LoL of 1 s are real or likely due to hardware outages.



Geographical distribution of GPS Loss of Lock events



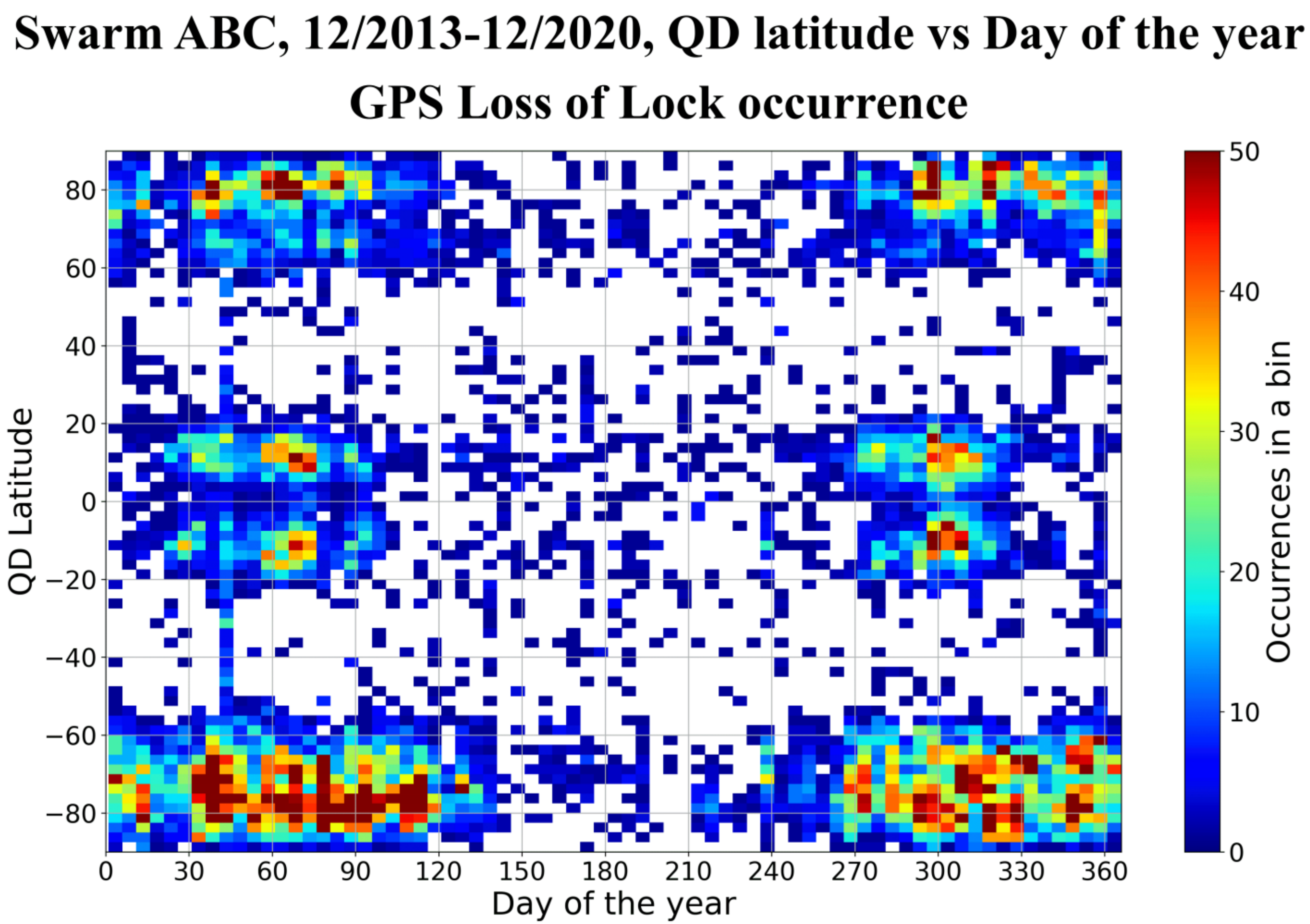
Discarding LoL of 1 s allows to eliminate most of the events located at mid latitudes, which are somewhat unexpected, not affecting at all the patterns characterizing both low and high latitudes.

In virtue of this result, the next analyses are based only on the dataset of GPS LoL events with a duration strictly greater than 1 s.

The figure shows that most of the LoL events **cluster at low and high latitudes**, for both hemispheres.

Their geographic distribution suggests a **strong connection with the Earth's magnetic field** (the magnetic equator is represented by the magenta curve).
In fact, the occurrences of **LoL maximize along the crests of the equatorial anomaly at low latitudes**, and **inside the auroral oval at high latitudes**.

Seasonal dependence of GPS Loss of Lock events



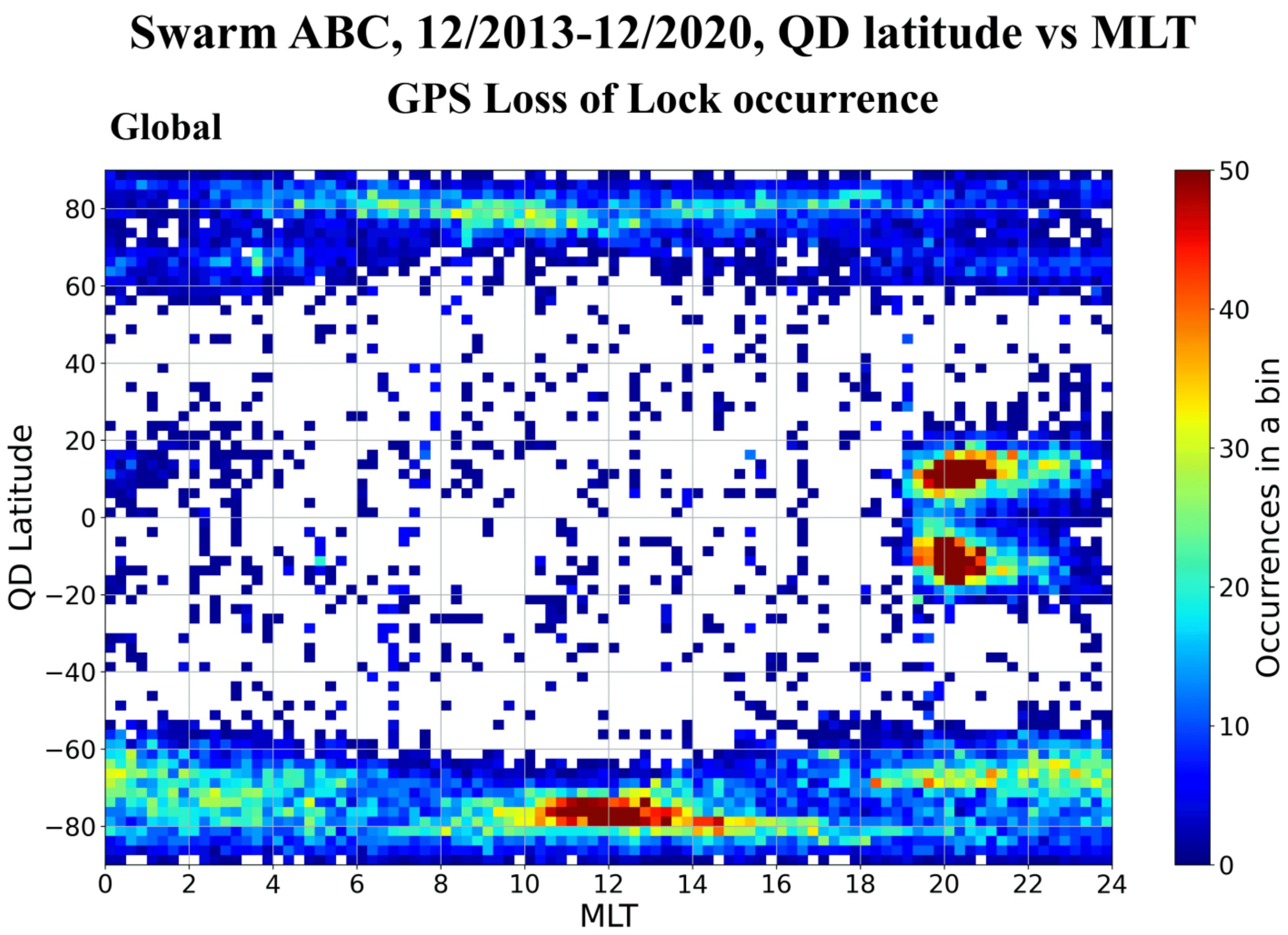
LoL are symmetrically distributed with respect to the magnetic equator.

At low latitudes they cluster around equinoxes.

At high latitudes the occurrence is bounded between about September and May, with a higher occurrence characterizing the southern hemisphere than the northern one.

For all latitudes, the minimum occurrence of LoL is in June, July and August, independently of the season.

Diurnal dependence of GPS Loss of Lock events



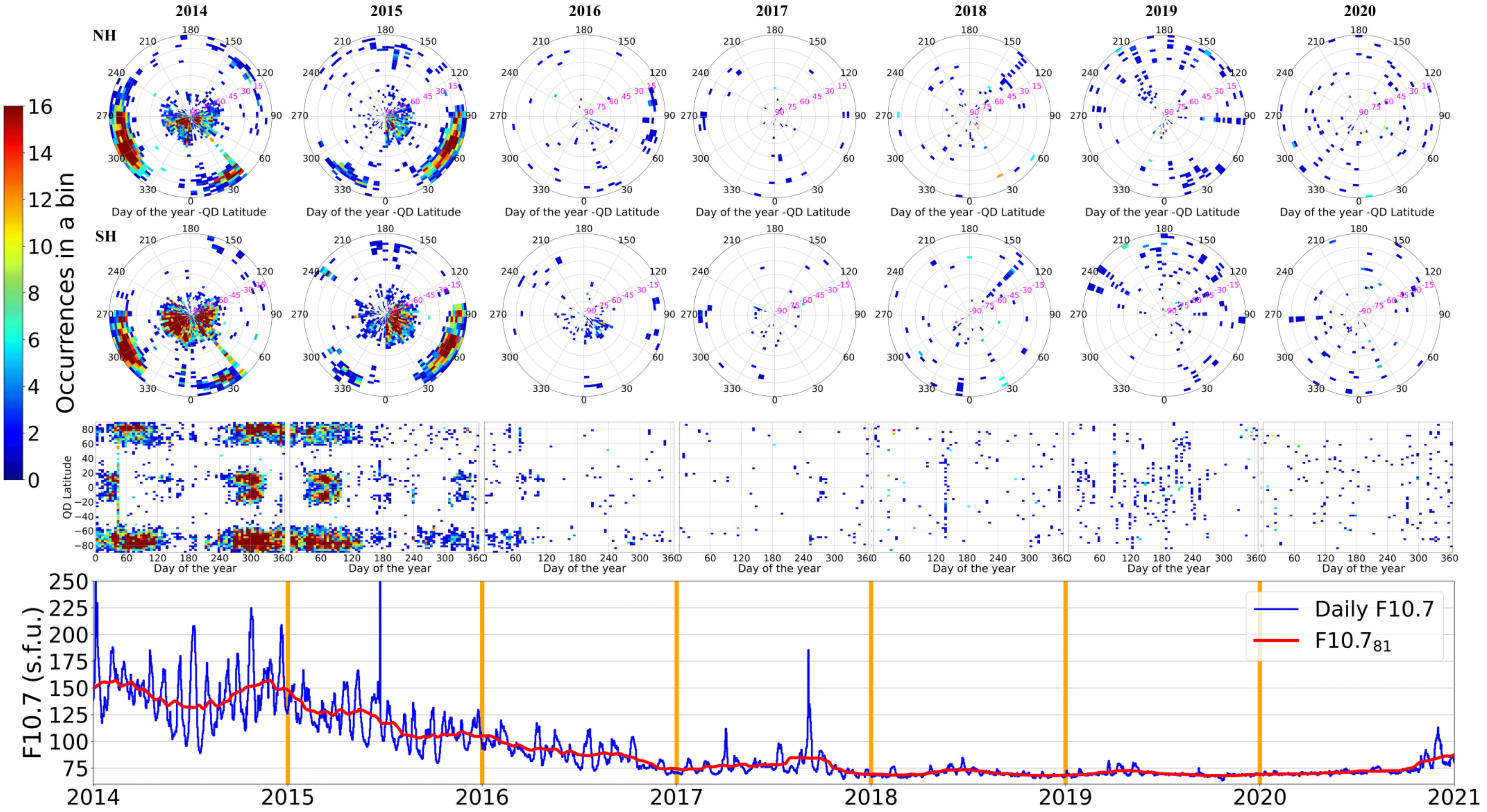
At low latitudes LoL cluster between 19 and 23 MLT, then for the post-sunset and early night hours.

Differently, at high latitudes the diurnal distribution is more homogeneous with maxima located around the local noon.

This is rather expected because, **contrary to low latitudes, at high latitudes the ionospheric irregularities do not show a preferential time window to occur**. They take place indifferently in the sub-auroral regions, in the dayside cusp, in the polar cap, as well as in the nightside auroral oval and ionospheric trough.

Maxima related to the local noon are linked to the irregularities characterizing the dayside cusp, while those related to the nightside sector are related to the irregularities characterizing the nightside auroral oval dynamics.

Solar activity dependence of GPS Loss of Lock events



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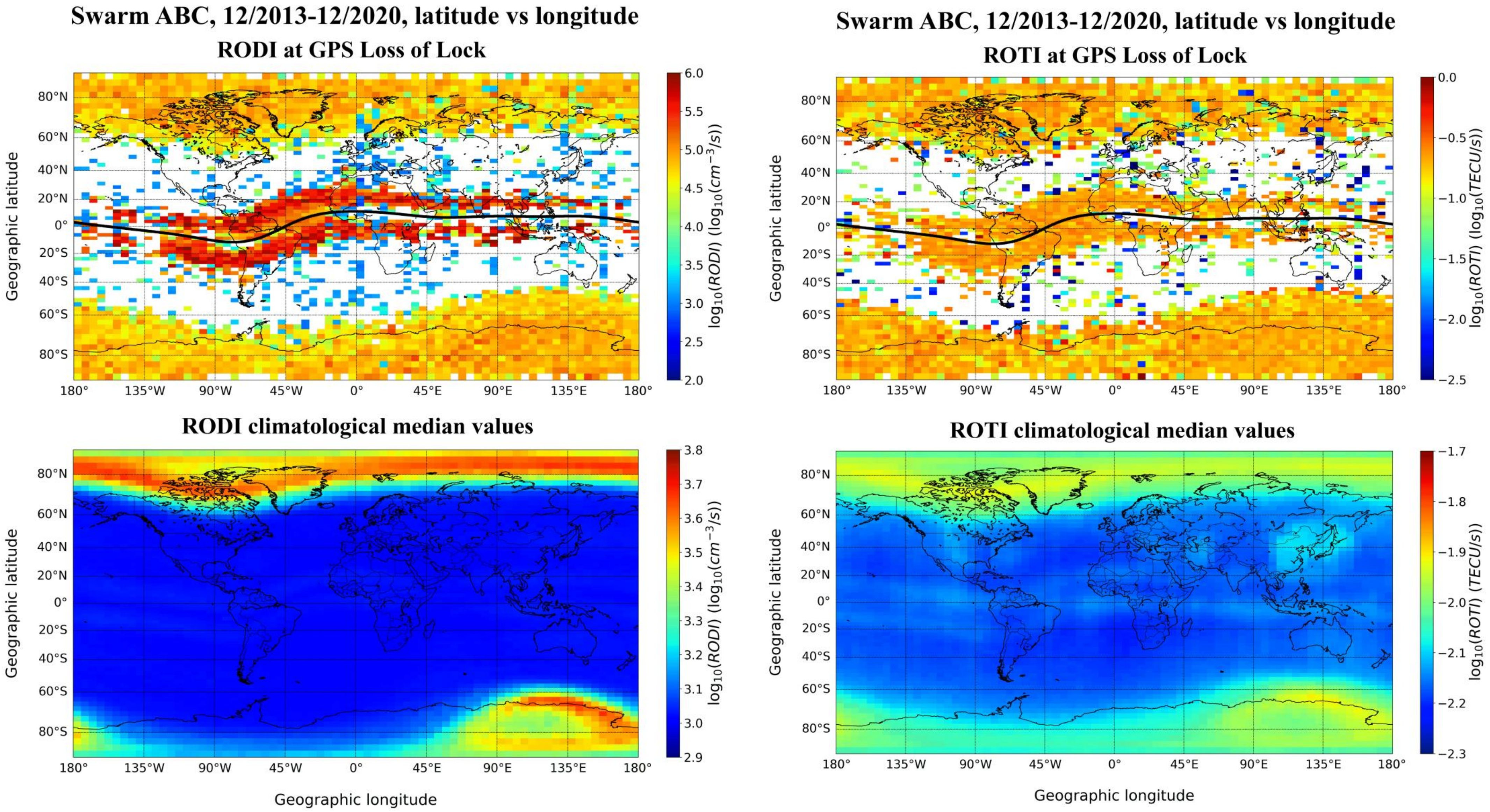
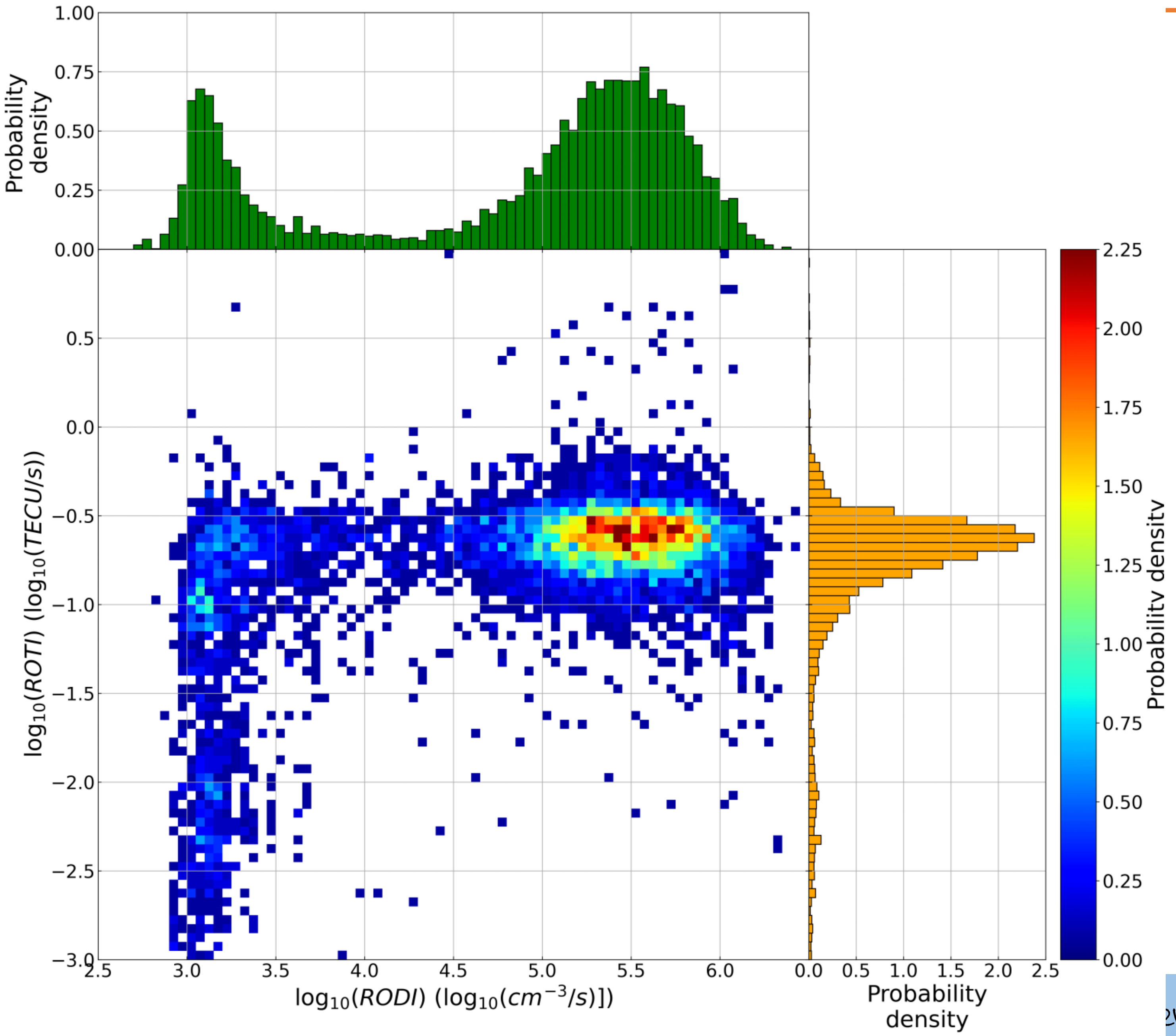
RODI Aand ROTI values at GPS Loss of Lock



RODI and ROTI values at GPS Loss of Lock
Swarm ABC, 12/2013-12/2020, |QD latitude| ≤ 45°



Summary and Conclusions

Considering data from the ESA Swarm constellation recorded from December 2013 to December 2020, **we analyzed the occurrence of GPS LoL events and characterized them in terms of RODI and ROTI**. **This is the first time that such an analysis, based on such a large time window, is carried out globally**, encompassing half a solar cycle, from the activity peak of 2013 to the minimum of 2020. The main outcomes of the study can be summarized as follows:

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2. At lo … n of occurre…

3. At lo … is more u…

4. LoL e…

5. LoL e … DI and ROTI fo…

remote sensing

MDPI

Article

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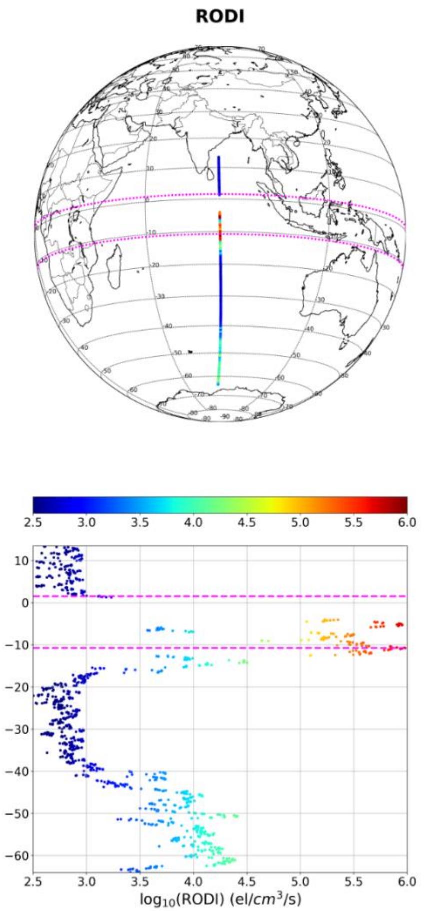
Michael Pezzopane [1,*], Alessio Pignalberi [1], Igino Coco [1], Giuseppe Consolini [2], Paola De Michelis [1], Fabio Giannattasio [1], Maria Federica Marcucci [2] and Roberta Tozzi [1]

In terms of RODI, the values are consistent with those recently found by studies focused on the turbulent nature of ionospheric irregularities, which suggests that LoL events are likely caused by irregularities triggered by processes of turbulent nature.

Thank you for your attention!



RODI…ROTI…

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TURBULENCE………

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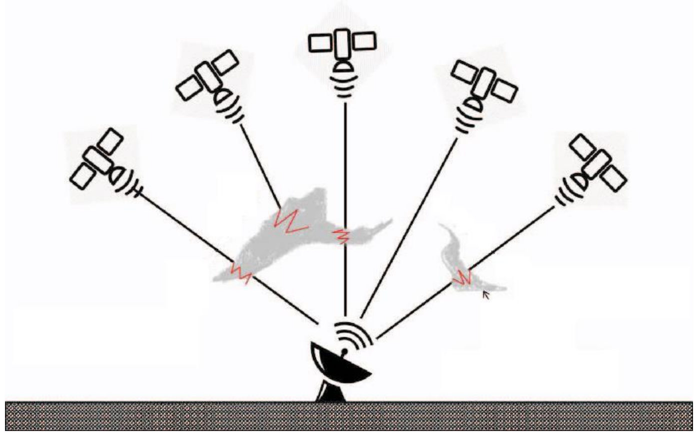

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LOSS OF LOCK……..