EGU21-8218
G5.2

European Geosciences Union
General Assembly 2021
vEGU21: Gather Online | 19–30 April 2021

UNIWERSYTET
WARMIŃSKO-MAZURSKI
W OLSZTYNIE

Seismic ionospheric disturbances related to Chile-Illapel 2015 earthquake and tsunami observed by Swarm and ground GNSS stations

Wojciech Jarmołowski[1], Paweł Wielgosz[1], Anna Krypiak-Gregorczyk[1], Beata Milanowska[1] and Roger Haagmans[2]

[1] University of Warmia and Mazury in Olsztyn, Faculty of Geoengineering, Poland
[2] European Space Agency, ESTEC, The Netherlands

Spectral decomposition of Swarm along-track data (Langmuir Probe (LP) and POD TEC) and validation by ground GNSS phase data (geometry free combination)

- **STFT spectral approach to along-track Swarm data gives an opportunity for distinguishing the signals of different origin.**

- **The classification of the spectral characteristics of disturbing along-track signals by STFT is supported by their simultaneous search in ground GNSS observations, which gives an opportunity for the validation of the spectral recognition.**

- **The disturbances observed by Swarm and reflected in large power spectrum density (PSD) at the selected frequencies along the orbital track can be directly visually compared to TIDs present in ground GNSS observations.**

- **IPPs, which indicate the location of geometry free ($L_{G\text{-}F}$) phase combination data are referred to the altitude of 450 km, which gives coincidence with Swarm A/C altitude, and approximate coincidence with slightly higher orbit of Swarm B.**

Two datasets – three steps

1. STFT SPECTROGRAMS are made for the selected LP ED high-pass filtered observations, using 70 sec. Tukey window.

- ED measured by LP and POD TEC are high-pass filtered by DFT to 70 sec.
- The PSD from the spectrogram is sampled at frequency of 50 sec, in order to visualize large PSD values along Swarm track together with scatter plot of ground GNSS data.

2. KEOGRAM based on band-pass filtered L_{G-F} combination of phase ground GNSS data and distances calculated from the earthquake (EQ) epicenter is prepared, and overlayed with the selected Swarm LP ED spectrogram sections.

- The L_{G-F} is band-pass filtered by DFT between the period from 1800 sec to 240 sec., which is intentional for the overview keograms of a wider spectrum of disturbances.

3. SCATTER plots describing several min of L_{G-F} from ground GNSS data and respective several min. of ED spectrogram section along the Swarm orbit. Two data sources are directly spatiotemporally compared.

Two datasets – three steps

1. STFT SPECTROGRAMS of Swarm LP disturbing signals.

- **Advantages**: the only way of recognition of short signals
- **Problems:** band-pass filtering fequencies selection issue, presence of solar-induced signals, fast speed of Swarm and other…

2. KEOGRAM assessment of ground GNSS data and preliminary comparison with Swarm.

- **Advantages**: correlation and evidence of TIDs (TIDs) is optimal
- **Problems:** keogram indicates distances from the epicenter or selected directions and therefore comparison with Swarm can be only initial

3. SCATTER assessment of ground GNSS data and comparison with Swarm.

- **Advantages:** scatter indicates exact places and Swarm-ground GNSS co-location can be exactly determined
- **Problems:** correlated TIDs (TIDs) are easy to observe only when data is dense !!!

Timeframe and area selection

The EQ of magnitude 8.3 took place in Chile-Illapel region on **16.09.2015** at **22:54**, however the orbits of **Swarm B** just after this EQ were more than **2000 km** to the west of this event, and **Swarm A/C** orbits were distant even more than **3000 km**.

Swarm satellites A/C passed this region on **16.09.2015** around **20:00 UTC**, whereas **Swarm B** passed the region around **22:00 UTC**.

The closest available **Swarm A** track after the mainshock in terms of close time and location is recorded on **17.09.2015, 7:25 AM UTC**, and this time also corresponds to tsunami propagation time. This pass of Swarm A took place around **8.5 h after** Mw=8.3 EQ, when there were many aftershocks and the tsunami was in the middle phase of the propagation in the ocean.

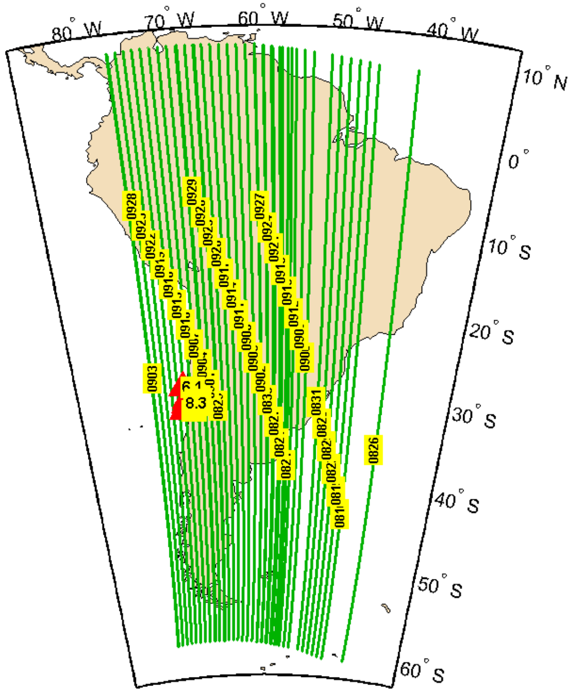
Timeframe and area selection

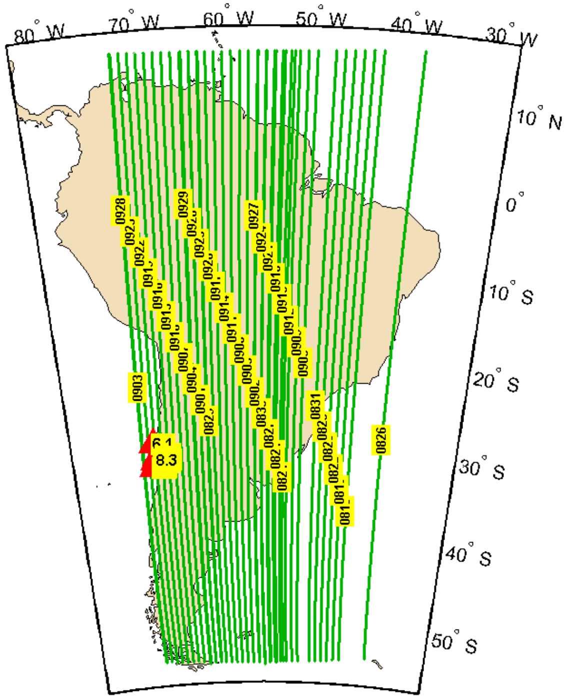
1. Firstly, we analyze Swarm B pass in UTC evening on 10.09.2015, which is six days before the mainshock.
2. Secondly, we study Swarm B at the moment just before the Chile-Illapel mainshock, and analyze ground GNSS data also up to an hour after this EQ on 16.09.2015.
3. Thirdly, we inspect the closest possible Swarm A/C pass several hours after the mainshock, in the morning of 17.09.2015.
4. Then we show additionally some other selected Swarm passes/ground GNSS

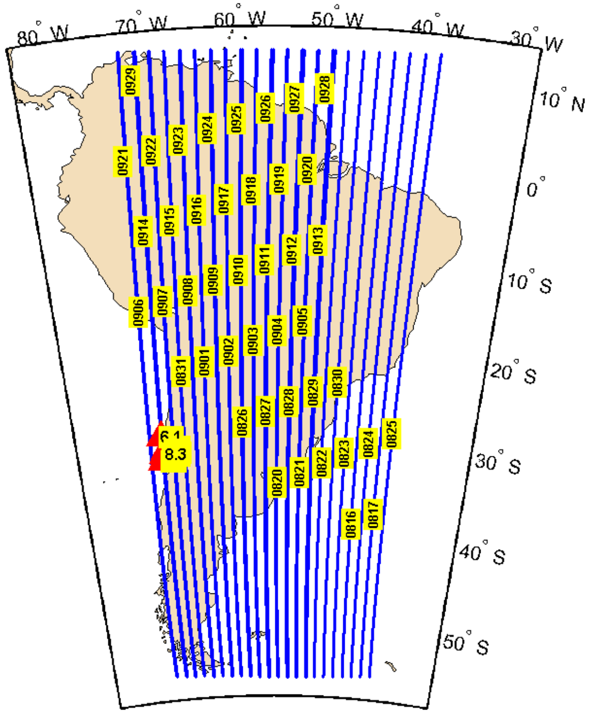
Swarm pass selection (1 morning, 1 afternoon)

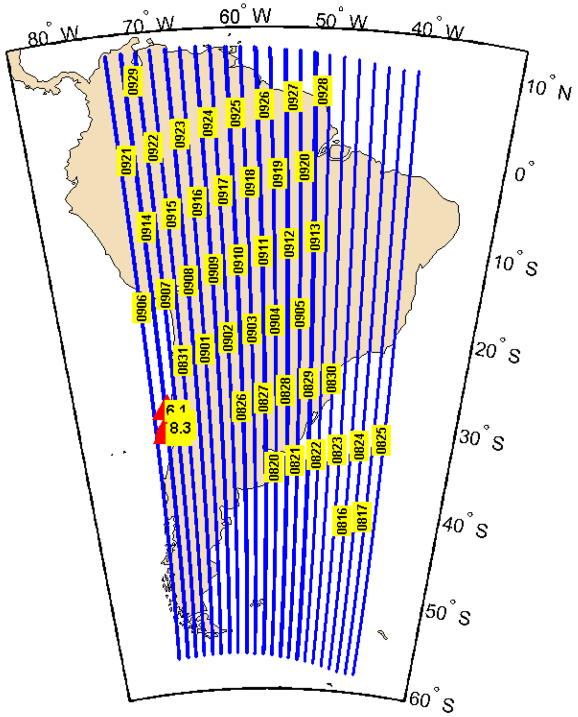
Swarm A - 2 tracks on **17.09** as central tracks in longitude.
1 in the morning (7:15 UTC). 2 in the evening (19:09 UTC).
In Chile: **3:15**, **15:09**

Swarm B – 2 tracks on **17.09** as central tracks in longitude.
1 - morning 9:30 UTC and 2 - evening 21:33 UTC.
In Chile: **5:30**, **17:33**



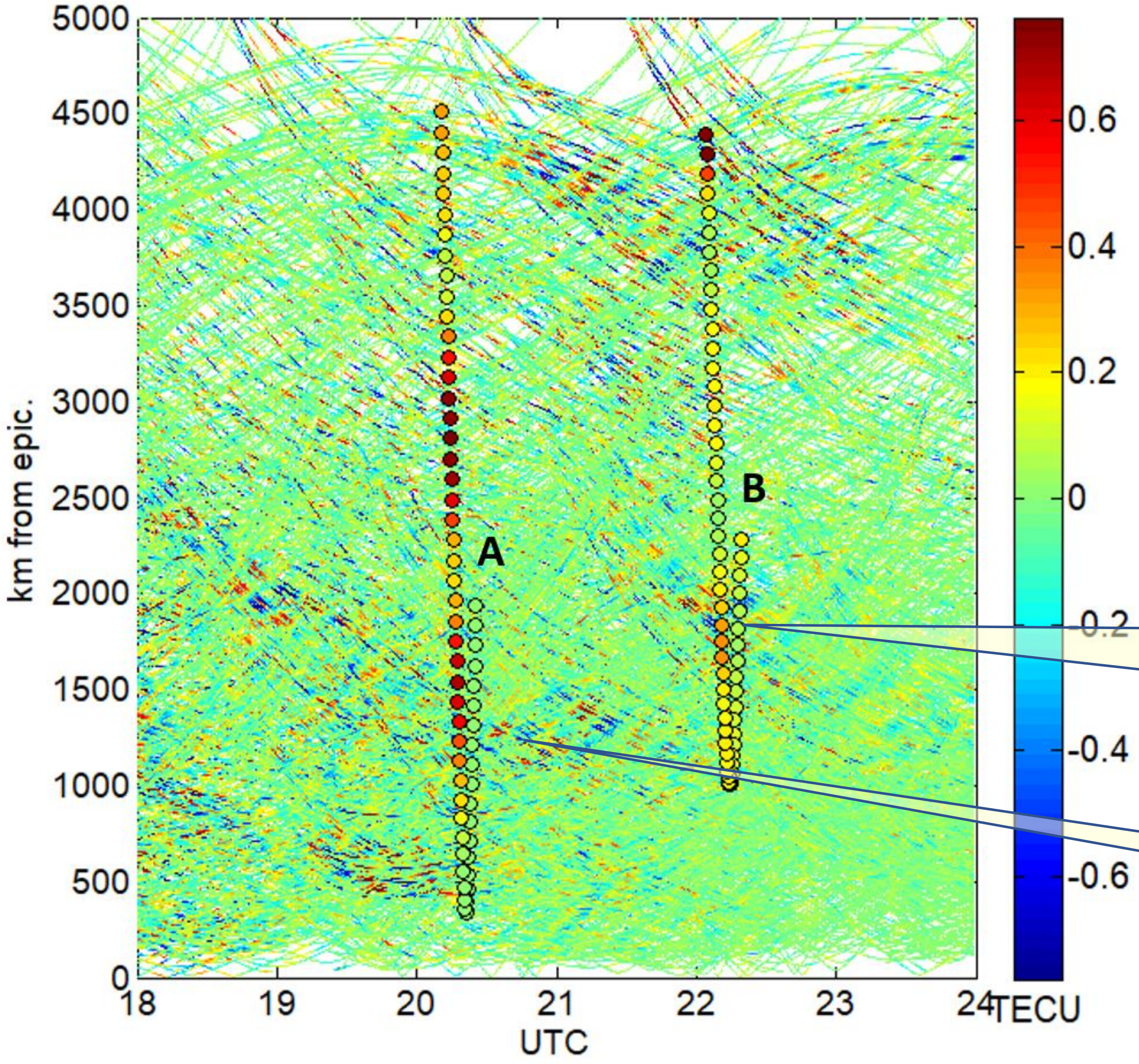






Selected similar time/place of passes from 28 days:
Tracks on the remaining days are selected as close as possible to base track, and can differ by:
Time - max. dif. 2.0 hr. , λ – max. dif. 23°

Chile-Illapel, The keogram + Swarm A on 10.09.2015



10.09.2015, which is 6 days before Chile-Illapel EQ and tsunami. The keogram presents blue-red strips at different distances from the mainshock location.

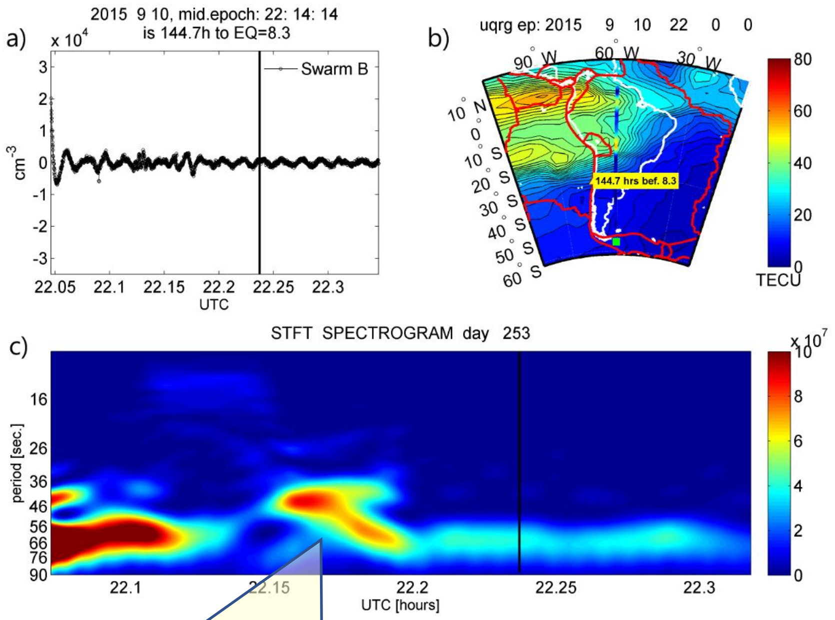
- L_{G-F} band-pass filtered - 1500-240 km,
- Swarm B high-pass filtered at 500 km.
- Color of Swarm dots from spectrogram section at 420 km
- spherical distance (vertical axis) always to mainshock Mw=8.3

Swarm B crosses the blue-red strips exactly and indicates a disturbance in ED. Let's then investigate Swarm B case. We will inpect these co-located disturbances using spectrogram and scatter plot

The disturbances in time of Swarm A pass slightly disappear for some time and come back after this pass.

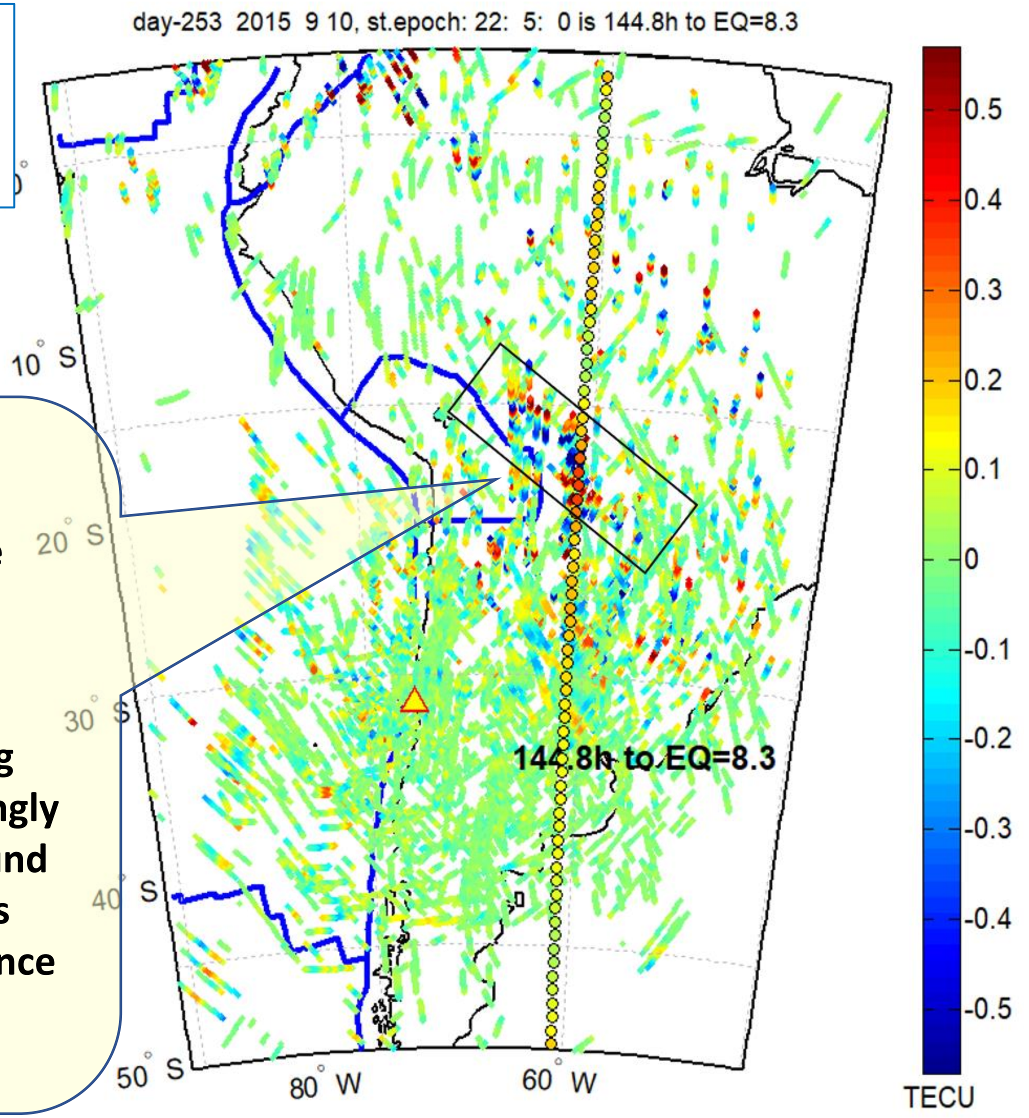
Chile-Illapel, Spectrogram & scatter for Swarm B on 10.09.2015

The PSD from the spectrogram sampled at 420 km frequency is visualized along several minutes of the Swarm B track together with the same amount of ground GNSS L_{G-F} data in scatter plot.

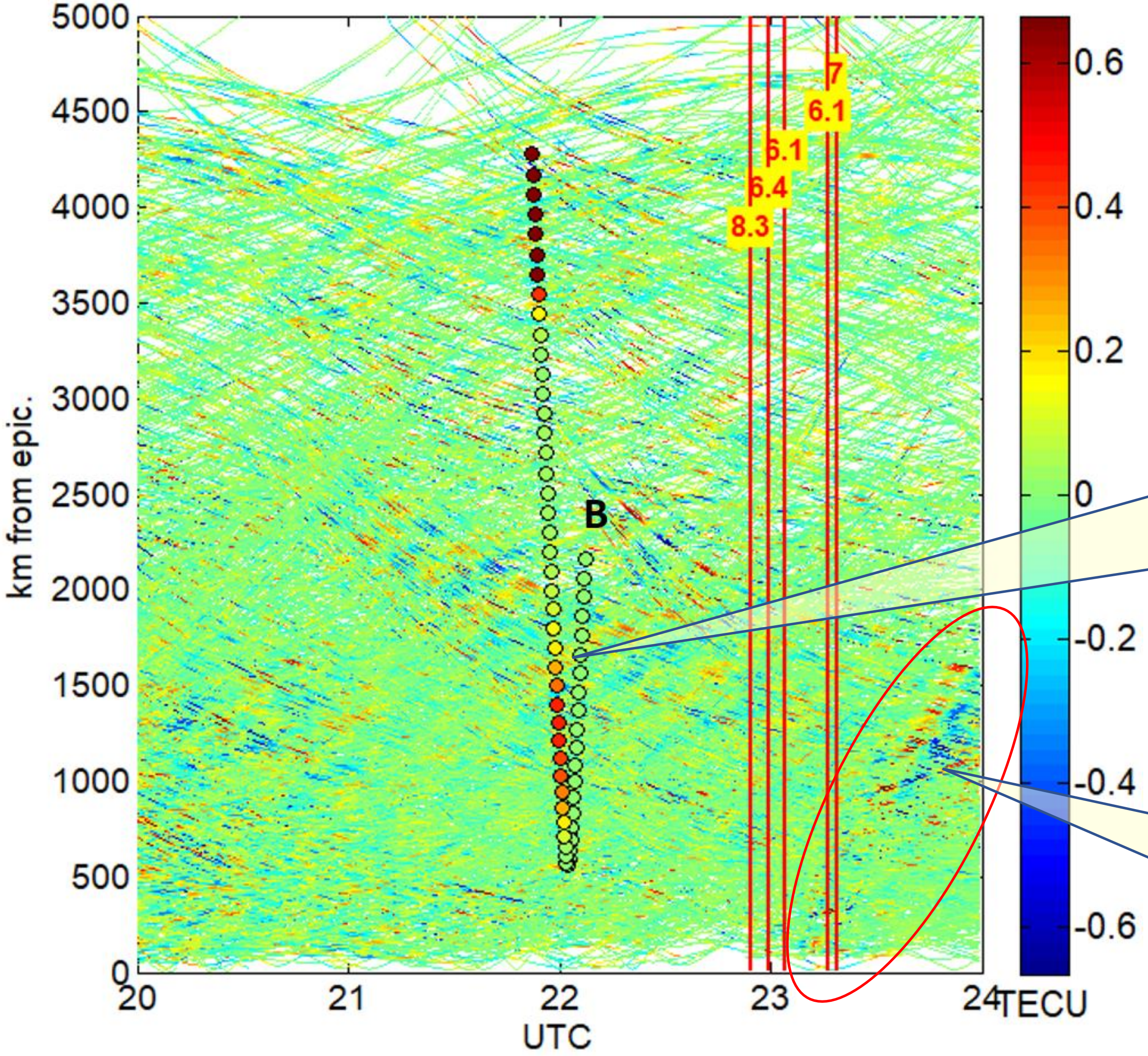


Spectrogram for Swarm B data shows ionospheric disturbance of increasing and decreasing frequency.

<u>16 min. of L_{G-F} + Swarm</u>
We can see clear TIDs located easterly from the Altiplano plate edge, and exactly co-located with Swarm pass and the disturbance of decreasing frequency. It can be strongly suspected that both ground TEC and Swarm LP signals indicate seismic disturbance and this is the same disturbance



Chile-Illapel, The keogram + Swarm B on 16.09.2015, mainshock time



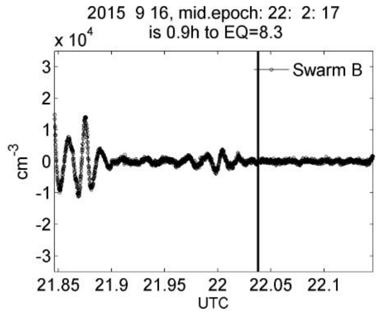
16.09.2015, which is just before the Chile-Illapel mainshock having moment magnitude 8.3, and up to an hour after this EQ. Several close large (above Mw=6.0) aftershocks occurred just after the mainshock.

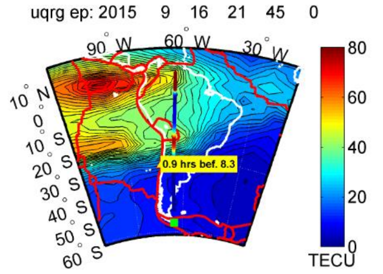
The closest Swarm track preceding the mainshock is Swarm B track occurring on 16.09.2015 around 21:50 UTC, which is 1 hour before the mainshock. Some of the TIDs, which are noticeable in the keogram before the mainshock have a very similar time and distance from the epicenter than Swarm B passing across the region .

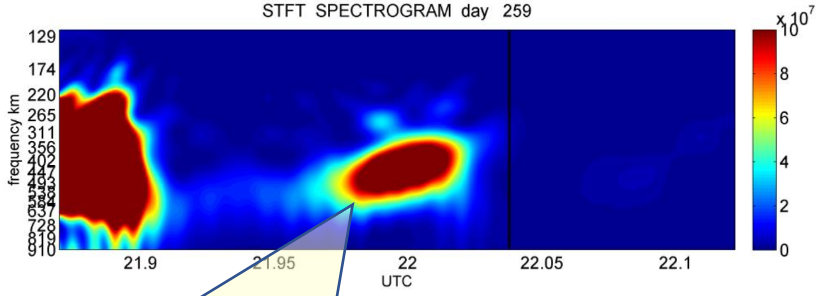
The 8.3 EQ mainshock has triggered TIDs easily detectable in the right-bottom corner. These disturbances, which have higher speed than these TIDs before the mainshock, can be also presented in the scatter plot as concentric rings.

Residual Swarm B data + spectrogram + scatter plot 16.09.2015

The PSD from the spectrogram sampled at 420 km frequency is visualized along several minutes of the Swarm B track together with the same amount of ground GNSS $L_{G\text{-}F}$ data in scatter plot.



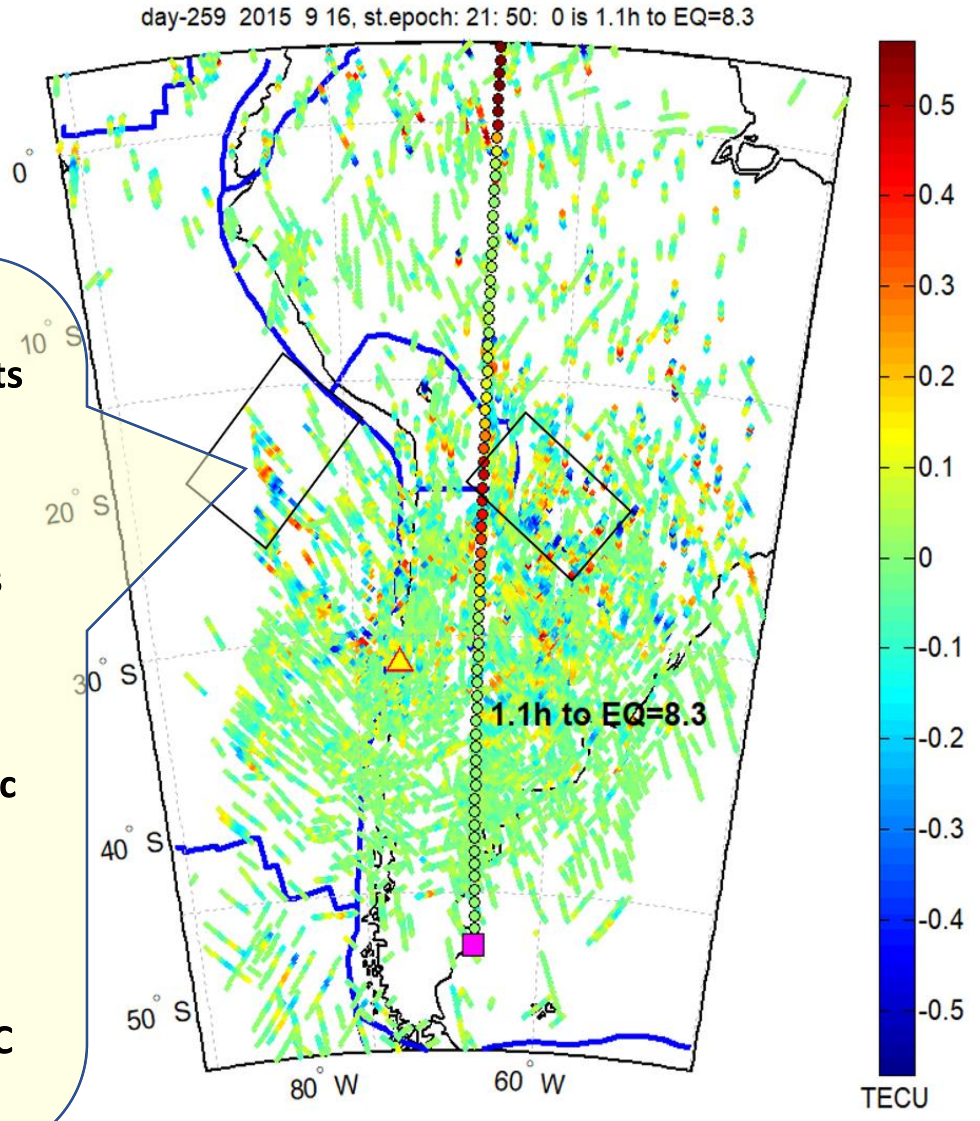




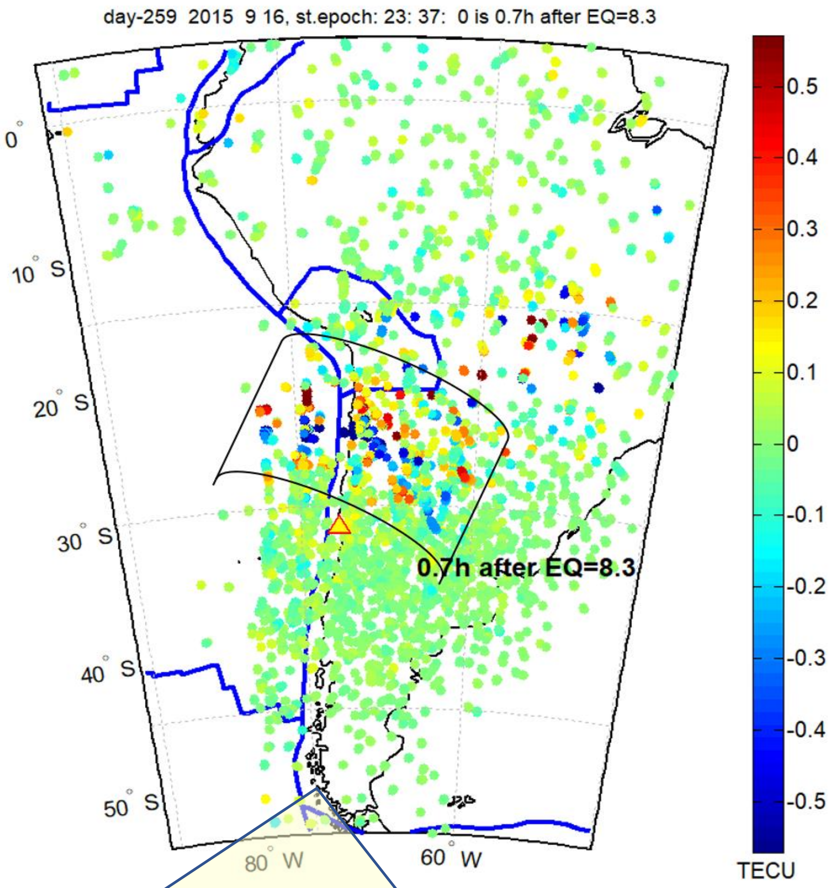
This spectrogram and accompanying UQRG TEC map show disturbance and TEC enhancement above the Altiplano minor plate, respectively.

<u>16 min. of $L_{G\text{-}F}$ + Swarm</u>

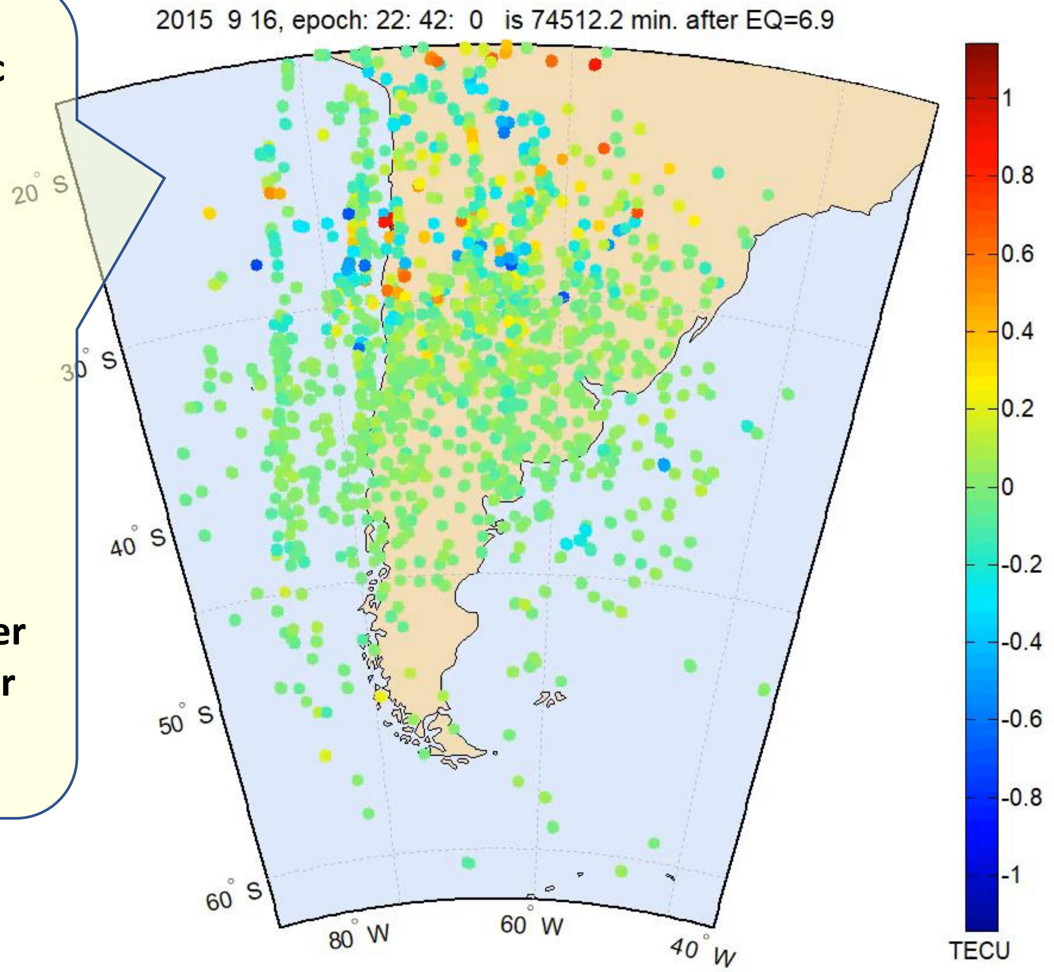
The scatter plot of $L_{G\text{-}F}$ presents some correlated disturbances rather westerly and easterly from the Swarm B track, however the density of IPPs is not satisfactory in the area of Altiplano plate. It is probable that two places of noticeable TIDs are continuous concentric ring of perturbations, passing also Altiplano plate, and their ionospheric response is here broken due to small number and adverse directions of STEC measurements



Residual Swarm A data + spectrogram + scatter plot 16.09.2015



The concentric rings after the mainshock move to the north. The southern direction is more clear apparently, which can be related with smaller number of electrons far from the Sun.

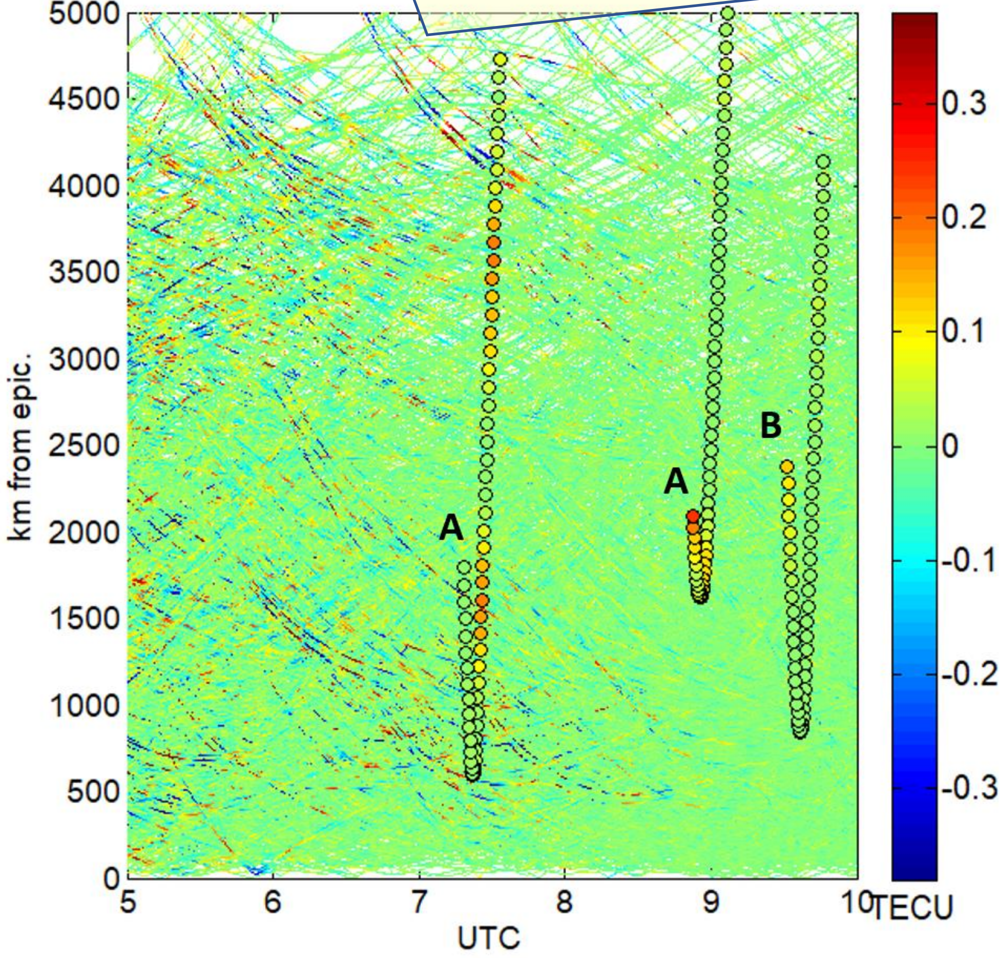


1 min. of L_{G-F} + Swarm

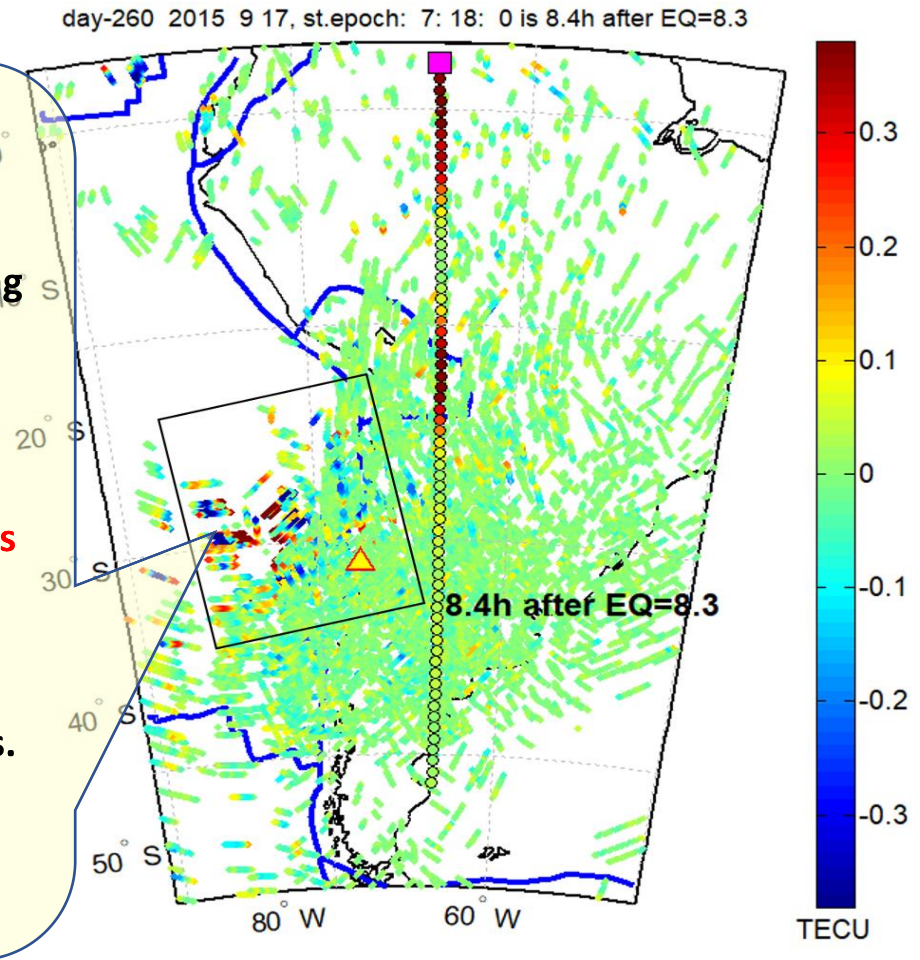
Scatter map of two close epochs of band-pass filtered phase LG-F combination, recalculated to TEC units, on 16.09.2015, 0.7 hour after the mainshock. Blue lines are tectonic plate boundaries. Black figure indicates places of the most evident TID

Chile-Illapel, The keogram + Swarm A on 17.09.2015

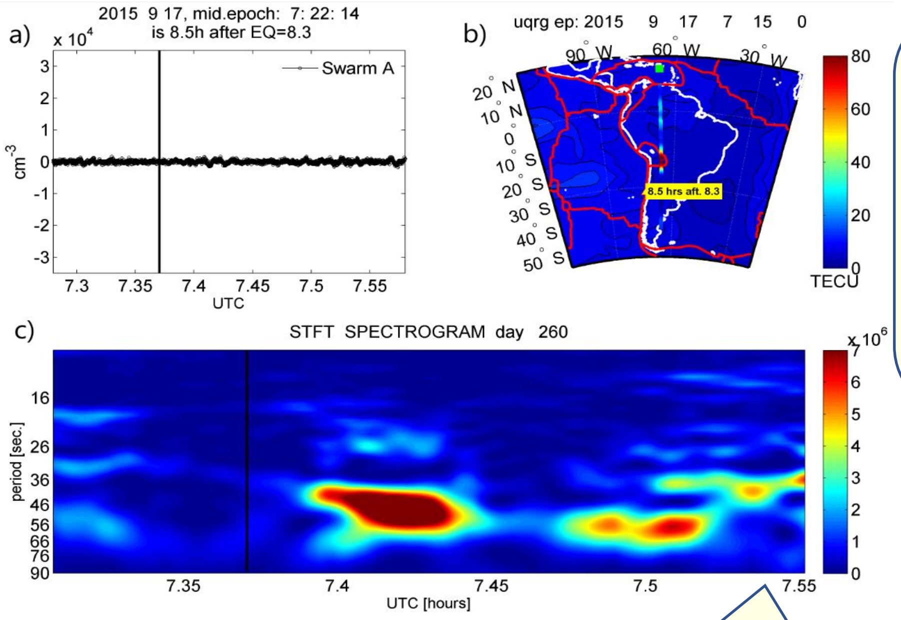
This keogram includes the closest possible Swarm passes after the Chile-Illapel mainshock, which are available in the morning on 17.09.2015, 8 hours after the mainshock. The first pass of Swarm A over this region was at 7:22 AM UTC, which is 3:22 AM of Chilean time. The Sun was on the opposite side and the TEC values were small at that time and red-blue strips are weaker in the keogram. The first pass of Swarm A around 7:22 UTC reaches some blue-red strips moderately visible in the keogram.



<u>16 min. of L_{G-F} + Swarm</u>
Blue-red strips directed to the ocean do not coincide with the disturbances along the Swarm A track. These presumable TIDs are located westerly from the epicenter of Chile-Illapel, over the ocean, which does not exclude their relation with the tsunami. Sparse IPP data impede the exact recognition of their shapes. These disturbances are away from the strong Sun activity

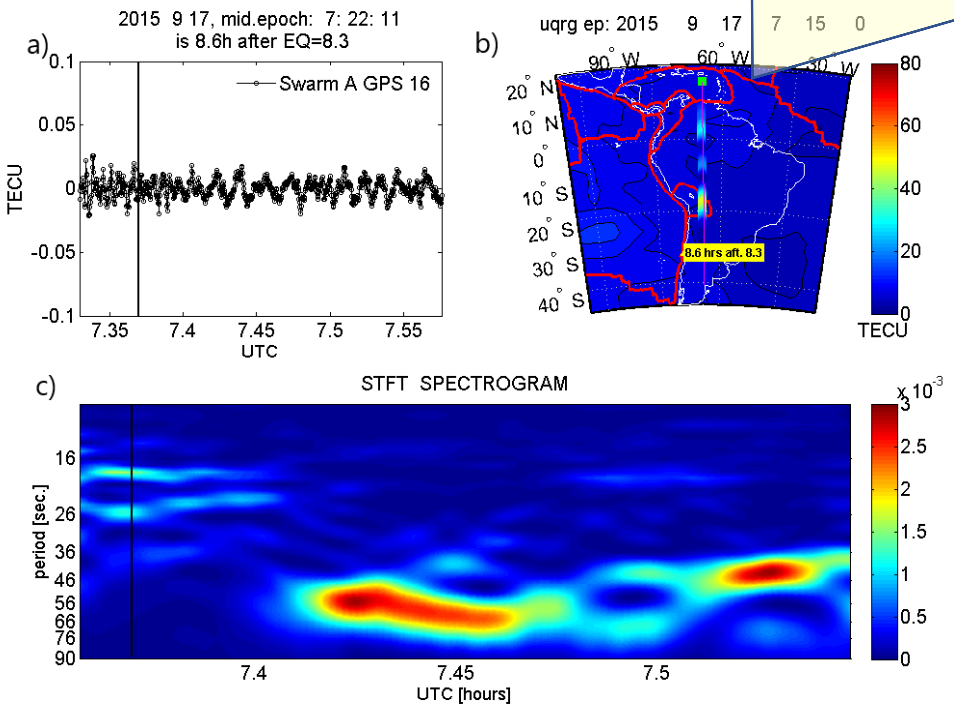


Residual Swarm A data + spectrogram + scatter plot 17.09.2015



POD TEC analysis is expected to show similar disturbances in relation to LP ED data, with some exceptions. The STEC measurements between Swarm A spacecraft and GNSS PRN point in spatially different directions.

The best corresponding TEC measurement from Swarm A (in terms of similar signals to LP data), along Swarm A track, is taken to the GPS 16, which runs west of Swarm A



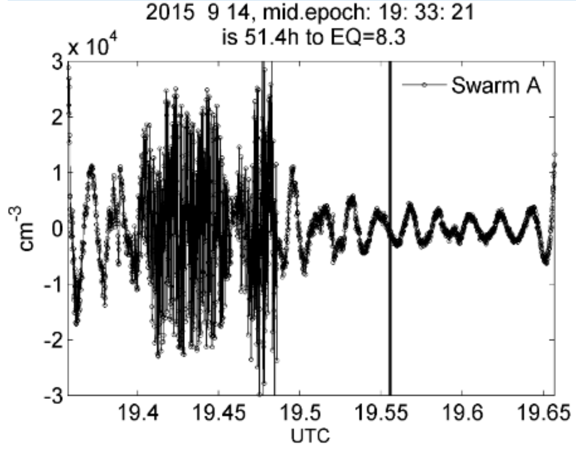
STEC is recalculated to VTEC at IPP altitude 50 km above the Swarm and we use VTEC in STFT analysis.
The parameters of STFT are exactly the same as for LP data analysis and the signal was also high-pass filtered to around 500 km.

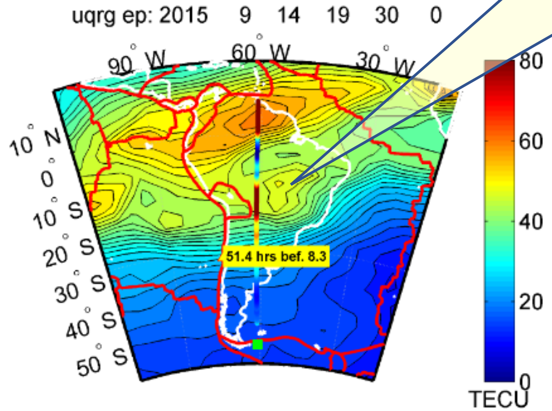
The spectrogram of Swarm A pass (ED from LP) shows clear disturbances over Altiplano plate and over the continent, which are of a smaller amplitude in relation to that observed during afternoon hours in the previous figures .

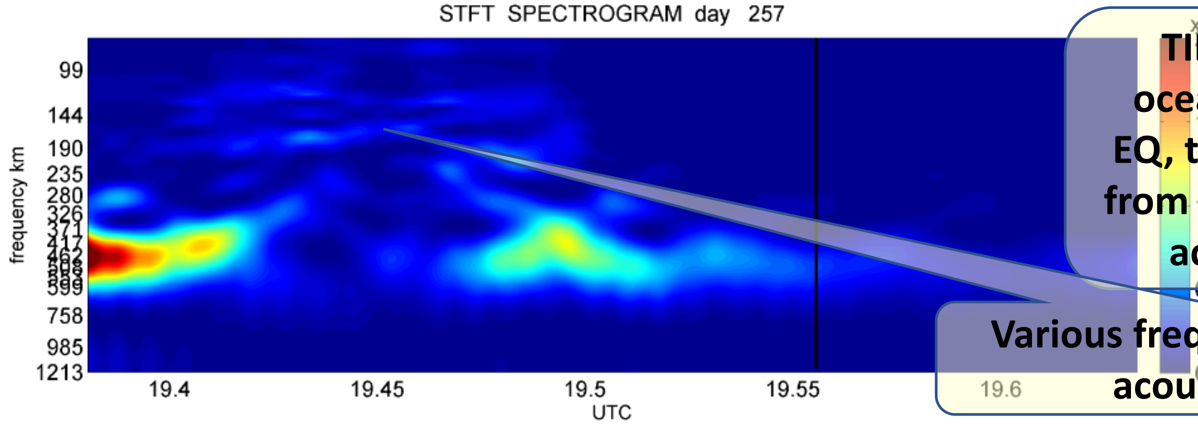
Other days, examples of TIDs at different time of the day and latitudes

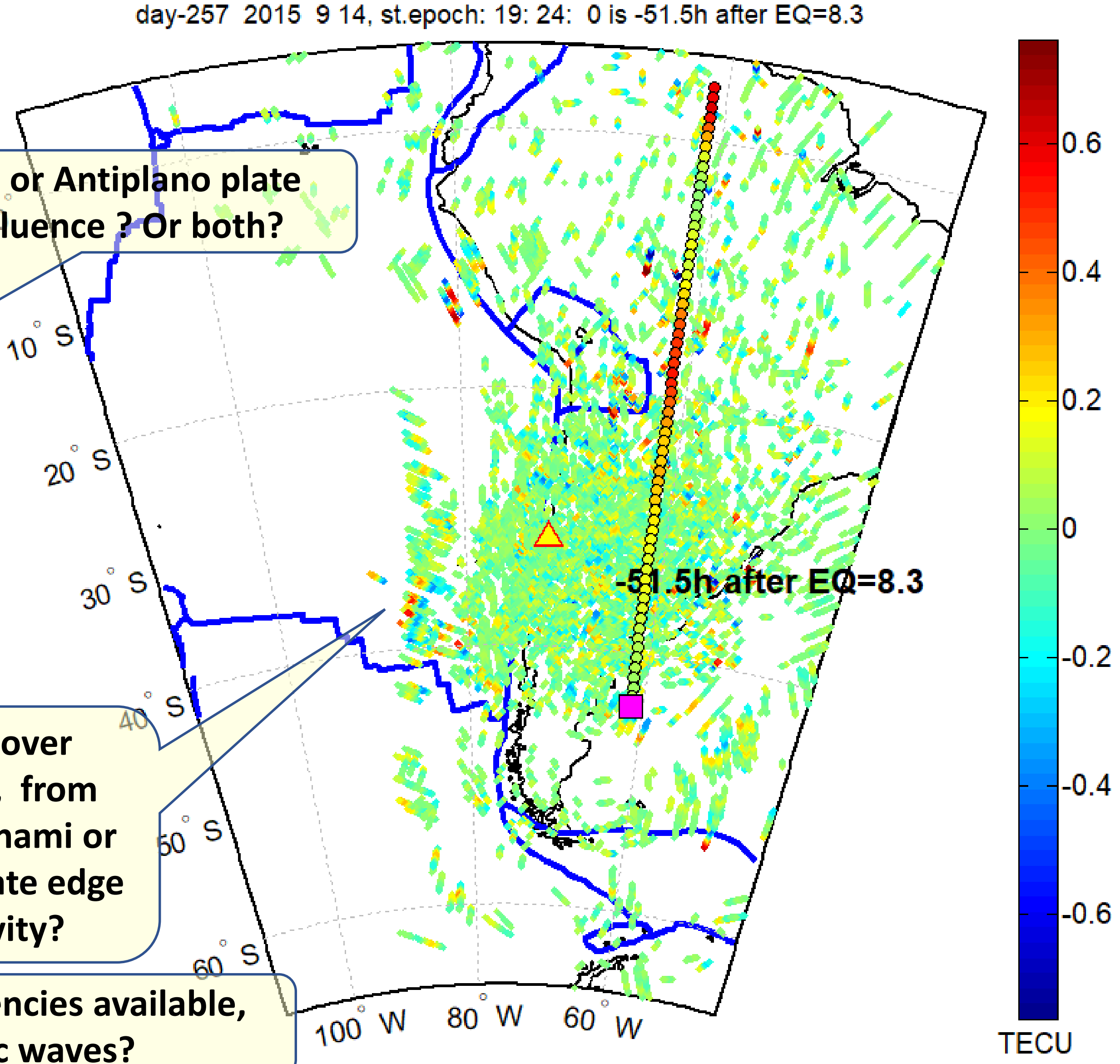
Residual Swarm A data + spectrogram + scatter plot 14.09.2015

Afternoon, Swarm A track (here UTC time, Chile -4h.).
Spectrograms have the same scale of PSD (power).
Scatters and PSD displayed along the track can have various scales, due to a large discrepancy between TIDs.
Around 12-14 min. of Swarm and GNSS tracks (scatter).
Magenta – last Swarm epoch – direction.









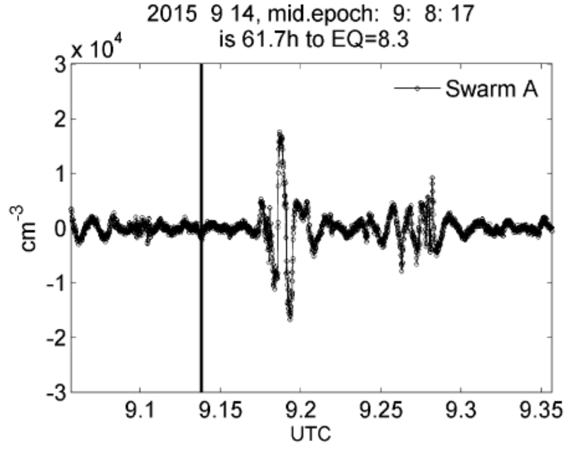
Sun or Antiplano plate influence ? Or both?

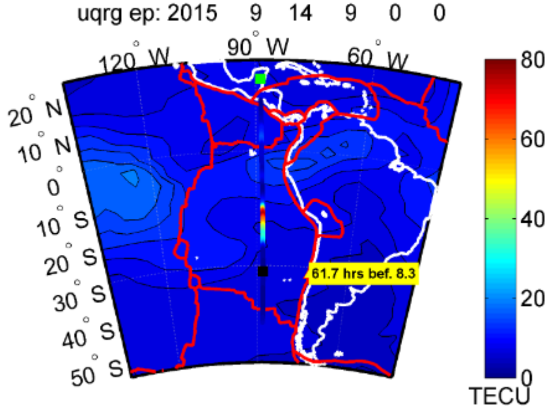
TIDs over ocean, from EQ, tsunami or from plate edge activity?

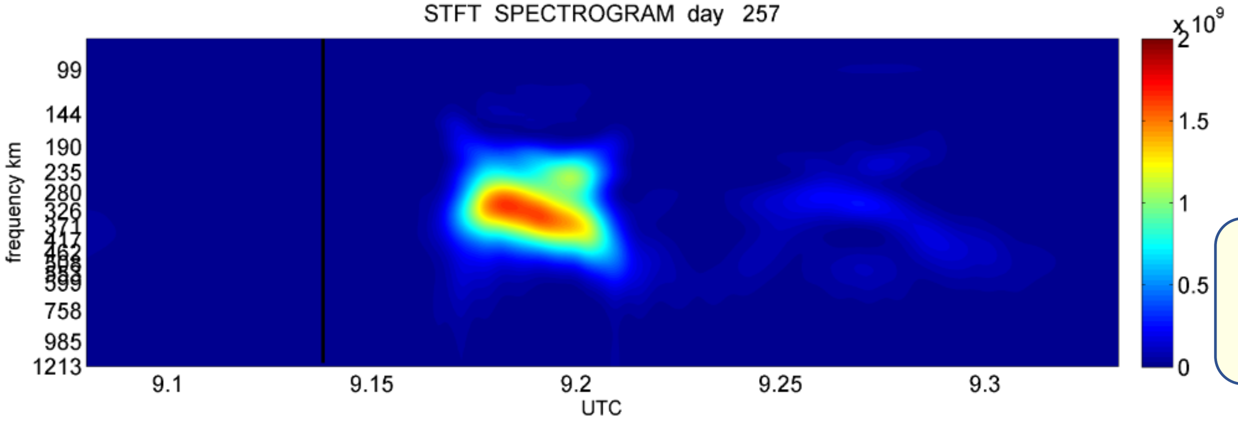
Various frequencies available, acoustic waves?

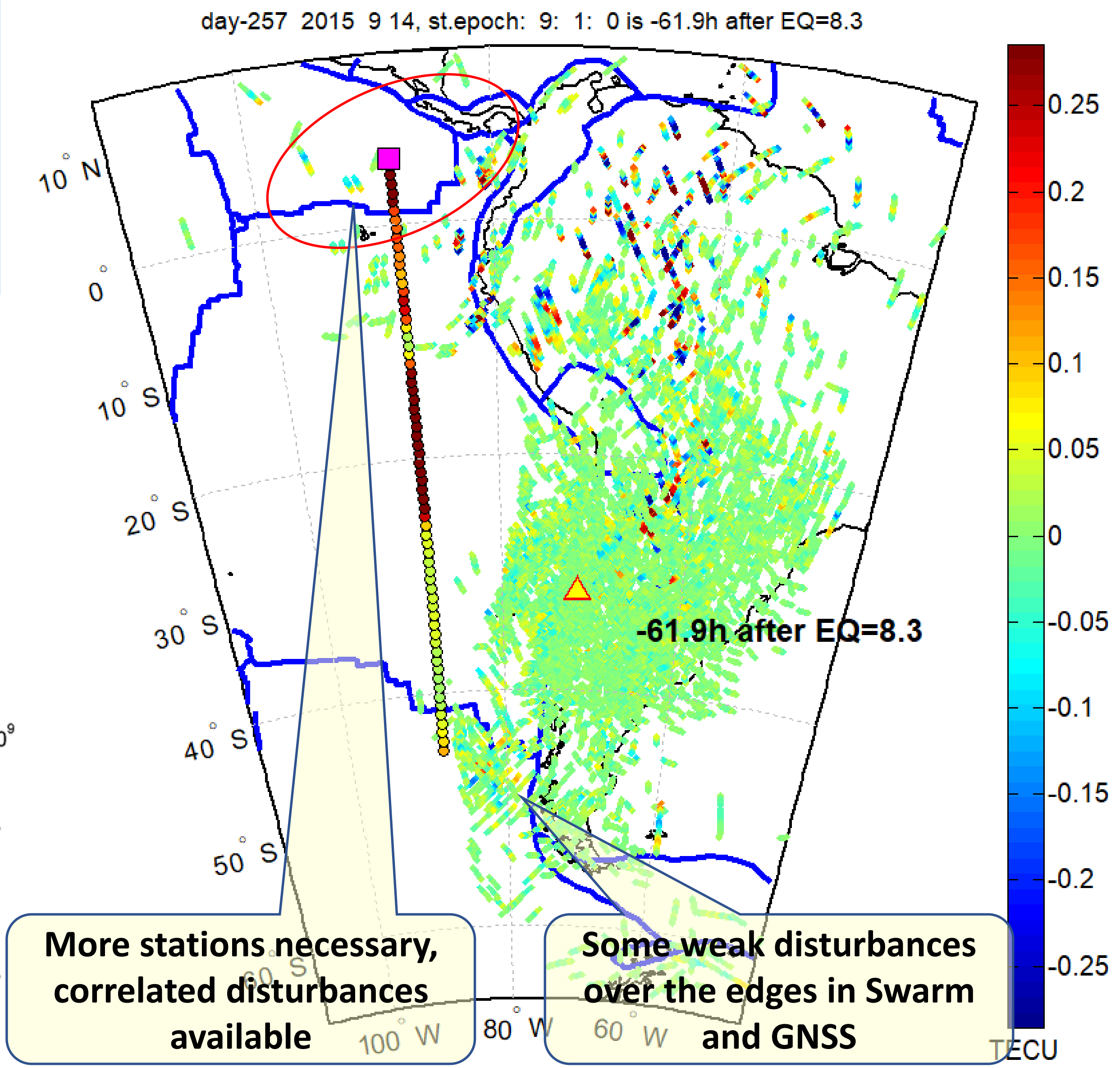
Residual Swarm A data + spectrogram + scatter plot 14.09.2015

Night - ocean, Swarm A track (here UTC time, Chile -4h.).
Spectrograms have the same scale of PSD (power).
Scatters and PSD displayed along the track can have various scales, due to a large discrepancy between TIDs.
Around 12-14 min. of Swarm and GNSS tracks (scatter).
Magenta – last Swarm epoch – direction.



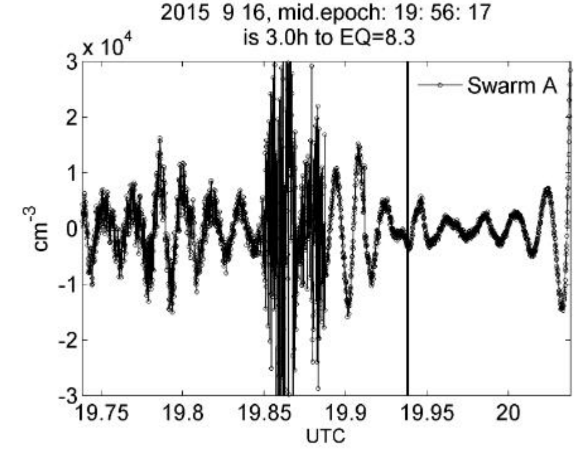


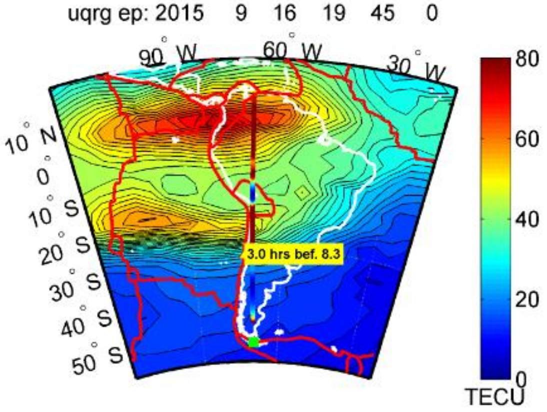


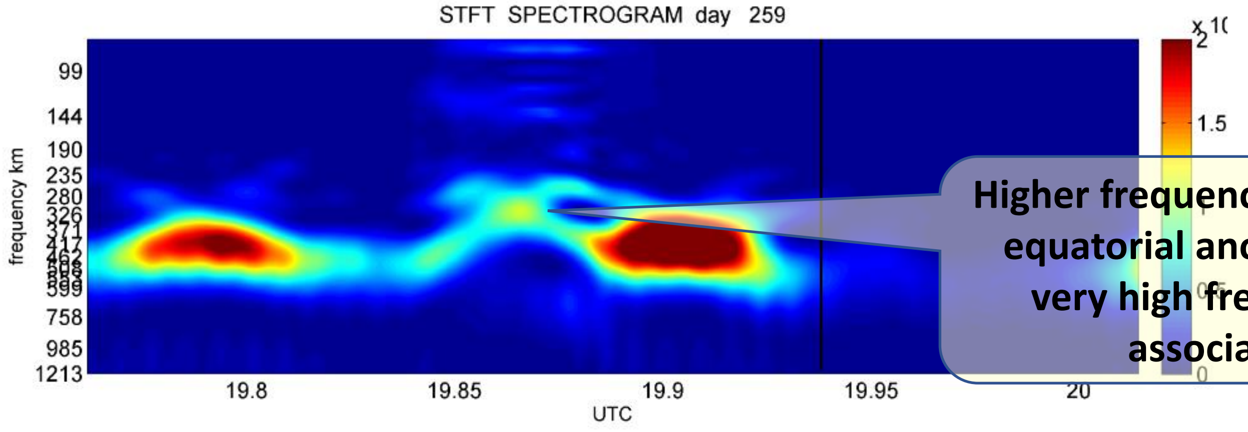


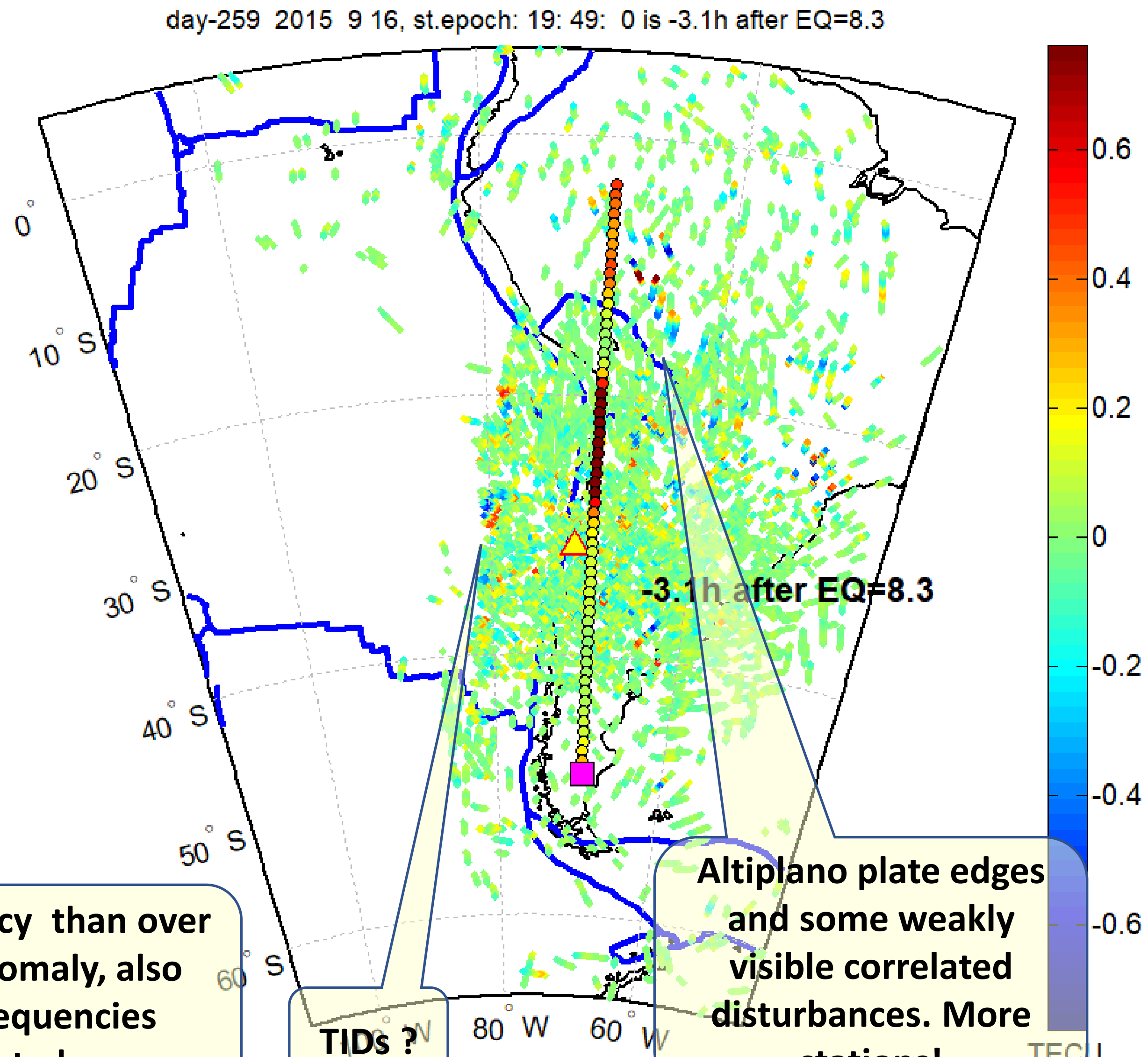
Residual Swarm A data + spectrogram + scatter plot 16.09.2015

Afternoon, Swarm A track (here UTC time, Chile -4h.).
Spectrograms have the same scale of PSD (power).
Scatters and PSD displayed along the track can have various scales, due to a large discrepancy between TIDs.
Around 12-14 min. of Swarm and GNSS tracks (scatter).
Magenta – last Swarm epoch – direction.









Higher frequency than over equatorial anomaly, also very high frequencies associated

TIDs ?

Altiplano plate edges and some weakly visible correlated disturbances. More stations!

CONCLUSIONS 1

- **Ground GNSS data** have shown many different responses of seismic activity to the ionosphere, including **ionospheric anomalies before the mainshock**, clear **response to the mainshock** (Mw=8.3), as well as **post-seismic disturbances**, presumably also related with the tsunami.
- Traveling character of these disturbances and their **relationship with seismicity are evident in the keograms**.
- Swarm along-track data also reveals ionospheric anomalies of small period (<500km along the track), and the **spectral analyses of Swarm data** also provided different interesting **spectral patterns of ionospheric disturbances**.
- The **coincidence of Swarm disturbances and ground GNSS disturbances is confirmed** many times, and their seismic character is unquestionable.
- **Enhancement of TEC** appear to be correlated with Altiplano plate

CONCLUSIONS 2

- **Finding Swarm pass over EQ or tsunami is easier than finding dense ground GNSS** data in many regions. Really fine and detail observations of TIDs in ground GNSS are actually possible only with such networks like GEONET
- **GNSS-station sights not always pass TID's**, which occur only in some selected places horizontally and vertically. This also confirms a need of dense networks. Therefore the sights GNSS satellite – LEO POD can be even less fortunate.
- Seismic signatures in ground TEC are **easier detectable in sunny** (daytime) conditions, however this time is also more noisy
- The validation process LEO-ground GNSS must be combined (**spectrogram+keogram+scatter**), as every tool show different properties
- We can think about the **system of global TID detection** based on combination LEO-ground GNSS

Acknowledgements

This work is supported by ESA programme:
„Swarm+ Coupling: High-Low Atmosphere Interactions”

Leader: University of Warmia and Mazury in Olsztyn, Poland

Consortium members: NOA (Athens), TUM (Munich), UPC (Barcelona)

Project name:

Contribution Of Swarm data to the prompt detection of Tsunamis and Other natural hazards (COSTO)