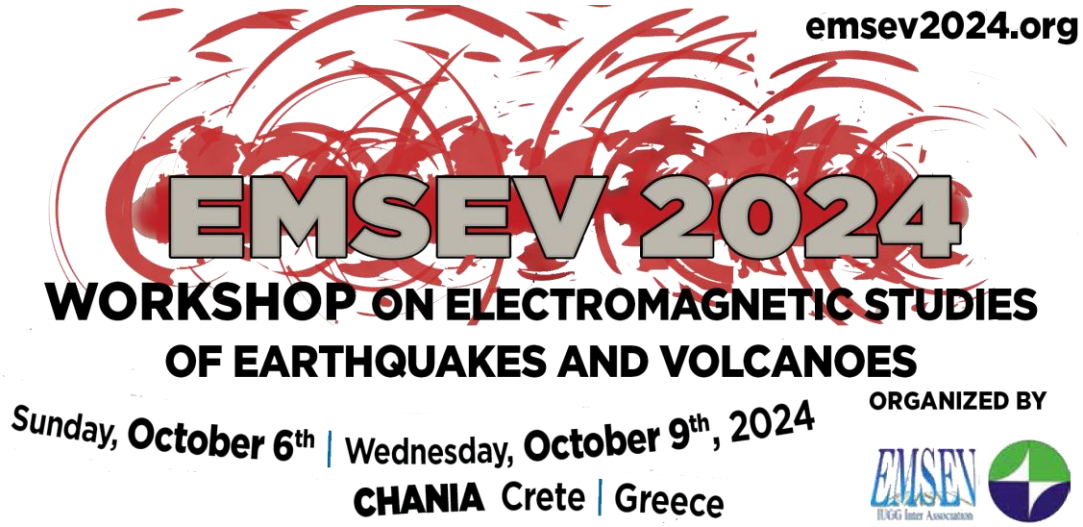
SEVERAL-DAY VARIATIONS OF ELECTRON DENSITY SENSED BY SWARM SATELLITES OVER TECTONIC PLATE JUNCTIONS



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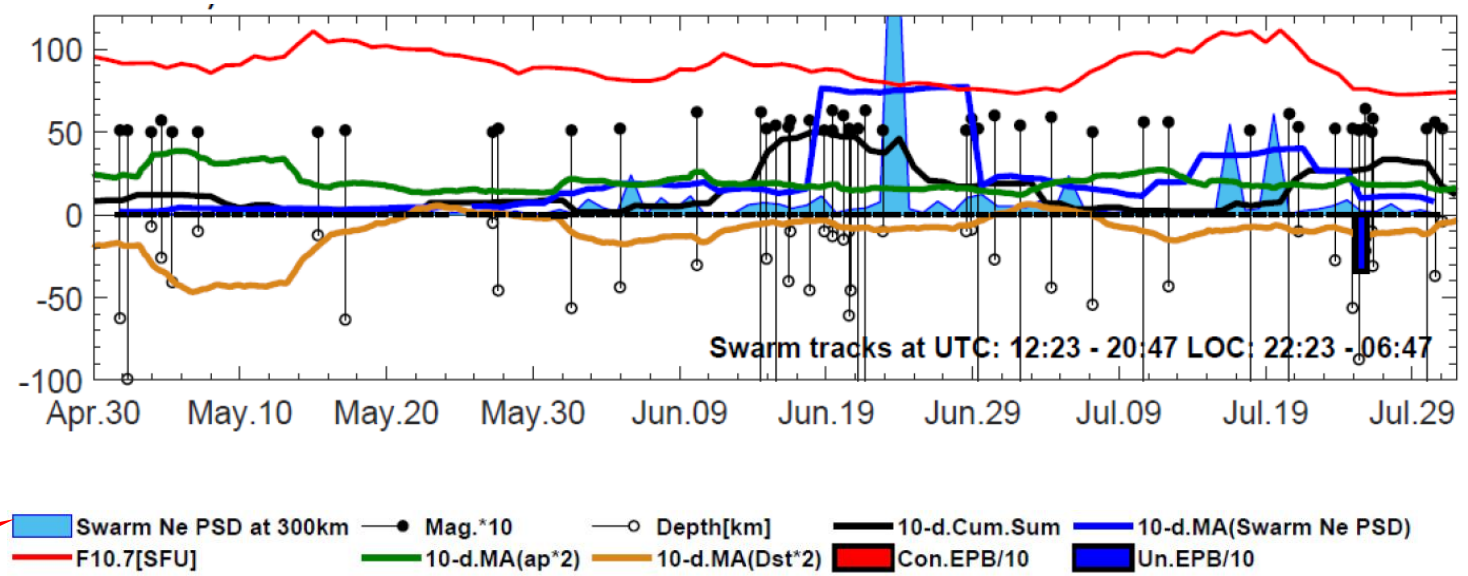
LAIC and Swarm

The objective of this work is detection of potential LAIC (lithosphere-atmosphere-ionosphere coupling) evidence in Ne variations at wave periods > 1 day

The reason of wave periods > 1 day is twofold:

1. We use Swarm data, which give only 2 orbital passes approximately over selected location
2. We initially found Ne variations persisting over days



Ne PSD – average power spectral density of Swarm along-track Ne at selected wave period
MA - moving averages of Swarm Ne PSD, Dst, ap
Cum.Sum. – cumulative sum of seismic energy

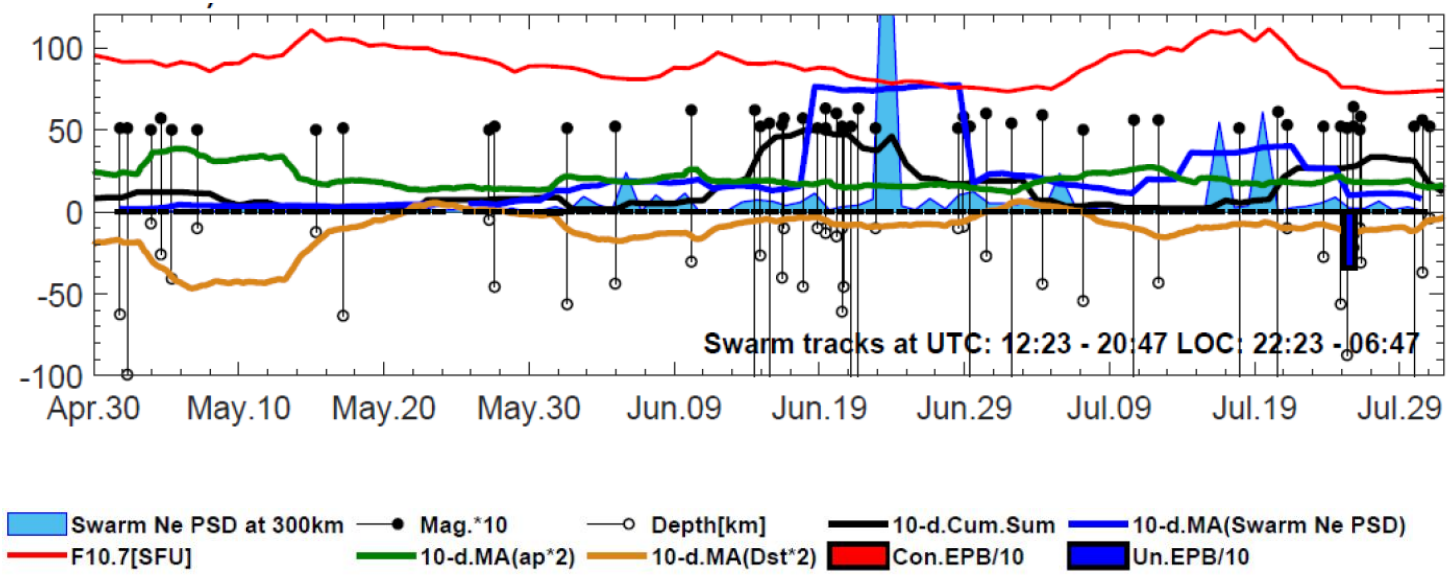
Jarmołowski,W., Wielgosz, P.; Hernández-Pajares,M.; et al... 2023, The Correlation between Ionospheric Electron Density Variations Derived from Swarm Satellite Observations and Seismic Activity at the Australian–Pacific Tectonic Plate Boundary. Remote Sens. 15, 5557. https://doi.org/10.3390/rs15235557

- Thanks to Prof. K. Hattori and colleagues for editing

LAIC channels and Swarm

The explanation of physical processes observed by Swarm is interesting, because Swarm provides data from entire globe.

However, the explanation is chalenging, because Swarm gives only two passes daily (daytime/nighttime)

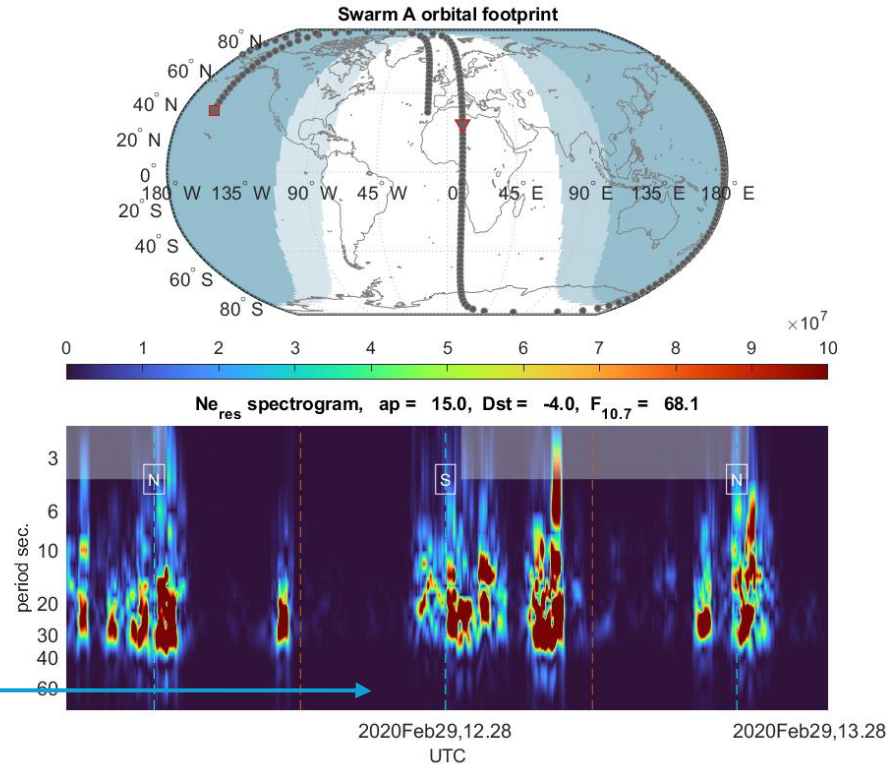


- Chemical channel (EFM channel) (radioactivity increase, ionization – days) - probable
- Acoustic channel (acoustic gravity waves, disturbances - minutes, hours) – less probable
- Electromagnetic channel (electromagnetic waves, particle precipitation – must be considered

Why spectral analysis and filtering?

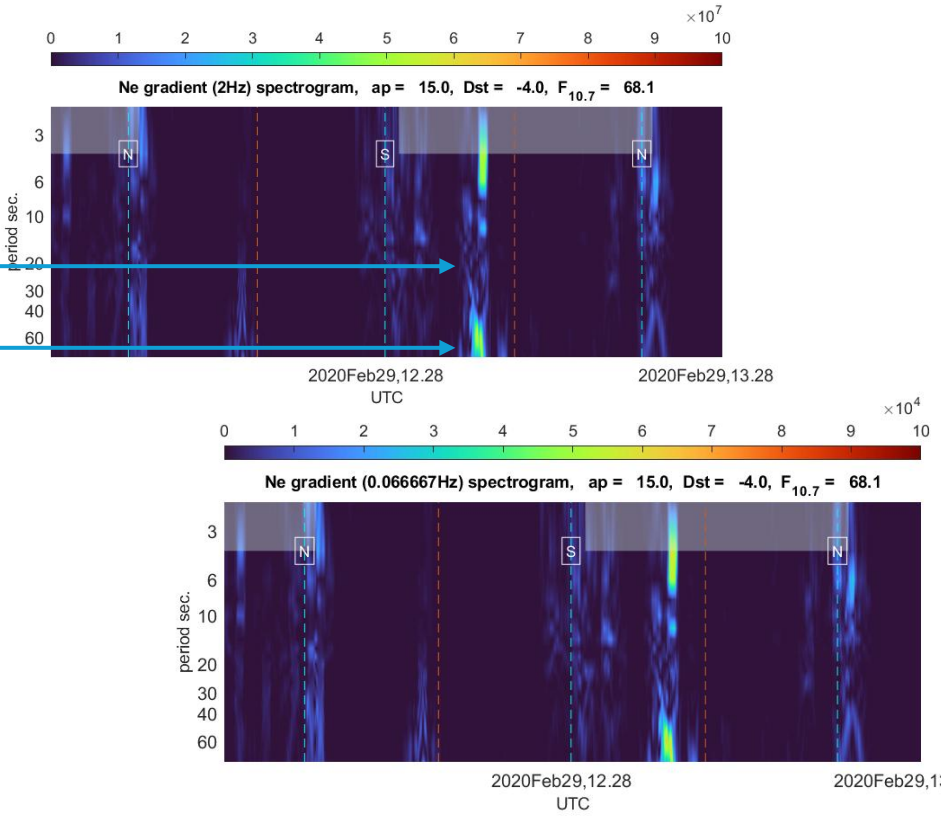
High-pass filtering by Fourier:

- Selects accurately desired data frequencies (band-pass)
- **Exactly removes trend at fixed frequency (high-pass)**
- Can elliminate noisy high frequencies (low-pass)



Gradient detrending, e.g. ROT:

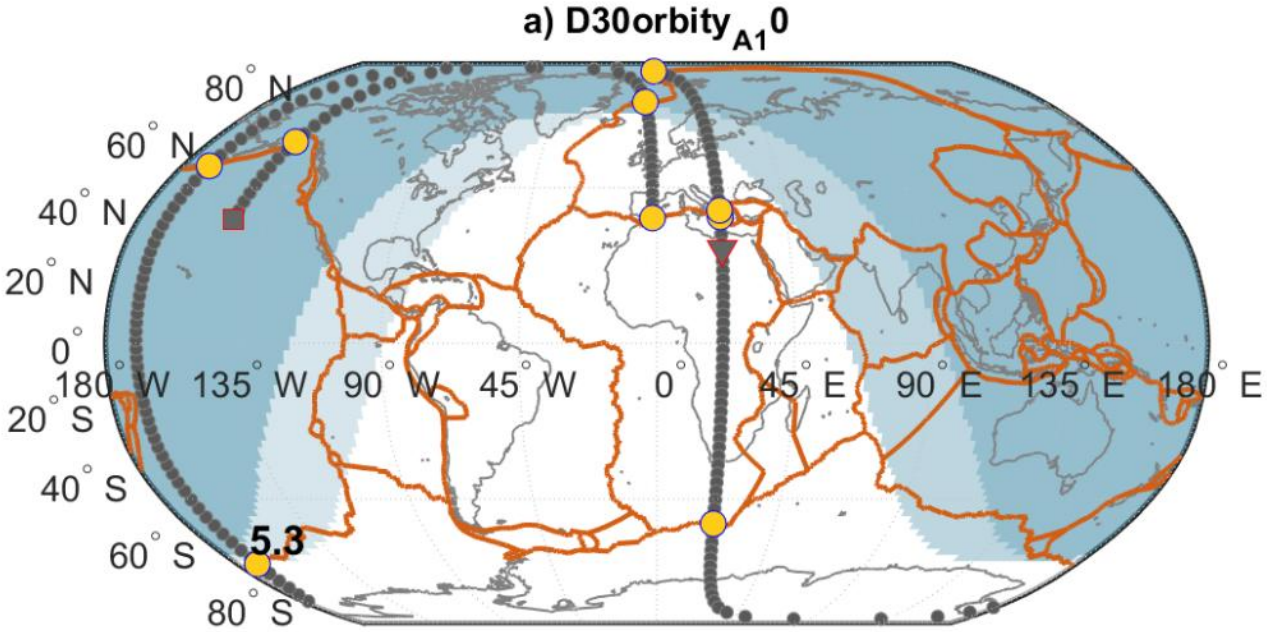
- Cannot select data frequencies (or needs combinations)
- Gradient leaves low-frequency features in some places
- Unintentionally elliminates signal from middle band



Swarm Ne processing, Short-term Fourier transform (STFT) along the track

Swarm in-situ Ne are divided into single orbital revolutions (with some margins):

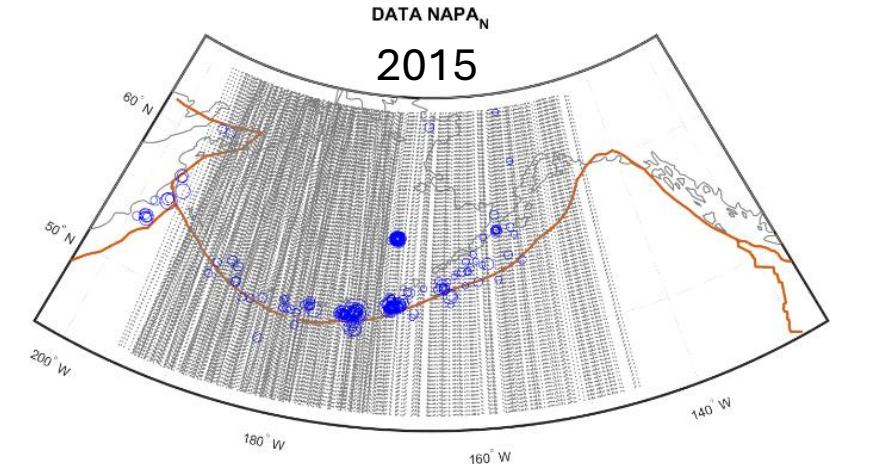
- Swarm orbital tracks cross several tectonic plate junctions almost orthogonally (such orientation of tectonic plates is frequent)
- Swarm observations differ between night and day. The high-frequency residuals also differ.
- Tectonic plate junctions are long – variable longitudes of Swarm passes on consecutive days can be collected
- Many latitudinal junctions are located in EIA region – therefore it is better to analyze Swarm Ne at frequencies higher than EIA crests

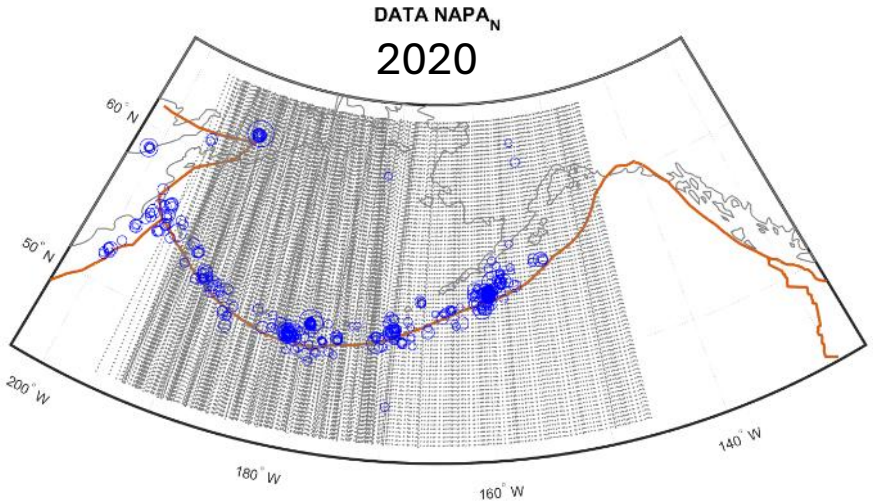


Selection of test areas: boundary between North-American (NA) tectonic plate and Pacific (PA) tectonic plate

Swarm in-situ Ne are selected from 2 full years:

- 2015 at solar maximum and 2020 at solar minimum of SC24
- As it was mentioned, Swarm passes quickly, only once a day at similar time of the day
- Latitude at NA-PA boundary is around 55°N
- Selected Swarm A, nighttime tracks

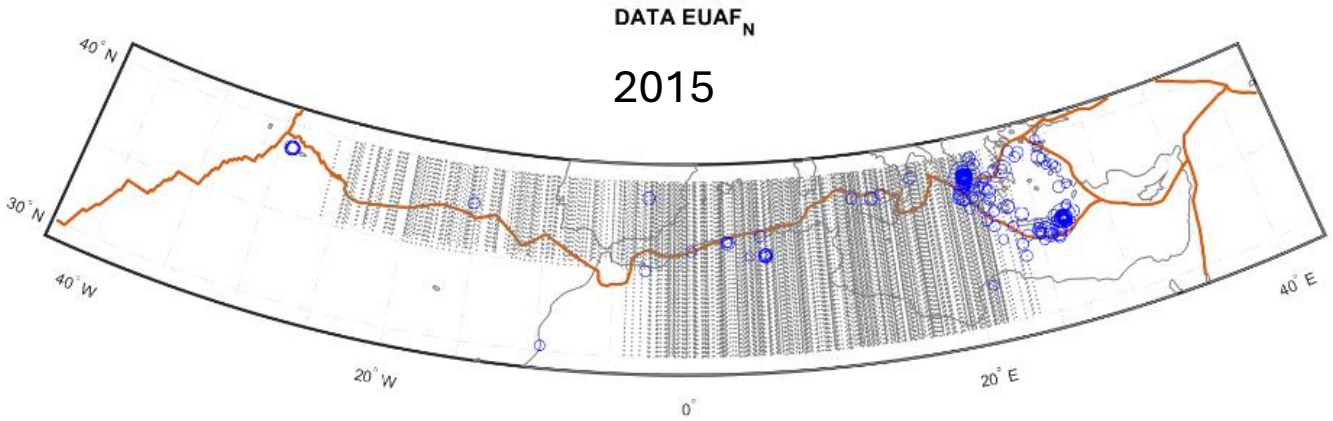


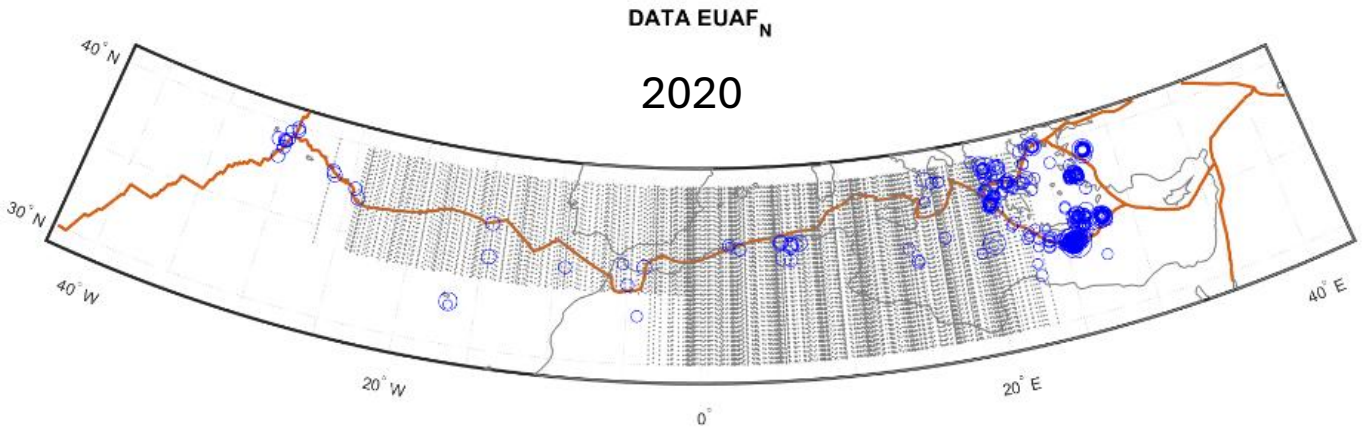


Selection of test areas: boundary between Eurasian (EU) tectonic plate and African (AF) tectonic plate

Swarm in-situ Ne are selected from 2 full years:

- 2015 at solar maximum and 2020 at solar minimum of SC24
- As it was mentioned, Swarm passes quickly, only once a day at similar time of the day
- Latitude at EU-AF boundary is around 35°N
- Selected Swarm A, nighttime tracks



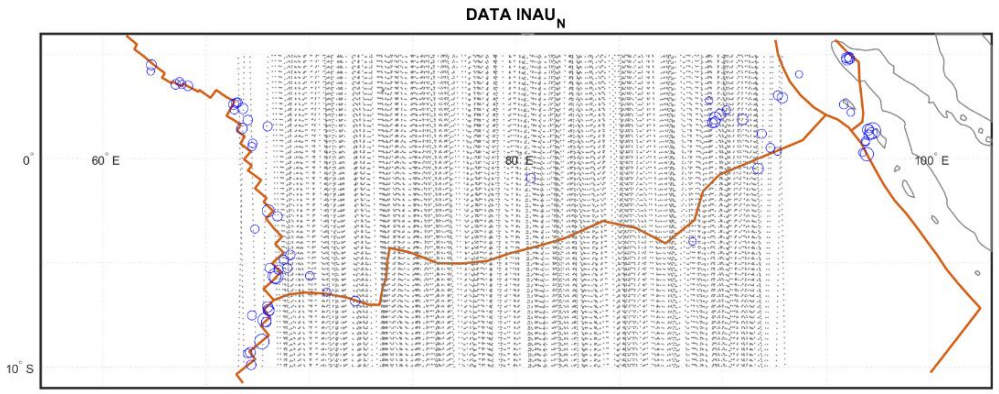


Selection of test areas: boundary between Indian (IN) tectonic plate and Australian (AU) tectonic plate

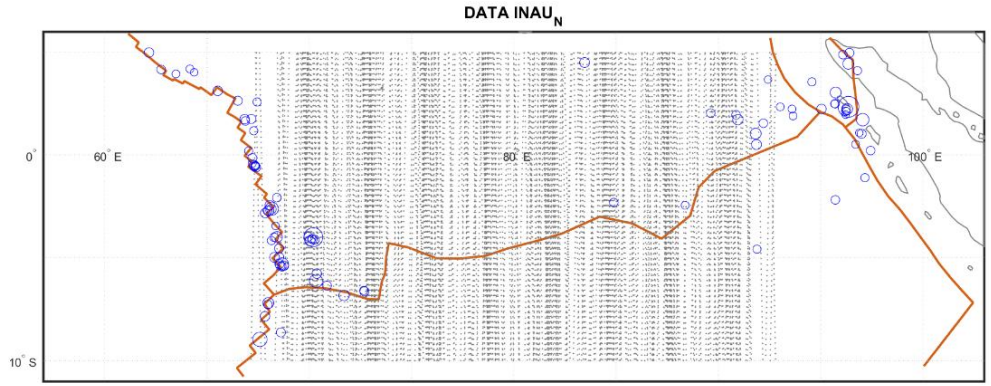
Swarm in-situ Ne are selected from 2 full years:

- 2015 at solar maximum and 2020 at solar minimum of SC24
- As it was mentioned, Swarm passes quickly, only once a day at similar time of the day
- Latitude at IN-AU boundary is around equator
- Selected Swarm A, nighttime tracks

2015



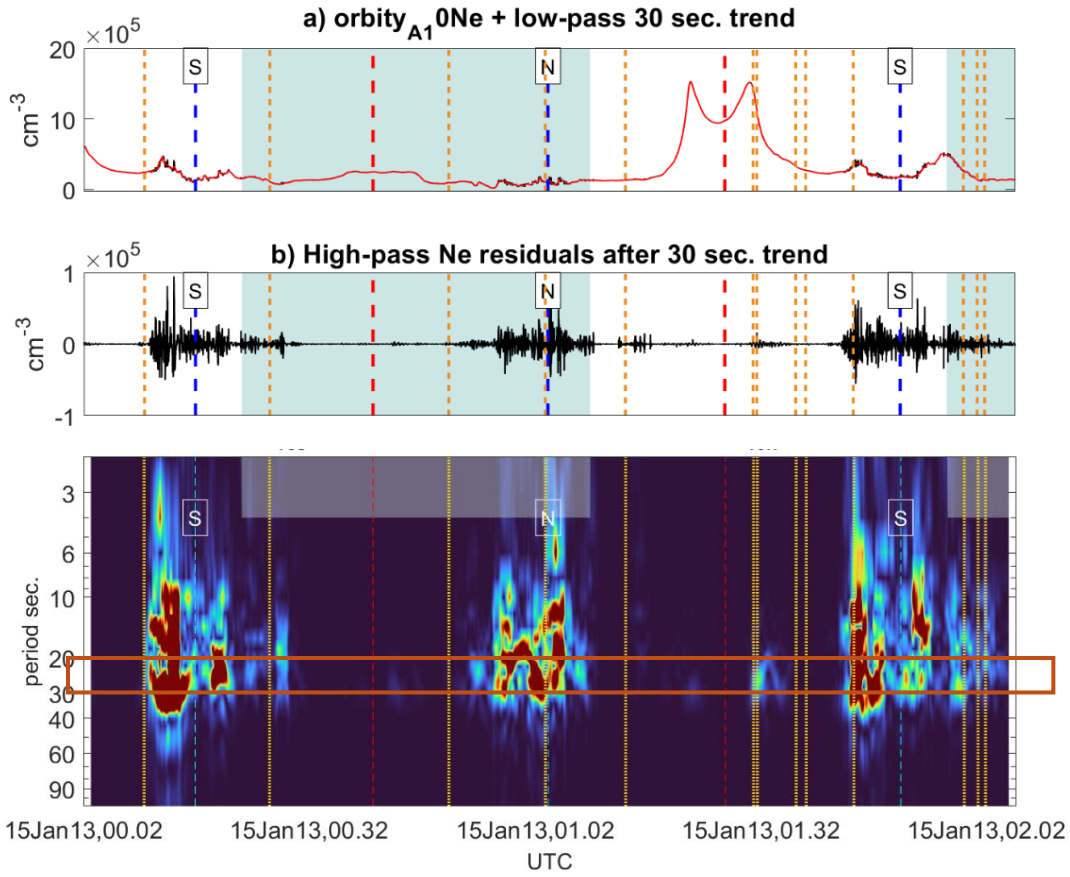
2020



Swarm Ne processing - STFT along the track

Swarm in-situ Ne are processed by application of STFT along the satellite tracks (time-space-frequency analysis):

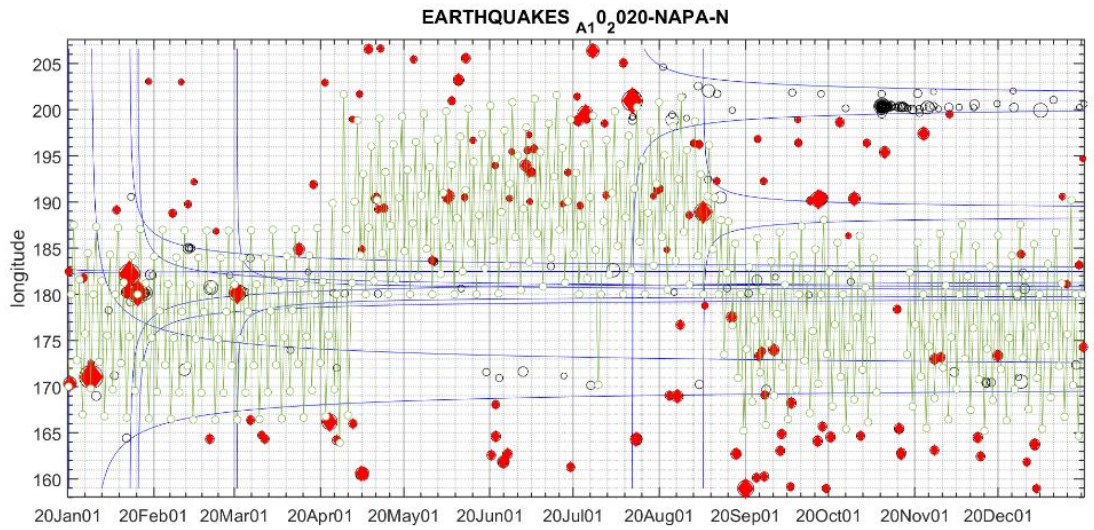
- Fourier-based high-pass filter (~230 km – 30 s.) to separate high frequencies (still sensitive like lower frequencies, but we elliminate EIA)
- STFT analysis and spectrograms of along-track data (UTC time)
- Average $PSD^{1/2}$ is calculated for Swarm passes over tectonic plate junction (selected latitude range) from selected frequency band – in this test 20-30 sec (experimental)

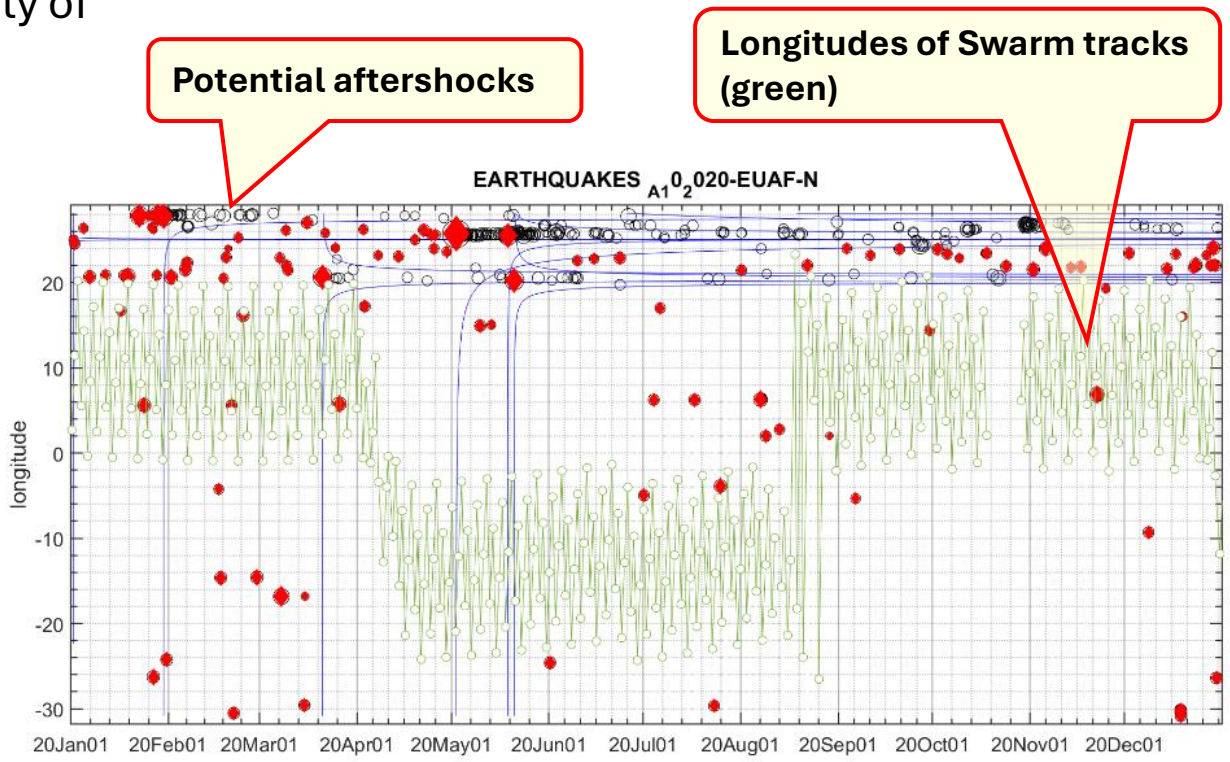


Adopted idea of declustering can be useful, but must be further adjusted more

Declustering elliminates aftershocks based on proximity of subsequent smaller earthquakes and time proximity

Zaliapin, I., & Ben-Zion, Y. (2020). Earthquake declustering using the nearest-neighbor approach in spacetime-magnitude domain. Journal of Geophysical Research: Solid Earth, 125, e2018JB017120. https://doi.org/10.1029/2018JB017120

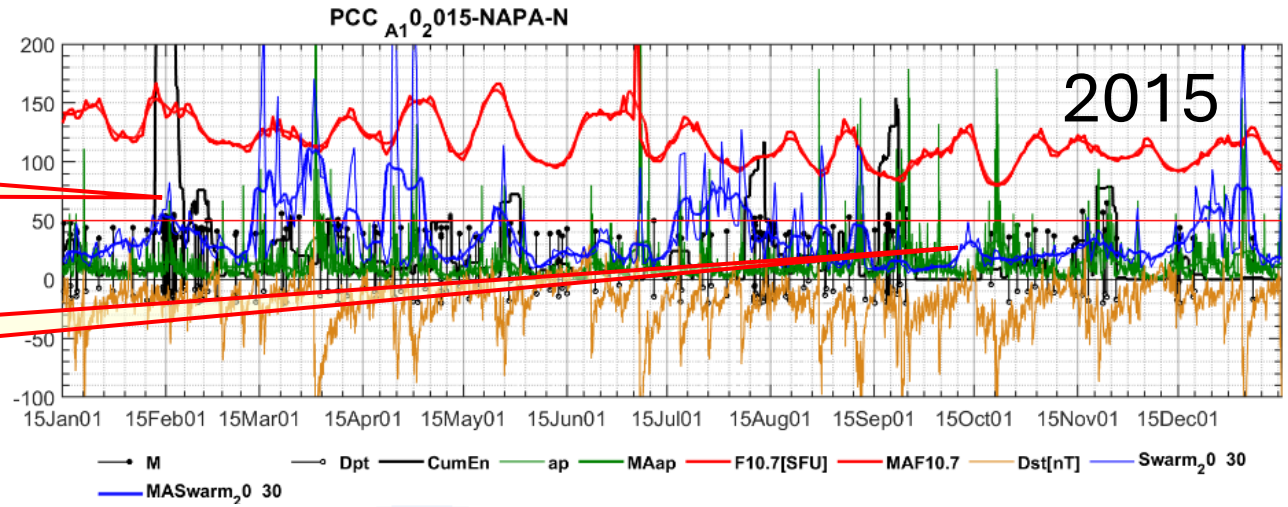




Mean(PSD)$^{1/2}$ of Swarm Ne residuals over time, compared to geomagnetic indices, solar radio flux, earthquakes and cumulative sum of seismic energy NA-PA

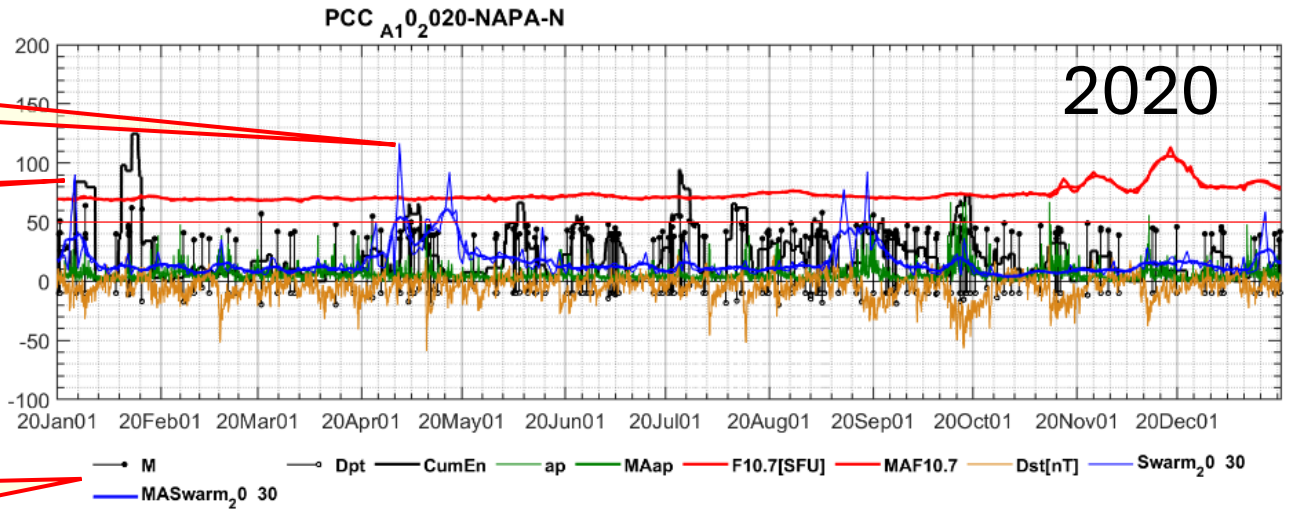
Swarm PSD increase – high ap – high seismicity

Swarm PSD increase – low ap – before earthquakes



Swarm PSD increase – low ap – high seismicity

Swarm PSD increase – higher ap – strong earthquakes



Swarm – SQRT(mean(PSD)) of Swarm along-track Ne from frequency band (wave period 20-30 sec.)
MA - moving averages of **Swarm Ne**, **ap**, **F10.7**
Cum.En. – cumulative sum of seismic energy

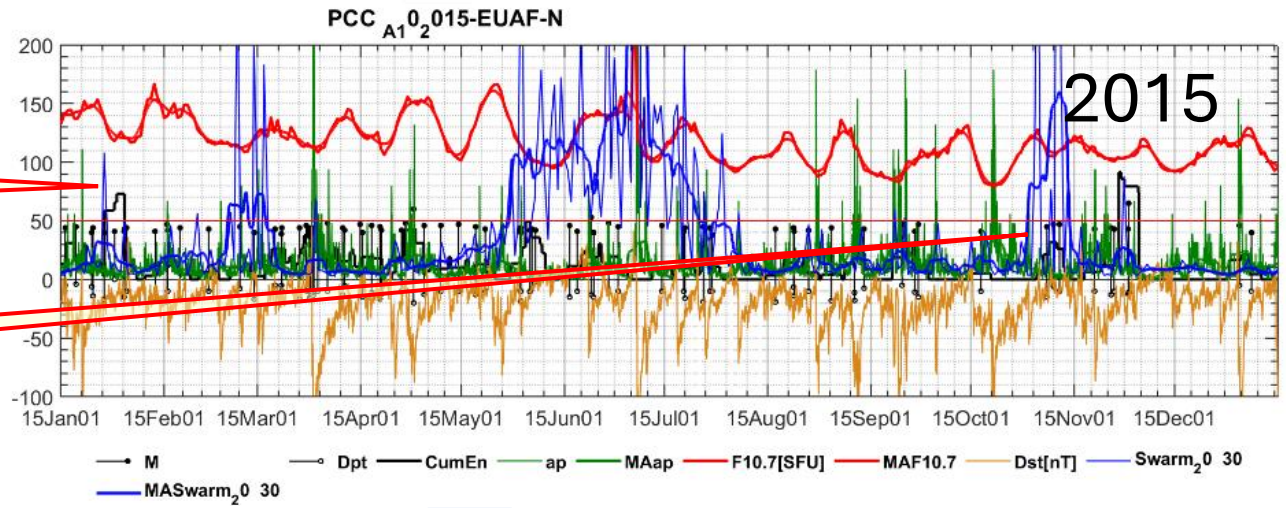
Mean(PSD)$^{1/2}$ of Swarm Ne residuals over time, compared to geomagnetic indices, solar radio flux, earthquakes and cumulative sum of seismic energy EU-AF

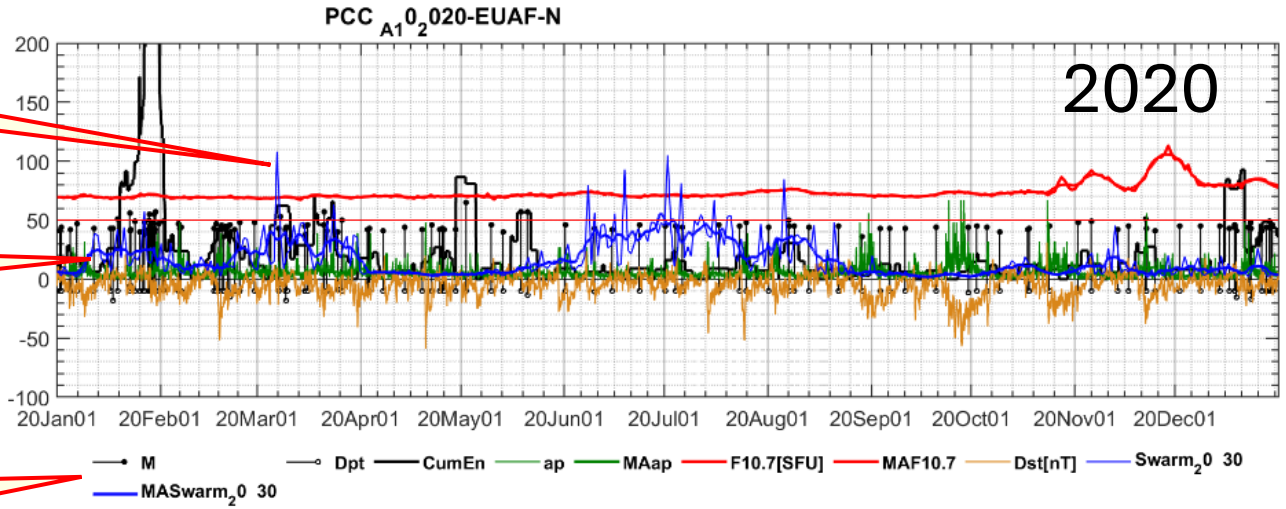
Swarm PSD increase – average ap – high seismicity

Swarm PSD increase – low ap – high seismicity

Swarm PSD increase – low ap – high seismicity

Swarm PSD increase – low ap – high seismicity





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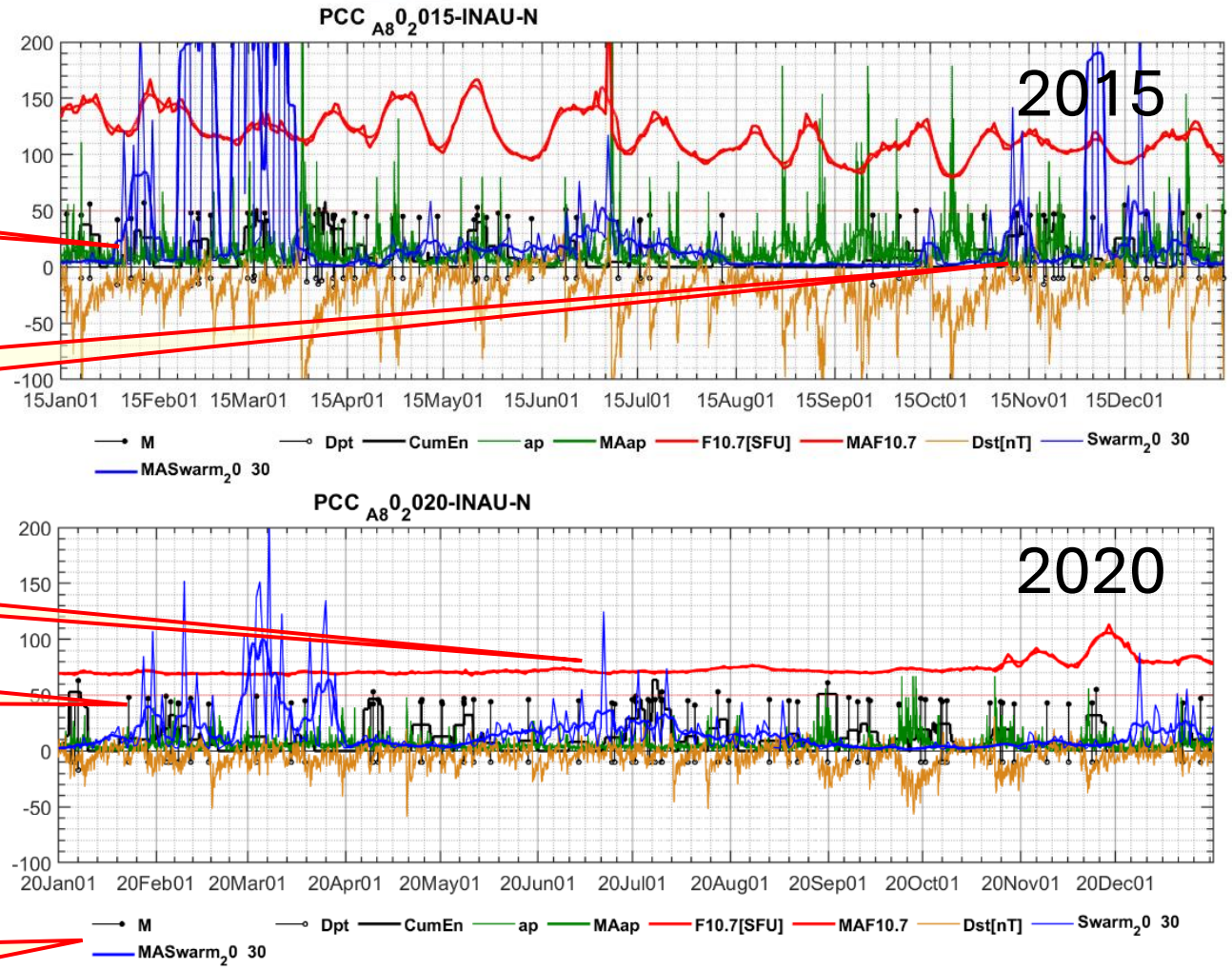
Mean(PSD)$^{1/2}$ of Swarm Ne residuals over time, compared to geomagnetic indices, solar radio flux, earthquakes and cumulative sum of seismic energy IN-AU

Swarm PSD increase – low ap – strong earthquakes

Swarm PSD increase – very low ap – strong earthquakes

Swarm PSD increase – low ap – high seismicity

Swarm PSD increase – low ap – high seismicity

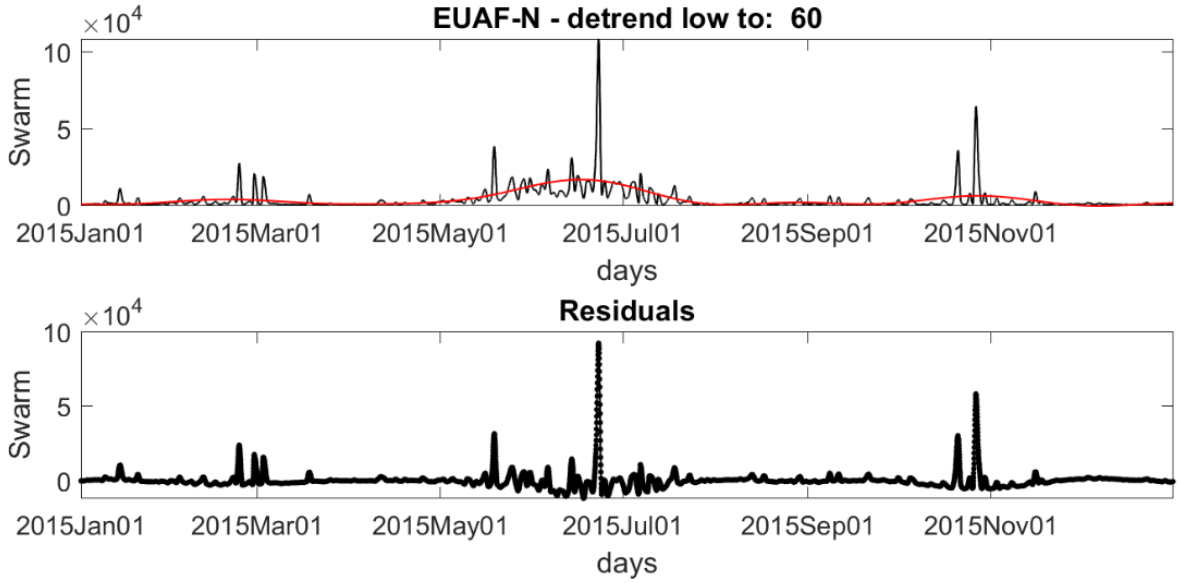


Swarm – SQRT(mean(PSD)) of Swarm along-track Ne from frequency band (wave period 20-30 sec.)
MA - moving averages of Swarm Ne, ap, F10.7
Cum.En. – cumulative sum of seismic energy

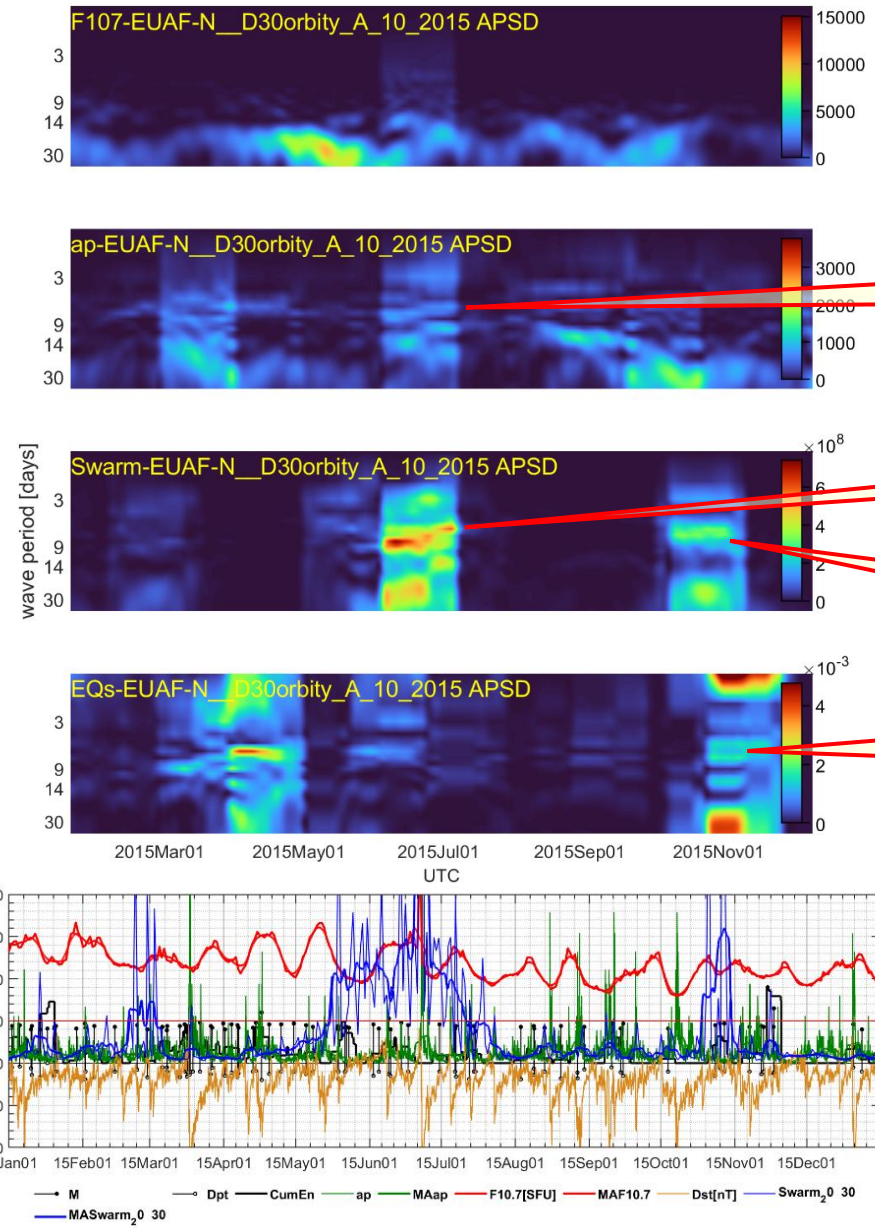
Concept of second round of STFT for Swarm, time-frequency approach (which for ap are easy to do)

Collected yearly series of sampled (20-30 sec.) PSD from Swarm in-situ Ne exhibit variations of different wave periods:

- High-pass filtering can be done to remove low frequencies, which are hard to analyse using this length of time series
- Filtering bound of 60 days is applied
- The same has been done for earthquakes, but regular series must be generated



Time-frequency analysis of Swarm Ne variations, in comparison to F10.7, ap and earthquakes (EU-AF, **2015**)



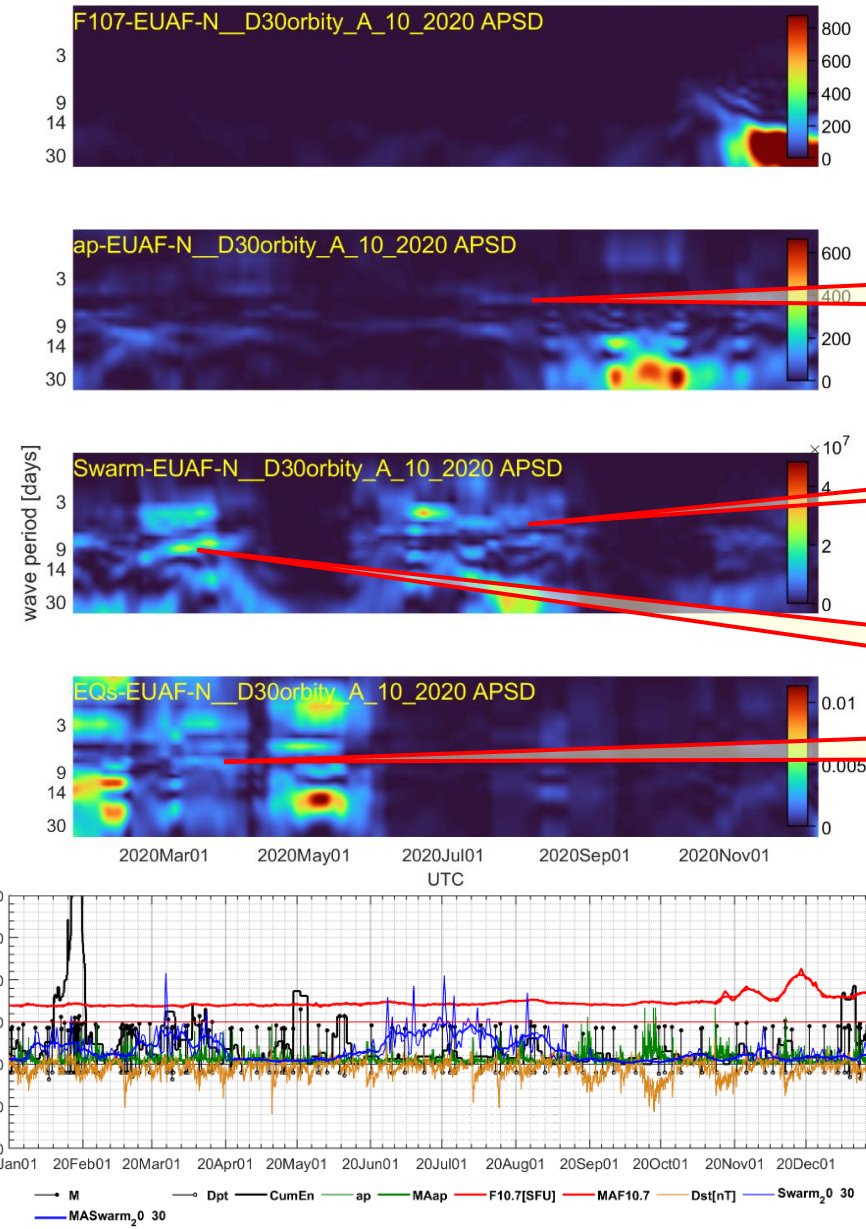
ap periodic signal pronounced around 7, 9-day wave period

Swarm periodic signal pronounced around 7, 9-day wave period

Swarm periodic signal around 9-day wave period

earthquakes periodic signal around 9-day wave period

Time-frequency analysis of Swarm Ne variations, in comparison to F10.7, ap and earthquakes (EU-AF, **2020**)



ap periodic signal noticeable around 5-day wave period

Swarm periodic signal noticeable around 5-day wave period

Swarm periodic signal around 9-day wave period

earthquakes periodic signal around 9-day wave period

Conclusions

- Every analysis over time contributes much to our knowledge on LAIC, because several-day ionospheric perturbations have different origins and are composed.
- The solar, geomagnetic, and seismic activity variations (shorter or longer periodic signals) resonate with Swarm Ne variations several times
- For Swarm main problem stems from different longitudes and hours of pass on different day – this causes that different diurnal Ne variations (which are high) can affect sensitivity of the residuals (but not their scale, as we work at high frequencies!)
- Fourier is clever, but a lot of work must be done to prepare the data and adjust the parameters. Not every Fourier nor wavelet analysis shows what we want to see.
- Remaining question is if PSD is the best choice for series creation? Maybe some frequency of Ne?