Accoppiamento Litosfera-Atmosfera-Ionosfera

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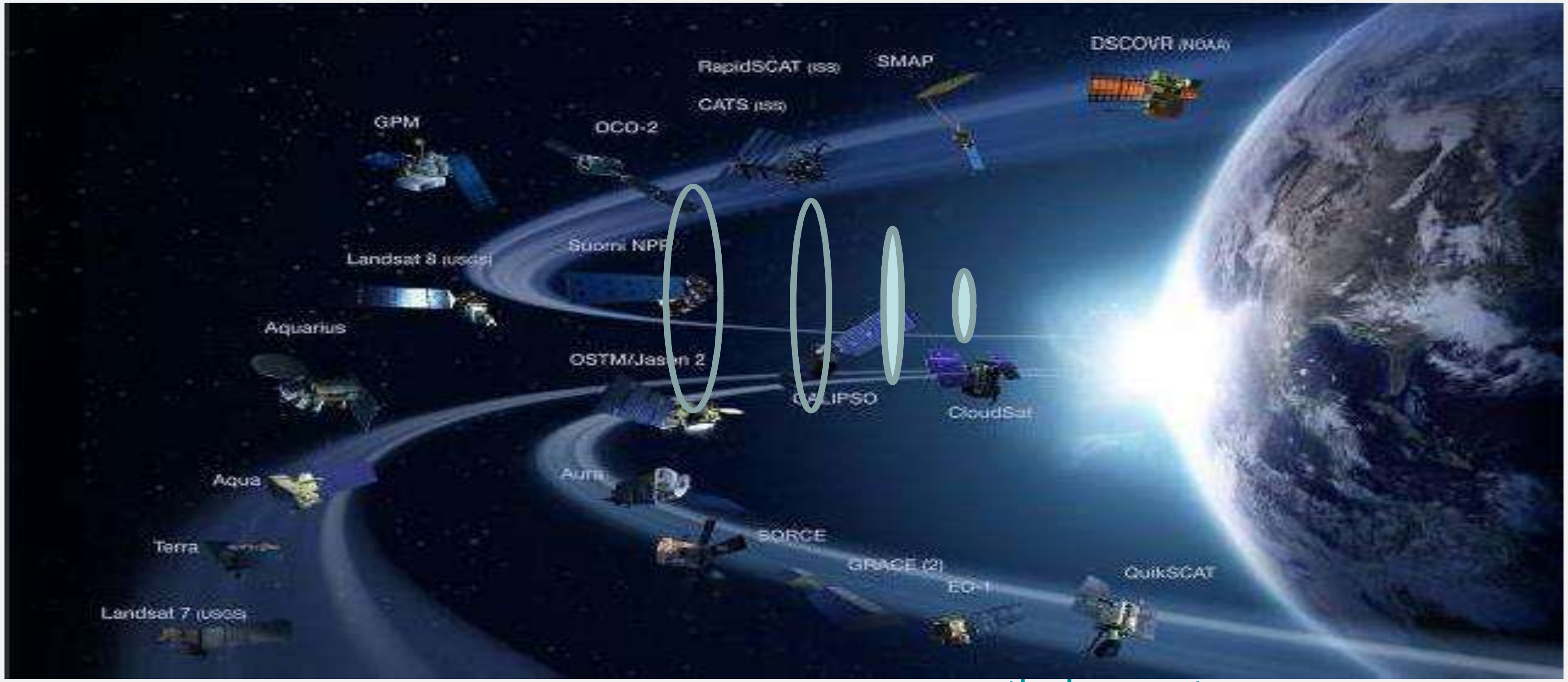
Introduction

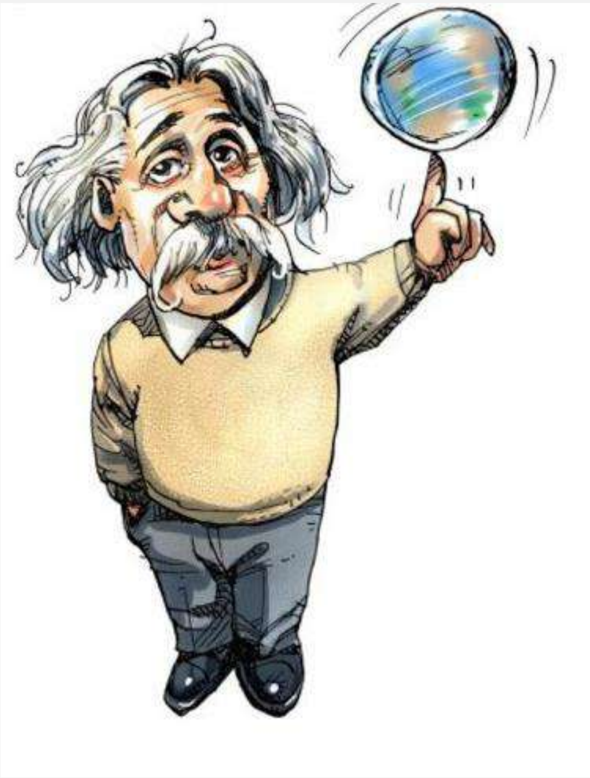
Questions

1.Is there any **Litho-Atmo-Ionosphere Coupling (LAIC)** before large EQs?

2. If yes, can **the LAIC effects** be detected **from space**?



earthobservatory.nasa.gov



Introduction

- In the last decades many papers shows potential EQ signatures in both the ionospheric/magnetospheric and atmospheric medium;
- Unfortunately none of them could strongly demonstrate the direct connection between EQ occurrence and anomalous signal detected;
- Two problems:
  1. analysis based only on correlation, but correlation is not casuality;
  2. lack of a global analytical lithospheric-atmospheric-magnetospheric model able to explain and possibly forecast anomalous signal.
- The last problem is the background: effect of the Sun and of the normal Atmospheric activity – how to disentangle?

Introduction

- In 2020 Piersanti et al. developed:

1. a global Magnetospheric – Ionospheric – Lithospheric coupling (MILC) model for EQ able to explain possible signals detected during EQ occurrence;
2. a robust approach able to disentagle between internal and external sources of such signal, respectively.

- Let's see some case events:

1. **The August 5, 2018 Bayan EQ;**
2. **The 2020 Haitian EQ (not shown);**
3. **The November 9, 2022 Italian EQ.**

Introduction

- We will move from down up to the ionosphere analyzing all the data available;
- We will analyze the CSES data available at the moment and before the EQ occurrence;
- We will discuss the co-seismic observations using the MILC model;
- We will discuss the pre-seismic potential observations;
- We will trace the path for future analysis and modeling of the pre-seismic phase behaviour.

The Bayan Earthquake

- On August 5, 2018 an earthquake stroke Indonesia.
- Mw= 6.8;
- λ=-8.3 °N - φ=116.5 °E;
- UT=11:46,34.

Terremoto di magnitudo **Mwp 6.8** del 05-08-2018 ore 13:46:34 (Italia) in zona: **Indonesia [Land]**

Dati Evento | Sismicità e Pericolosità | Impatto | Localizzazioni e Magnitudo | Meccanismo focale | Download

Un terremoto di magnitudo **Mwp 6.8** è avvenuto nella zona: **Indonesia [Land]**, il

- 05-08-2018 11:46:34 (UTC) 7 mesi fa
- **05-08-2018 13:46:34 (UTC +02:00) ora italiana**
- 05-08-2018 19:46:34 (UTC +08:00) orario locale nella zona del terremoto (Asia/Makassar)

con coordinate geografiche (lat, lon) **-8.3**, **116.5** ad una profondità di **10 km**.

Il terremoto è stato localizzato da: **Sala Sismica INGV-Roma**.

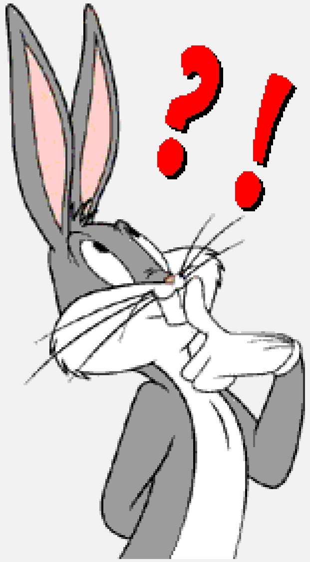
Ricerca terremoti: Qualsiasi nel raggio di 30 km

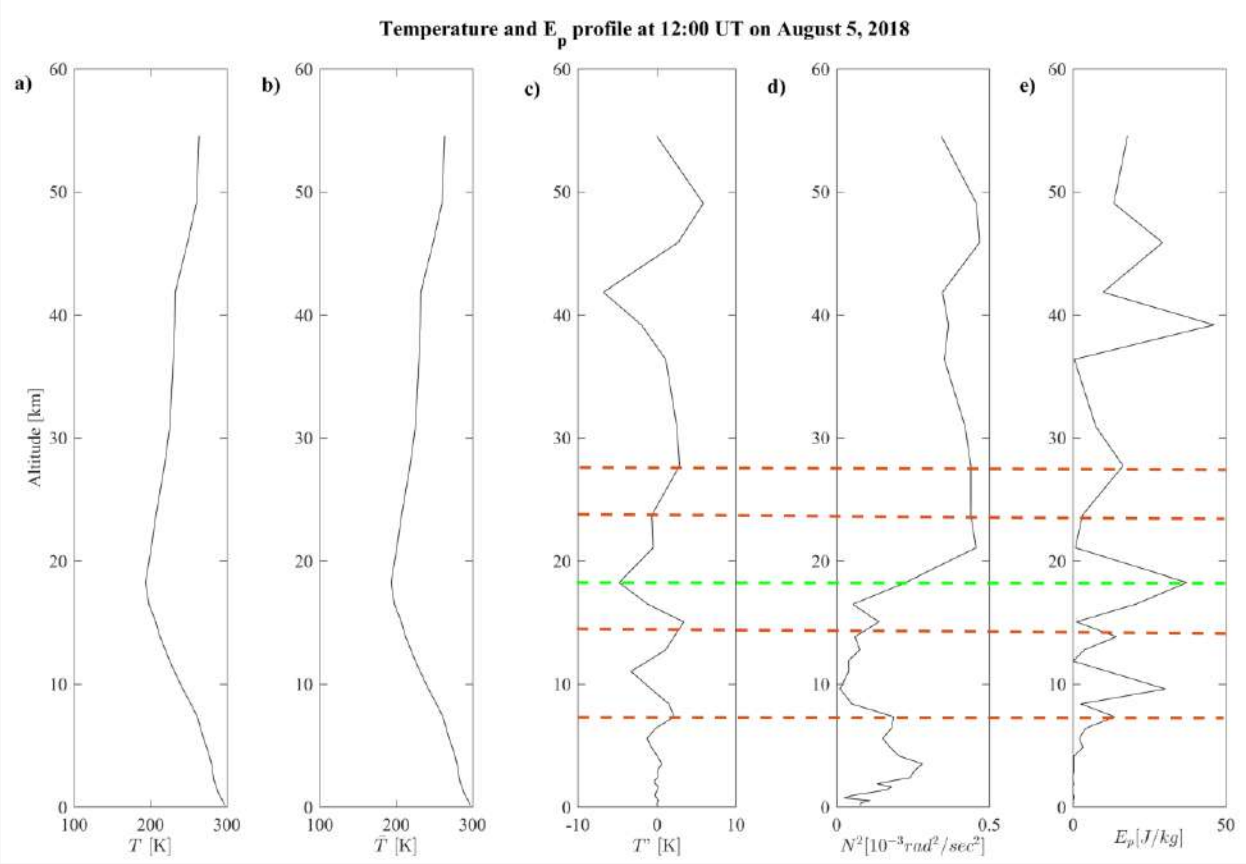
August 5, 2018 – AGW observations

Copernicus
ERA-5 Atmospheric
Temperature data

AGW – What?

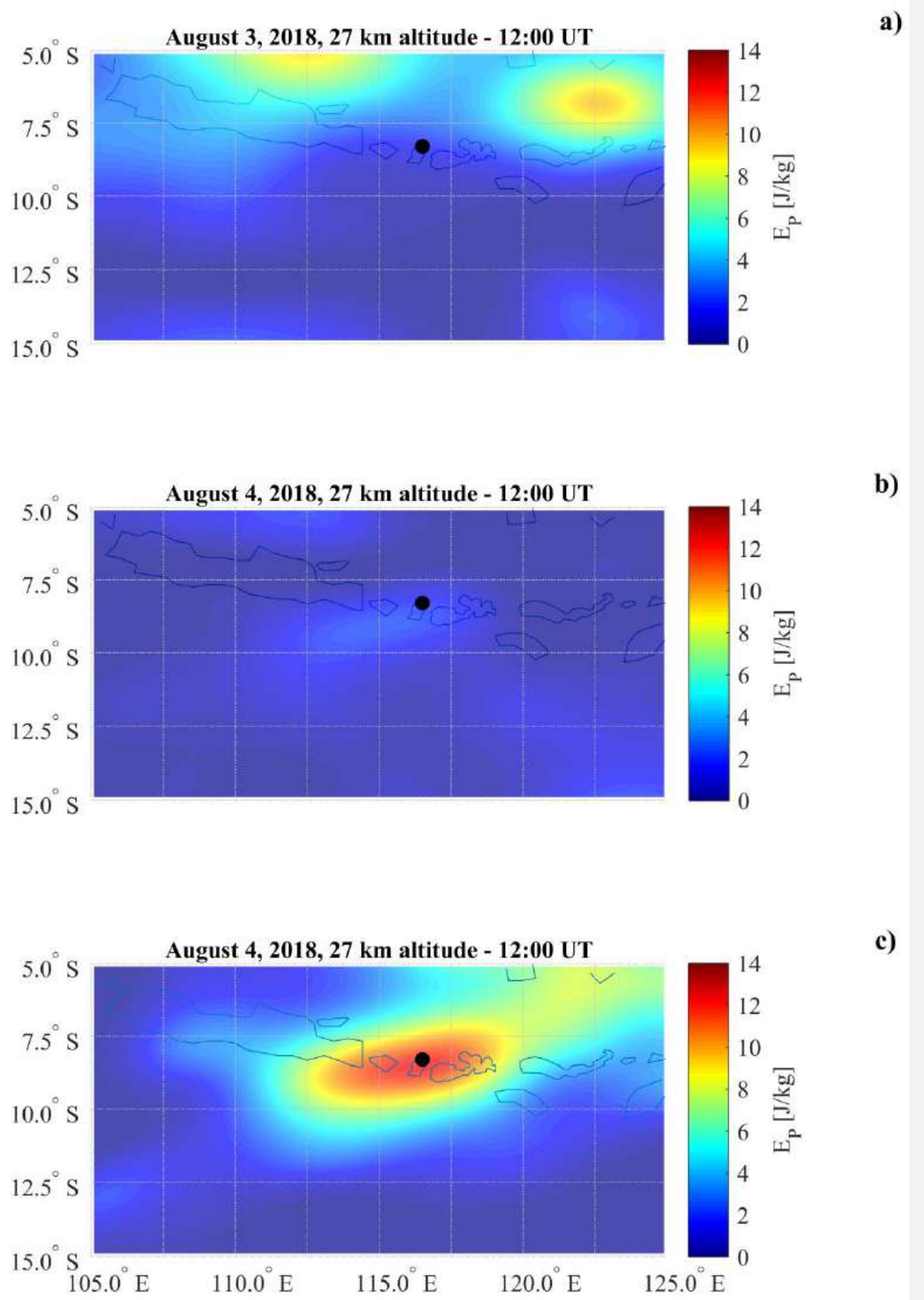
- Acoustic gravity waves are mainly caused by weather systems, synoptic-scale atmospheric systems and circulations, and high terrain;
- Those waves can disturb wind fields and temperature in the stratosphere;





- Four wave crests are found in the temperature deviation profile at the altitudes of 17.8, 27.6, 36.6, and 44.8 km. There exist two sinusoidal periods, and the corresponding vertical wavelengths are 9.8 and 7.2 km, respectively.
- On the other hand, the *E*P profile maximizes only for the first wavelength.

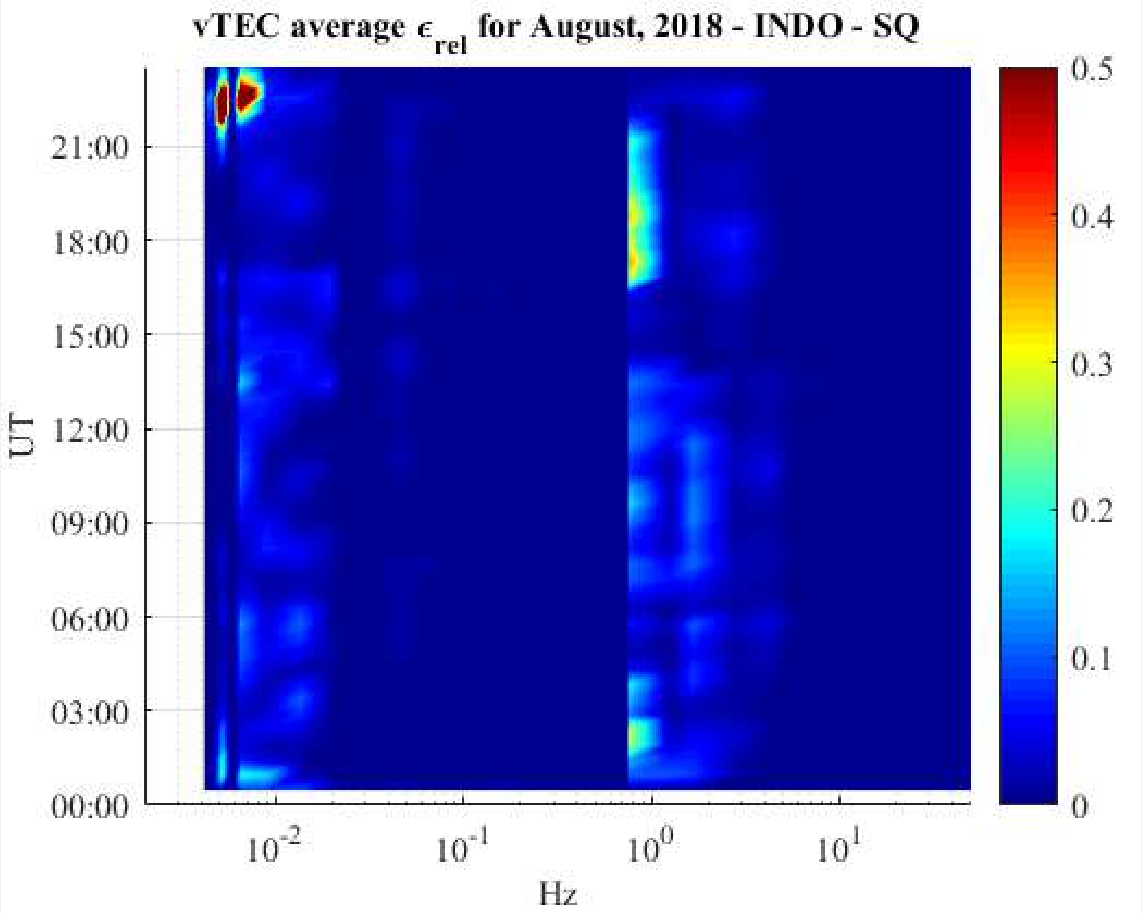
So, there is a AGW of 9.8 km wavelength propagating in the atmosphere .

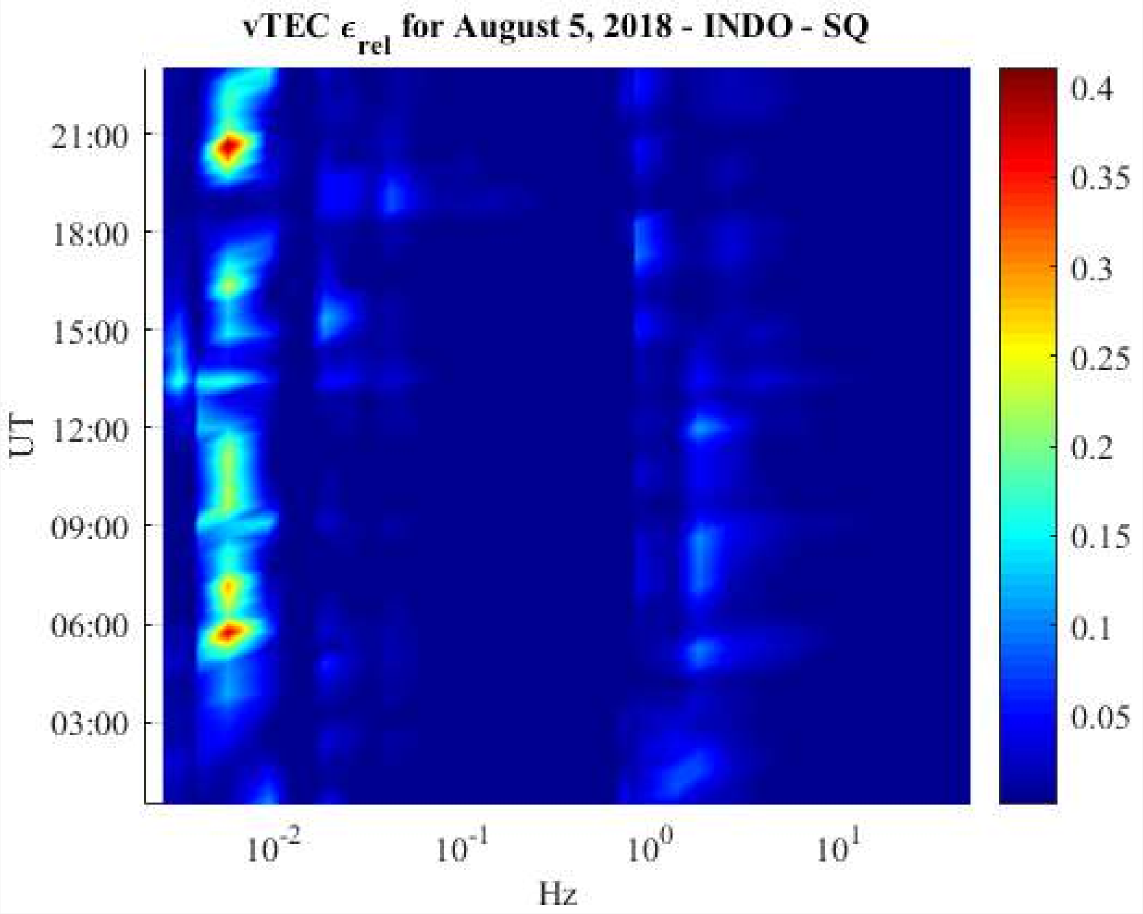


August 5, 2018 – Ionospheric observations

vTEC
from
GNSS observations

August , 2018 – vTEC



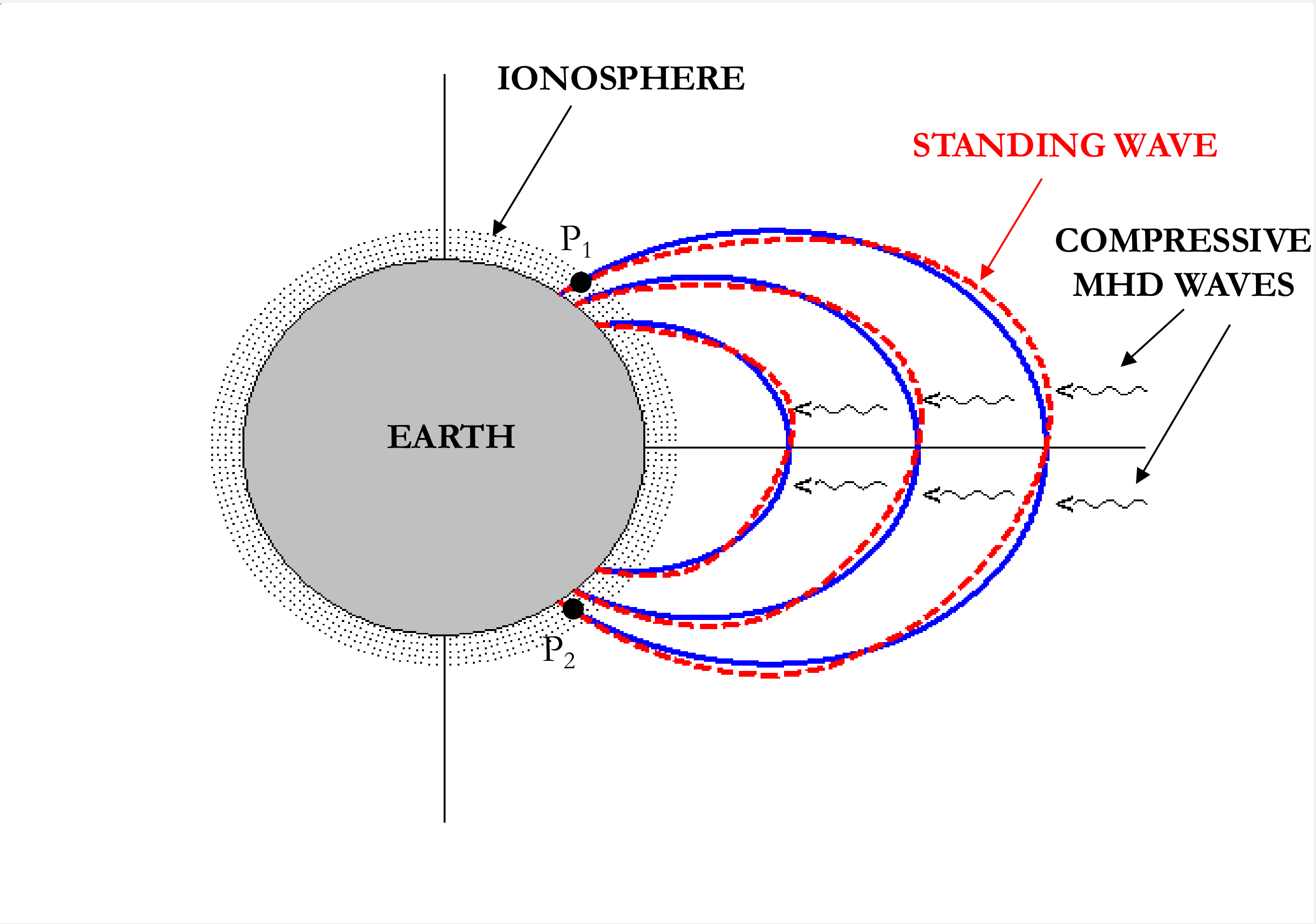


- The Background only for SQ days (~23 consecutive days).
- Clear anomaly of vTEC with respect to monthly average.
- The first anomaly starts around 5:45 UT.
- The second anomaly starts around 09:00 UT with its peak at the EQ.
- Possible clear relation with EQ.

August 5, 2018 – FLR frequency observations

Geomagnetic Field Line Resonance frequency evaluation

Geomagnetic Field Line Resonances (FLR)

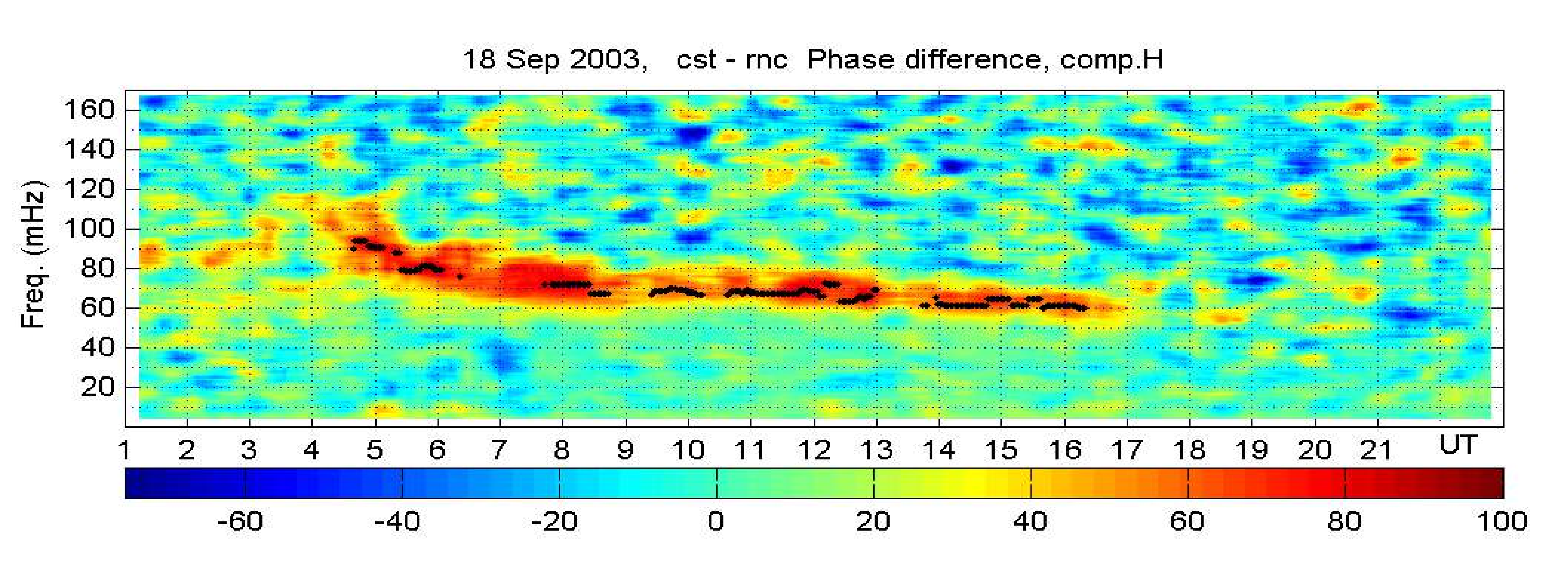


$$T(L) \cong \int_{P_1}^{P_2} \frac{ds}{V_A(s)}$$

$\mathbf{V_A}$: Alfvén velocity

$$T(L) = 2\mu_o \int_{P_1}^{P_2} \frac{\rho^{1/2}(s)}{B(s)}\, ds$$

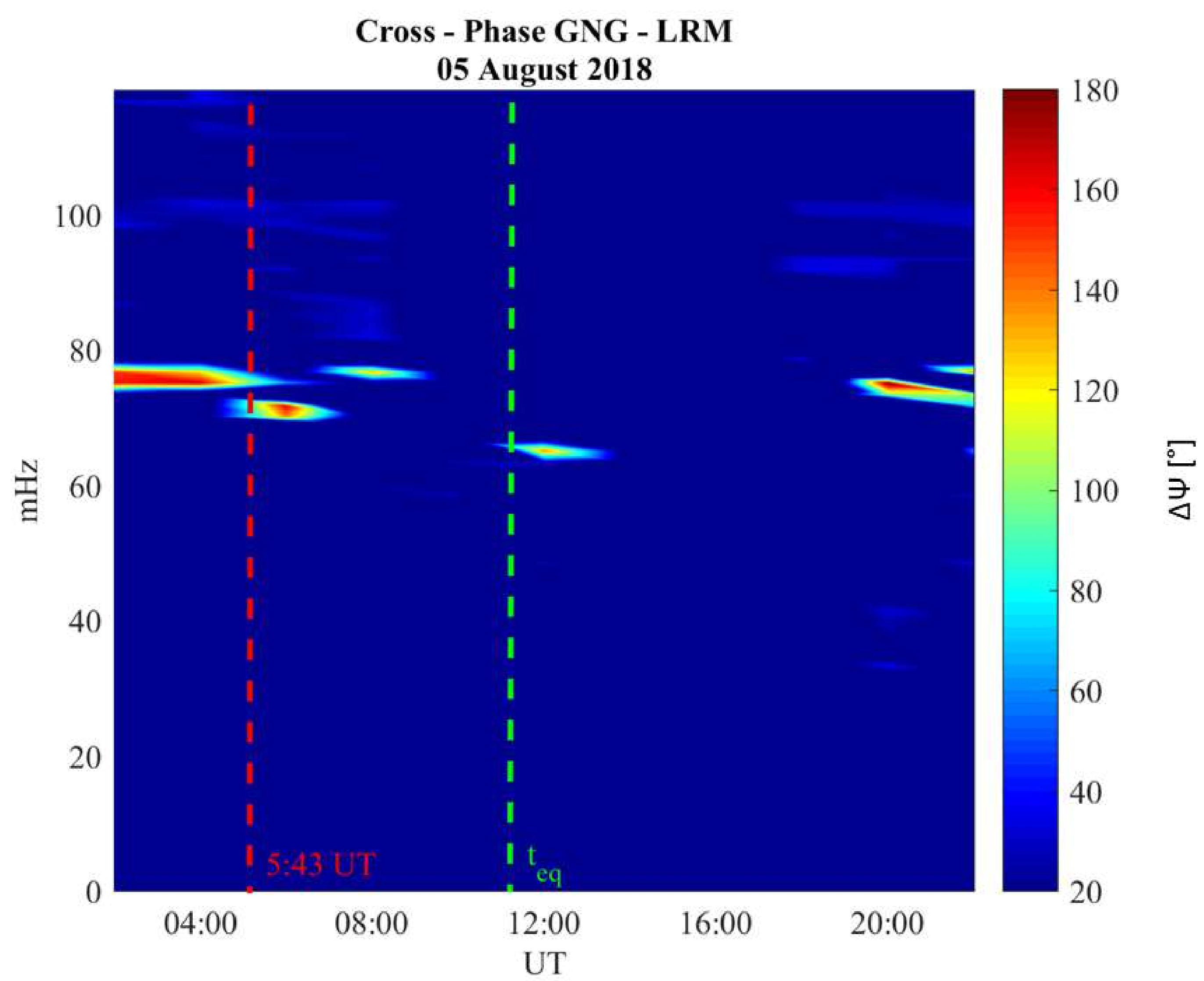
Example of FLR detection over middle Italy



FLR evaluation over the EQ location

- We made the same analysis during the EQ.
- As expected, the eigen-frequency ***(f)*** is around 75 mHz (close equatorial station).
- There are an interesting modification of ***f***:

1. Around 5:43 UT, there is a decrease from 78 mHz to 70 mHz
2. Around 11:45 UT, there is a collapse from 78 mHz to 64 mHz.



The Bayan Earthquake - CSES

- On August 5, 2018 an earthquake stroked Indonesia.
- Mw= 6.8;
- λ=-8.3 °N - φ=116.5 °E;
- UT=11:46,34.

Orbit CSES #2797: 2018/08/05 - 05:20 - - 06:00 UT

Terremoto di magnitudo **Mwp 6.8** del 05-08-2018 ore 13:46:34 (Italia) in zona: **Indonesia [Land]**

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Ricerca terremoti: Qualsiasi nel raggio di 30 km

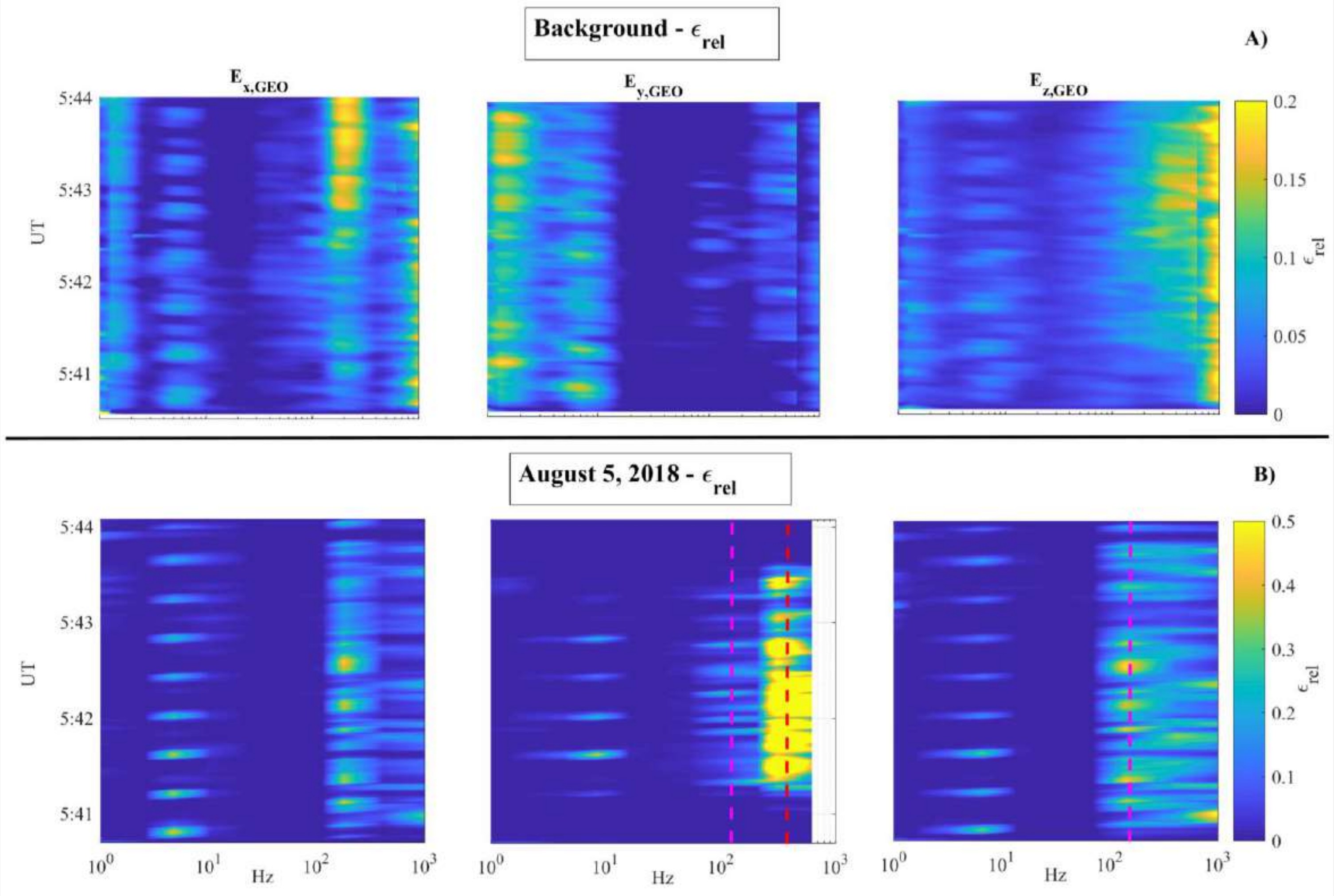
- CSES payloads: what did they observed?

August 5, 2018 – CSES observations

EFD – SCM - LAP

EFD observation

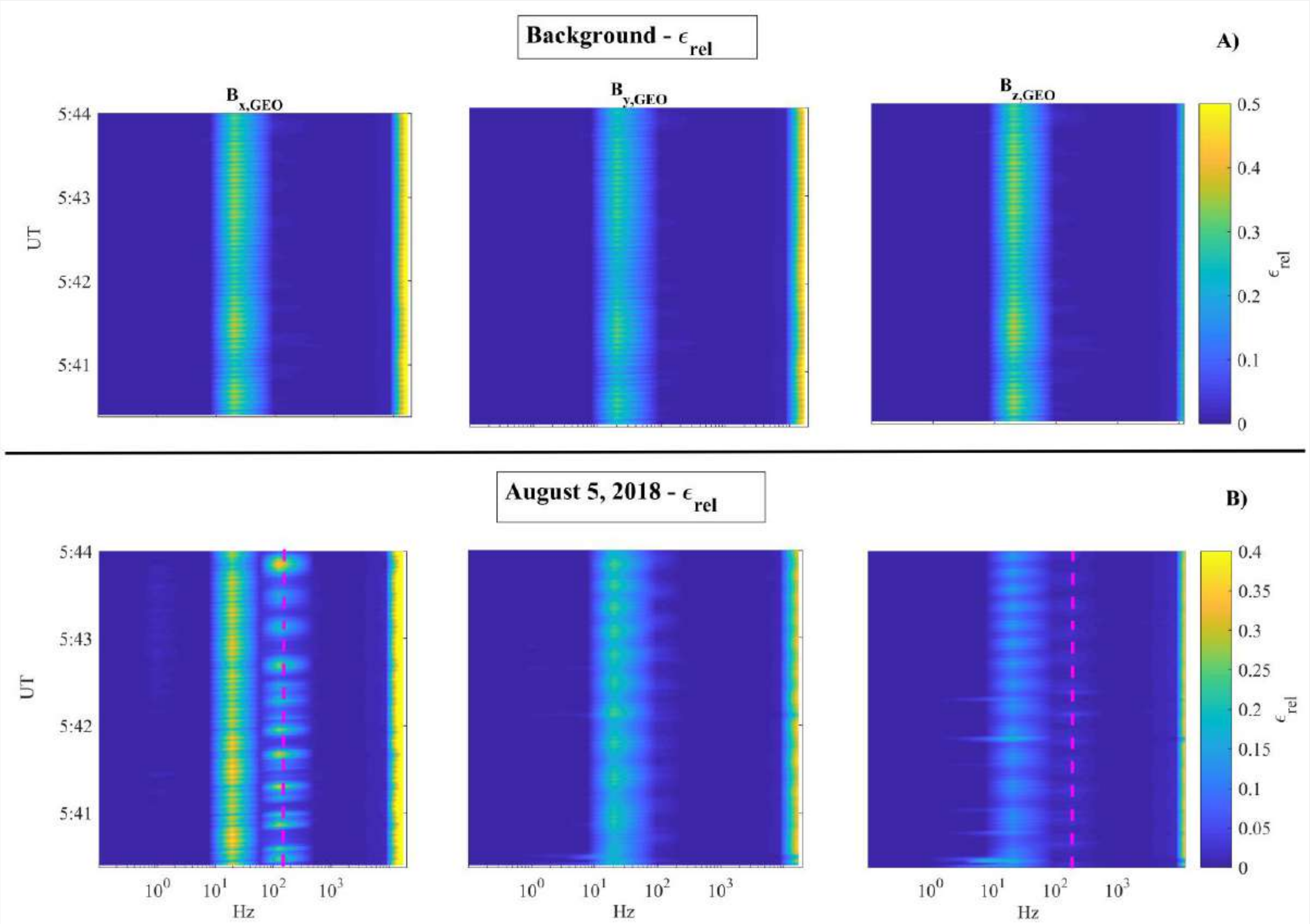
- On the basis of Recchiuti et al. [2022], we first evaluated both the environmental and the instrumental background over Bayan cell [3°x3° - latxlon] for SQ conditions.



- A signature (pink circle) at ≈8 Hz is visible at all components, related to the Schumann ionospheric resonance at CSES orbit.
- The peaks detected at frequency around 2 Hz are due to the VxB electric field present in the ELF band.
- The peak around 1kHz is the signature of the Plasmaspheric hiss [Balazs, 2008; Vellante et al, 2014; Zhima et al., [2019].
- The peak around 250-300 Hz are a portion of the whistler mode chorus generated around L=5 propagating into the plasmasphere [Li et al. 2009; Zhima et al., 2019].

- Anomalous peaks at 180 Hz (E_y and E_z component, magenta) and at 630 Hz (E_y component, red line) with respect to the background has been detected.

SCM observation



- As for EFD we evaluatd the Background

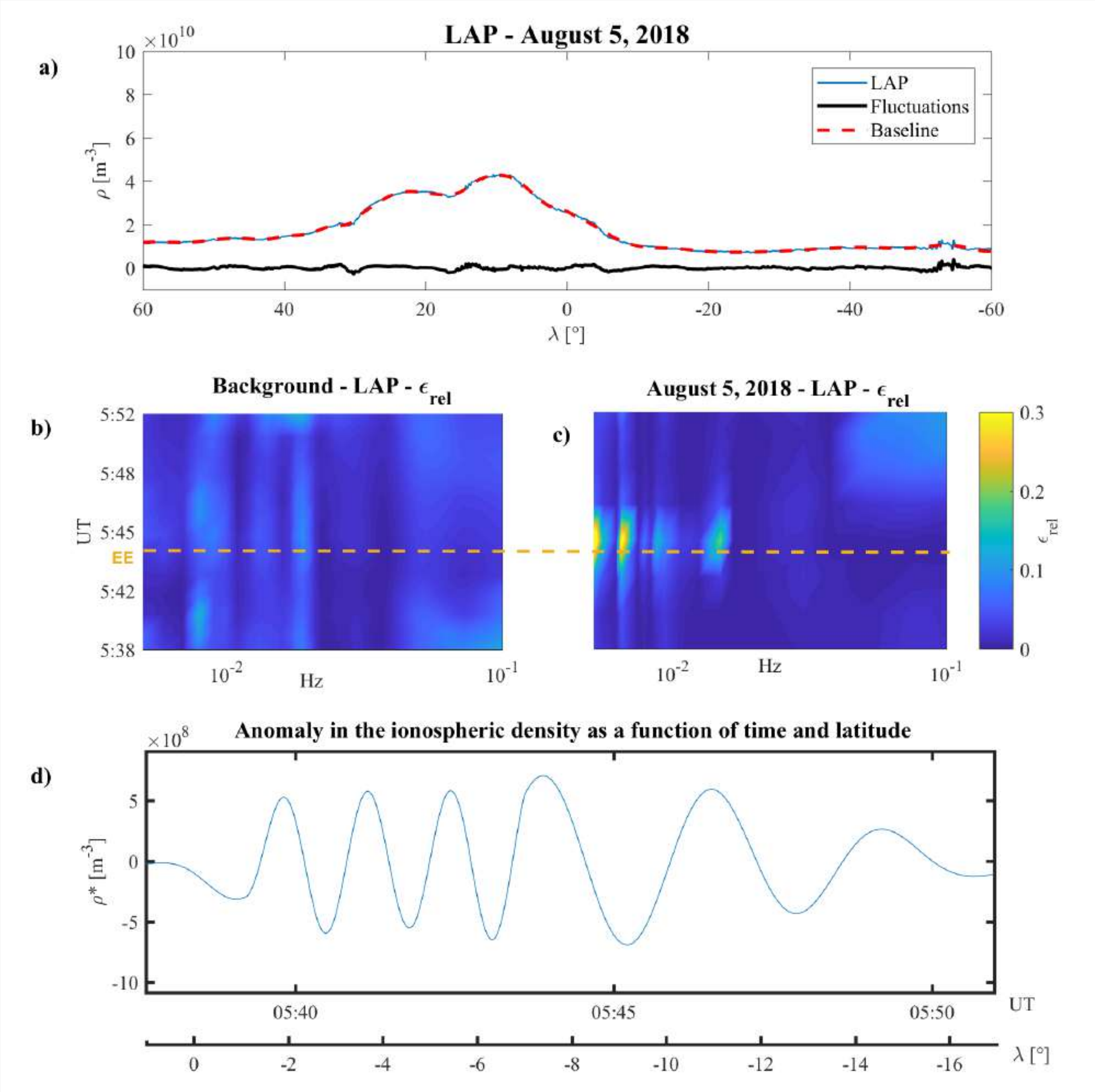
- A signature at ≈20 Hz is visible at all components, related to the Schumann ionospheric resonance at CSES orbit.
- The peak around 12 kHz is the signature of the lower-hybrid resonance of the ionosphere F2 layer.

- Anomalous peak (magenta line) at 180 Hz with respect to the background has been detected along the Bx and Bz component.

- **Interestingly, this oscillation is perpendicular to the one detected to the EFD. It is an EM wave!**

- **The Poynting flux analysis confirms the injection of EM wave coming downward**

August 5, 2018 – LP observations



- Typical plasma density variation observed during the CSES orbit from higher to lower latitudes during SQ period.
- Let's analyze fluctuations (black) we identified after baseline remotion (red).

- Two anomalous density components switched on over Bayan epicenter at 5:45 UT, at T1=111 s and T2=67 s
- The signal switches on near the EQ epicenter (EE), reaches its maximum at EE and then vanmishes

- It is a clear plasma density wave detected over EE.

Discussion

- Atmospheric temperature data confirms the injection of a clear AGW with ~ 9.8 km vertical wavelength.
- 1 minute after the EQ occurrence there is a clear vTEC perturbation with a period of ~ 97 ± 5 s.
- A clear decrease in the magnetospheric FLR frequency ~ 2 minutes after the EQ.
- EM and plasma wave detected by CSES satellite ~ 6 hours before the EQ

Discussion

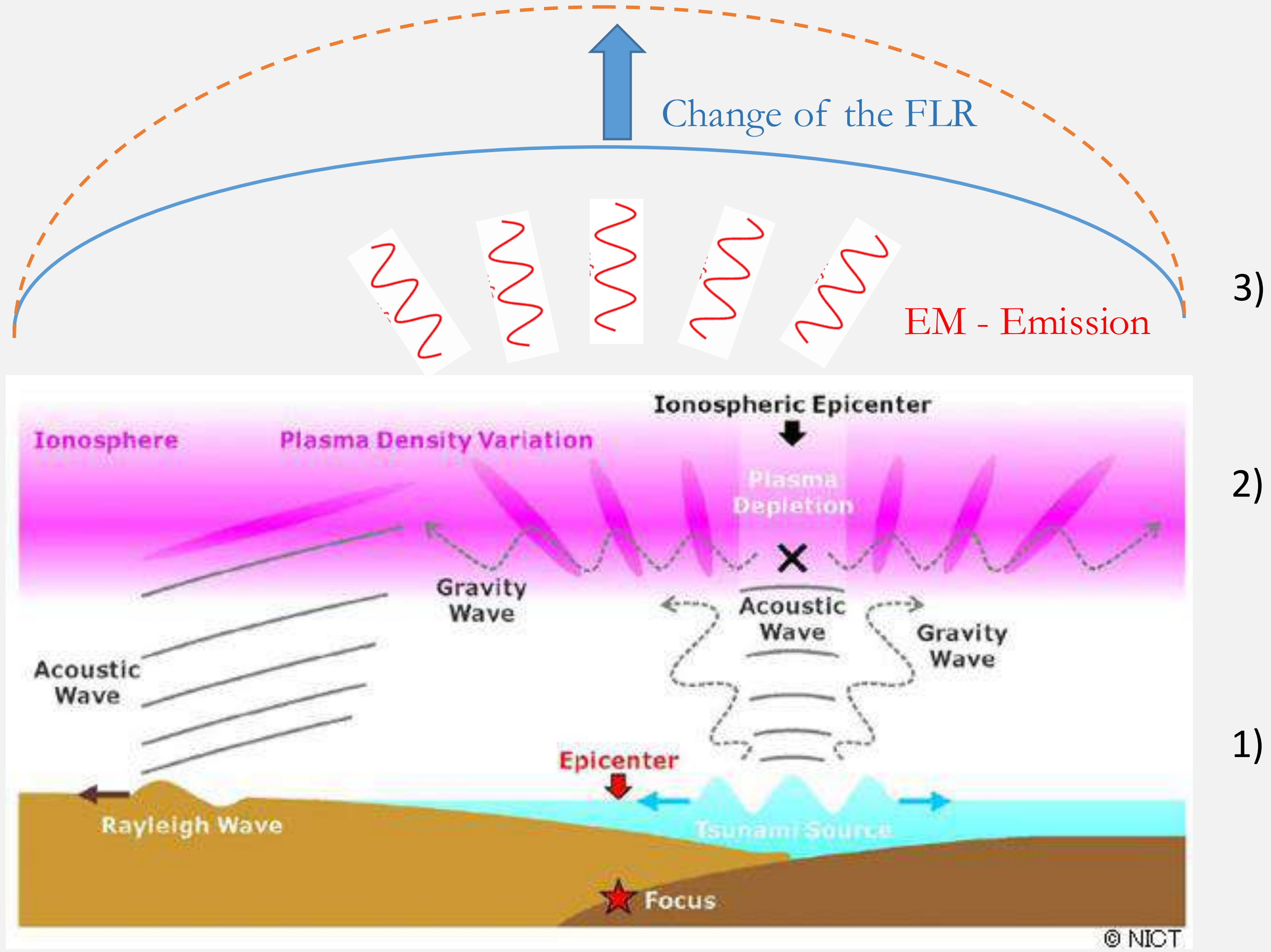
How to explain?

The MILC analytical model

Piersanti, M., Materassi M., Carbone V., et al., Magnetospheric–Ionospheric–Lithospheric Coupling Model. 1: Observations during the 5 August 2018 Bayan Earthquake. Remote Sens., 12, 3299, doi:10.3390/rs12203299, 2020.

Carbone V., M. Piersanti, M. Materassi, A mathematical model of Lithosphere-Atmospherecoupling for seismic events, Scientific Report, Nature, in press, 2021.

The MILC model – Piersanti et al.[2020]



The model is based on three steps:

1) The earthquake generates an AGW, propagating through the atmosphere;
2) The AGW interacts with the ionosphere generating local instability in the plasma distribution through a pressure gradient
3) The ionospheric plasma variation generates EM waves propagating through the magnetosphere that interact with the magnetospheric field
4) The interaction causes a FL eigen-frequency change.
5) Since the FL is stretched, its eigen-frequency has to lower.

The LAIC model: Lithosphere -Atmosphere

STEP 1

- A seismic event manifests itself through surface waves detected by seismograms, whose dispersion relation is described by Love-Reynolds.
- the dynamics of the upper part of the layer (ground) can be roughly described within the shallow water approach.
- **We solved our equations via linearization obtaining both the surface perturbation at the first atmospheric layer H*, and the relative dispersion relation**

The LAIC model – AGW injection

STEP 2

- Once the fluctuations have been generated at H*, a pressure fluctuation is generated.
- We started from fluid equations propagating in a neutral atmosphere with gravity $\boldsymbol{g}$ to obtain the equation of the pressure propagation.
- It is needed because we have to perturbate the ionospheric plasma with a pressure gradient.
- We checked for **the condition for not-evanescent AGW propagating towards the ionosphere**

The LAIC model – STE

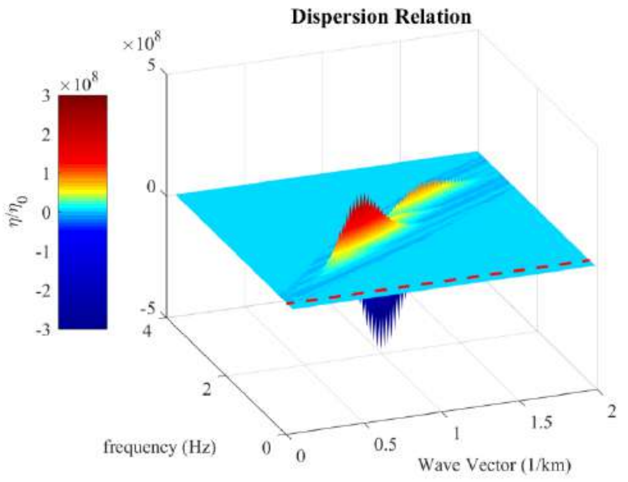
- So, once the principal caracteristics of an earthquake are known, the the AGW propagation can be easily predicted.

- What we need is:

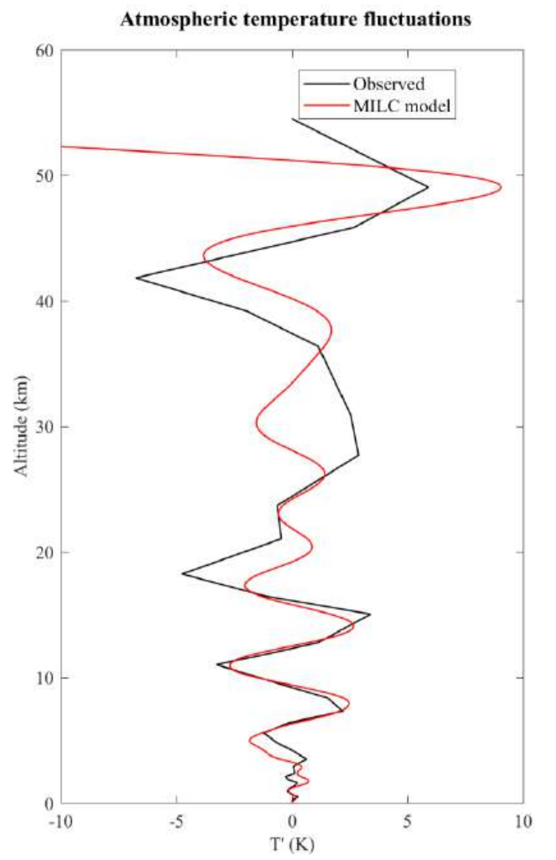
1. L: Length of the fault;
2. ω_S: the decay time of the seismic event;
3. β0: the Peak Ground Acceleration;
4. α: the time duration of the seismic event;
5. vs is the ground speed of the earthquake;

In case of the Bayan Earthquake, the dispersion relation allows the injection of AGW propagation till the ionosphere.

MILC model vs Observations



Dispersion Relation evaluated for the 2018 Bayan Earthquake using the parameters in the Table below (USGS website). The dashed line represents the parameter c0/2h (ω=0.2).



The Temperature fluctuations predicted by MILC agree very well with the observations (RMSE = 0.8 K ϱ_{corr} = 0.86). In addition, the χ2 test gives 47.3, suggesting that our model is able to reproduce the observations with >90% probability.

EQ	M	L (km)	ω_S (Hz)	PGA (g)	α (1/s^2)	vs (m/s)
Bayan	6.9	21	0.1	0.4	0.0013	1151

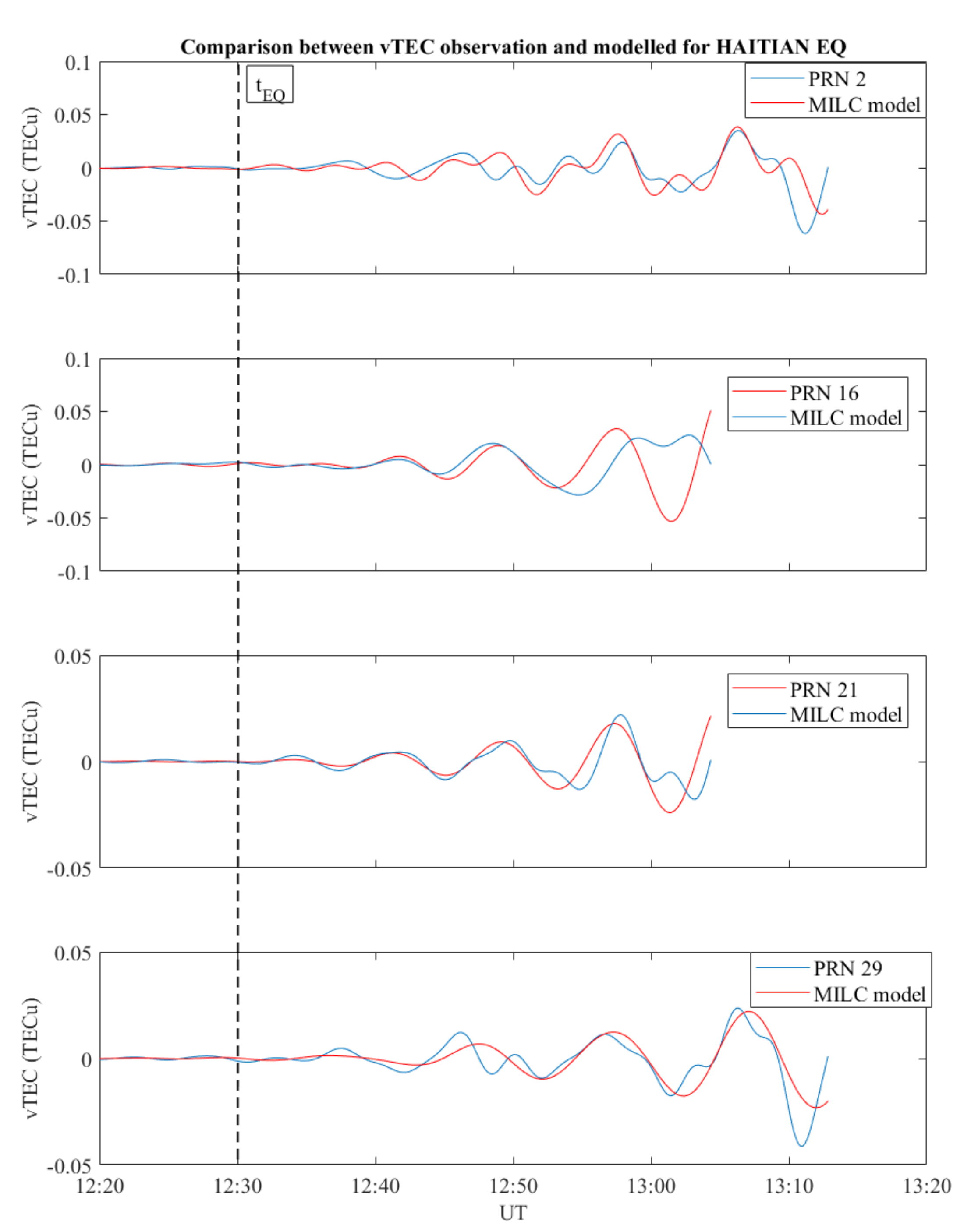
The LAIC model: Atmosphere – Ionosphere

- We started from MHD equations related to a EM wave propagating through the ionosphere.
- It is needed because we need to know the k-ω relation of the EM wave couming out from the Ionosphere.

We solved the system imposing ***as a boundary condition*** the solution of the AGW equation
Also in this case we used the linear approximation to solve the system obtaining both an EM wave and plasma wave.
The dispersion relation of the solution gives a frequency band estimation: ***60 Hz < f < 700 Hz***

TID – MILC model results

- The MILC model expects a plasma wave (TID) caused by the AGW injected by the EQ;
- The comparison between the observations and the model results is very good;
- **The χ2 test gives a 87% probability of our model to reproduce the observed signal.**



The LAIC model: Ionosphere - Magnetosphere

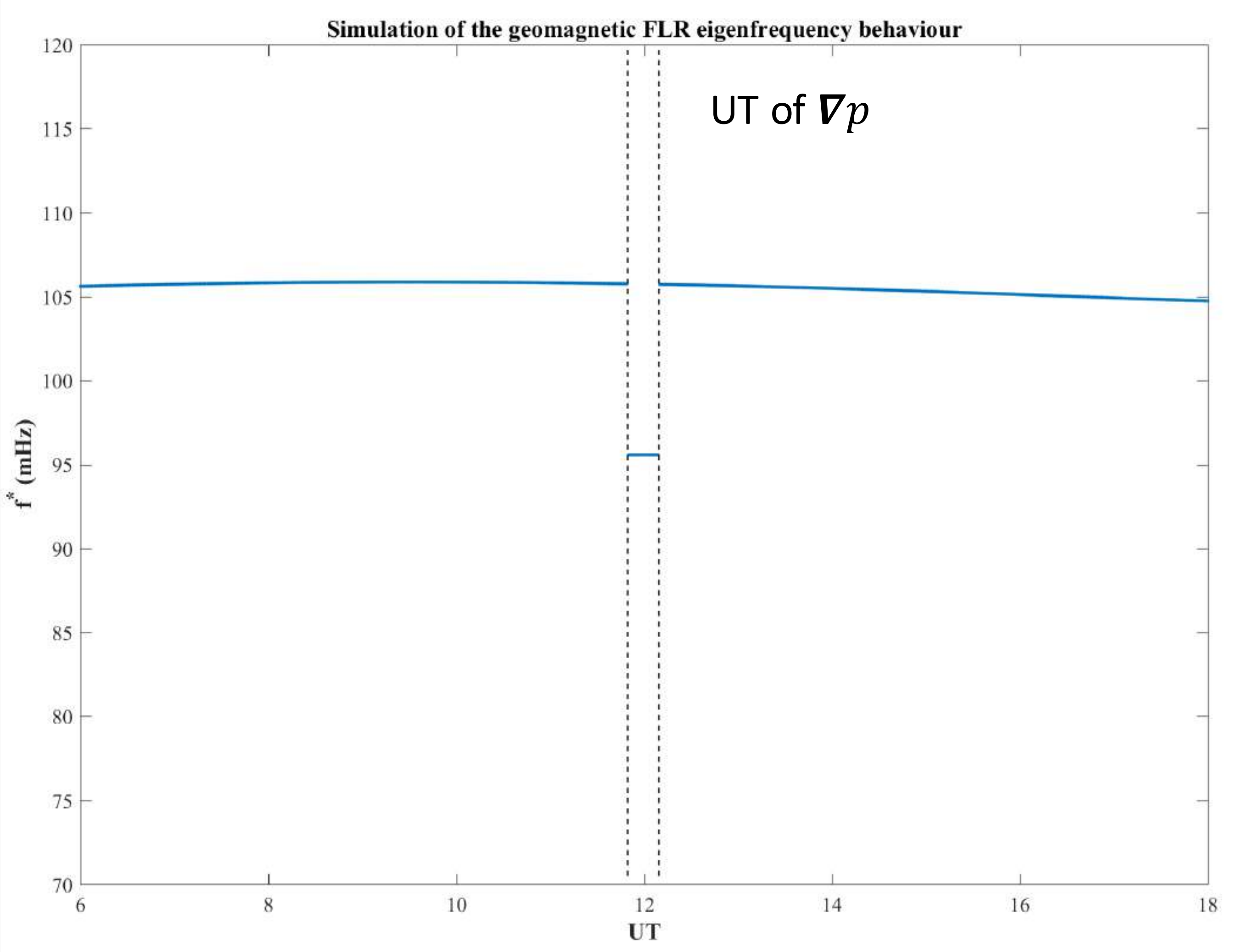
- We started from MHD equations related to stationary EM wave (FLR theory) to obtain the equation ruling the magnetospheric field line eigen-frequency.
- It is needed to evaluate the variation of the FLR eigen-frequency under an EM wave perturbation.
- We found a FLR frequency w^* as:

$$\boldsymbol{\omega^* = \frac{B_0^2}{\mu_0 \rho_0} \cdot \frac{\lambda^{1/2}}{l}}$$, where l is the length of the field line and B_0 is the local magnetic field.

FLR - Simulation results

- The result of the modeled **ω** variation of a field line footprinted at λ=10°, under the assumption of real Earth's magnetic field, associated to a pressure gradient driven by an earthquake of Mw=6.9 is reported in right figure.

- **A clear decrease of ω is visible in coincidence to the pressure gradient (∇p) driven by the AGW injected by the earthquake.**



Discussion

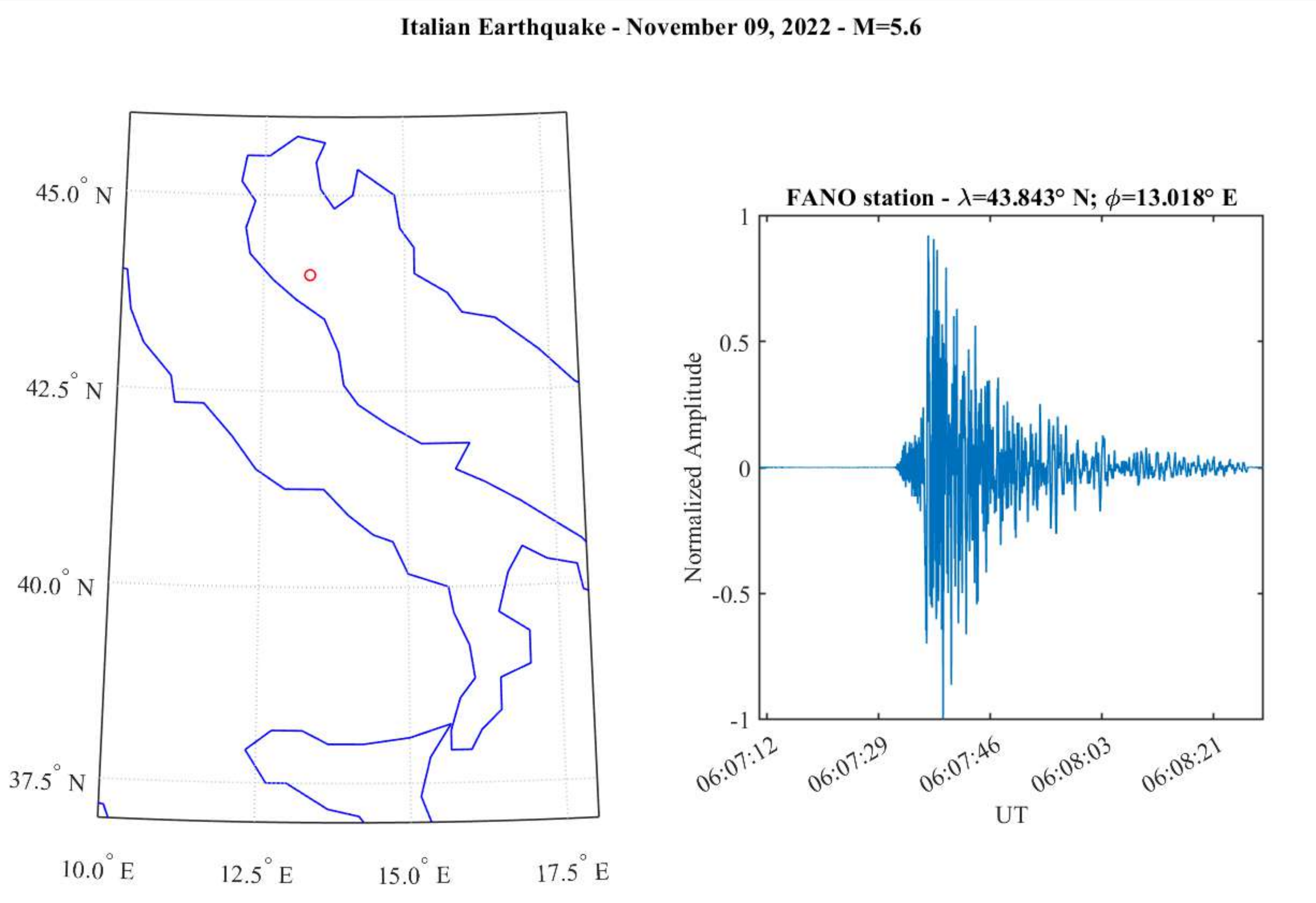
1. **The observational scenario can be explained in terms of the M.I.L.C. model**

- According to MILC model, the Bayan EQ characterized by $M=6.9$, $PGA=0.4g$, $V_s=1153$ m/s and $\omega_s=0.1$ Hz will excite AGW in the frequency range $0.5 \text{ Hz} < \omega < 2 \text{ Hz}$ and wavevectors $500 \text{ m} < k < 9000 \text{ m}$.
- **The previsions completely agree with the observed AGWs before and during the EQ occurrence.**

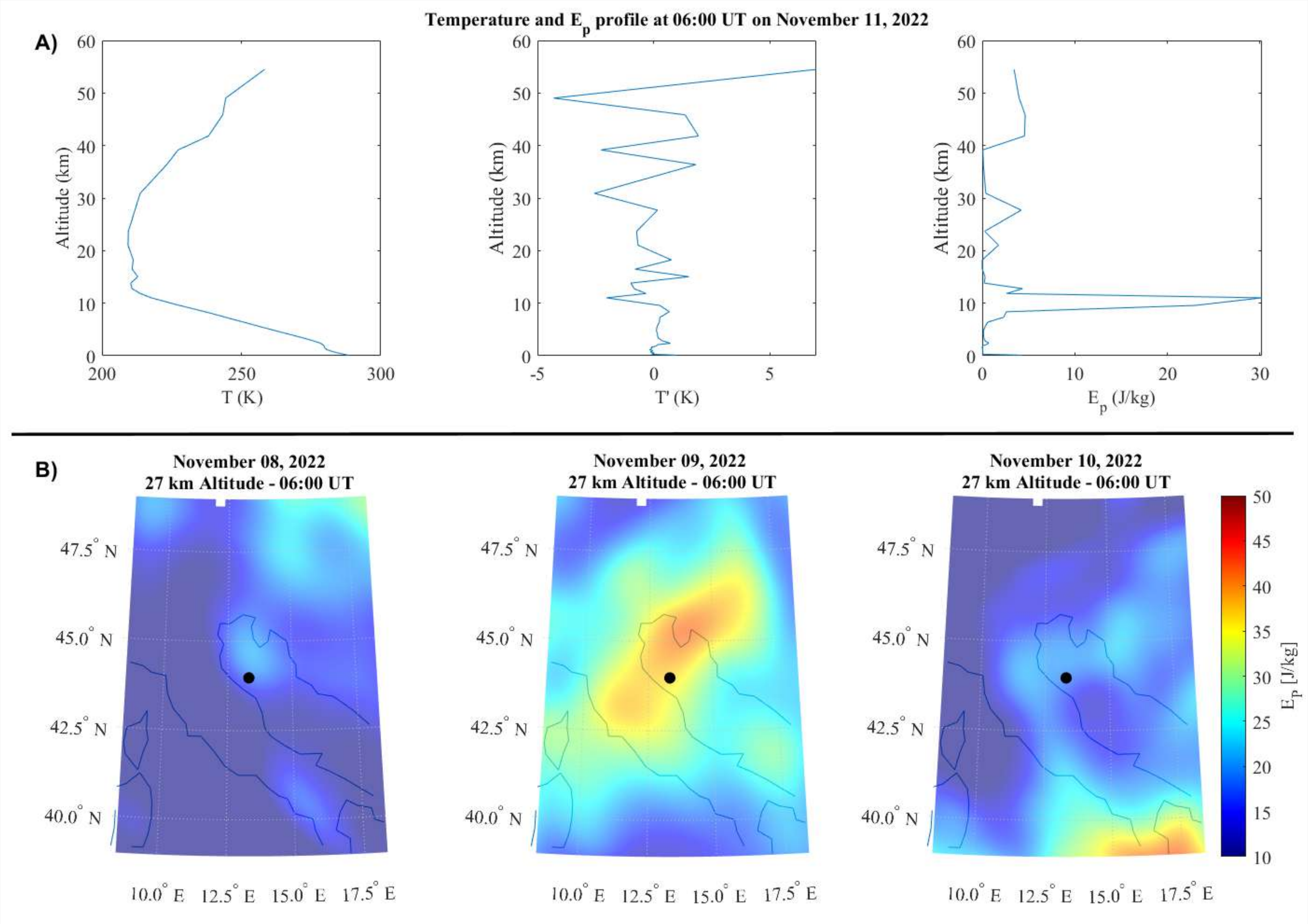
- The frequency range expected by MILC model applied to this EQ for the EM waves propagating from the Ionosphere is [100 – 400] Hz
- **Previsions agree with the observed EM wave detected by CSES satellite.**

- MILC model expected to observe a FLR frequency decrease.
- **Previsions agrees with the observed FLR frequency behaviour**

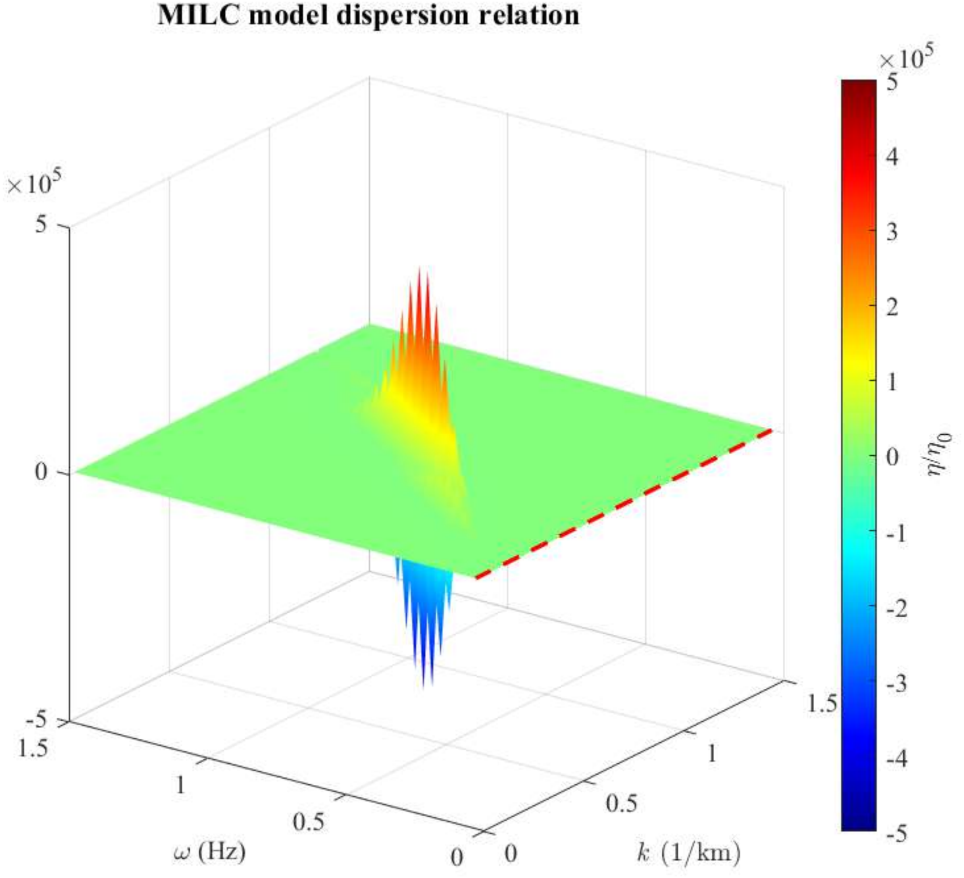
Italy - Marche

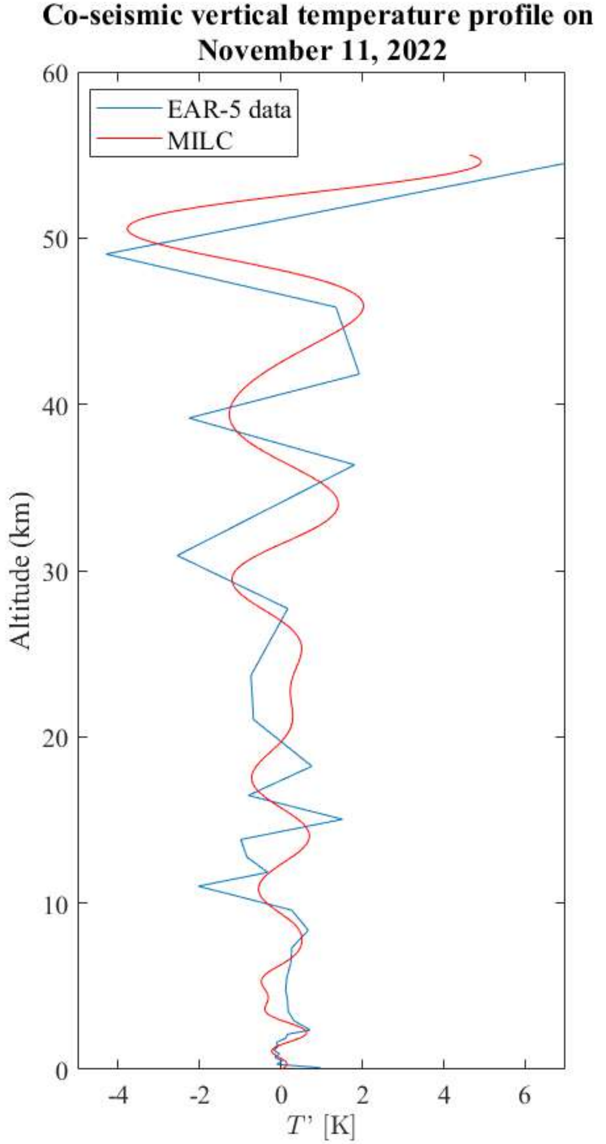


AGW analysis



AGW – MILC results

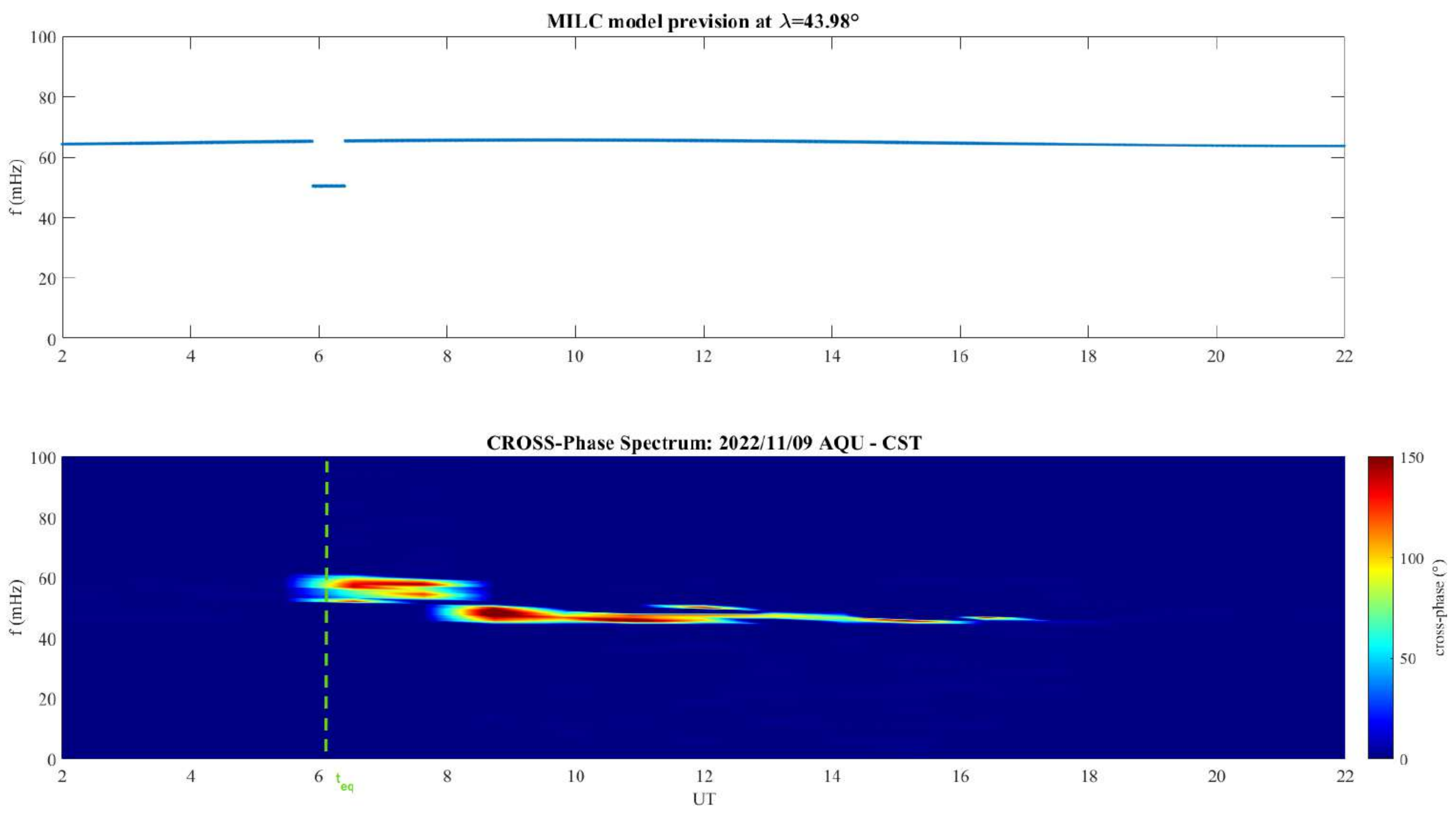




EQ Char	Value
L	25,000 km
ω_s	0,0422 Hz
v_s	1614,4 m/s
Δt	42.5 s
PGA	0,35 g
ω_0	0,047 Hz

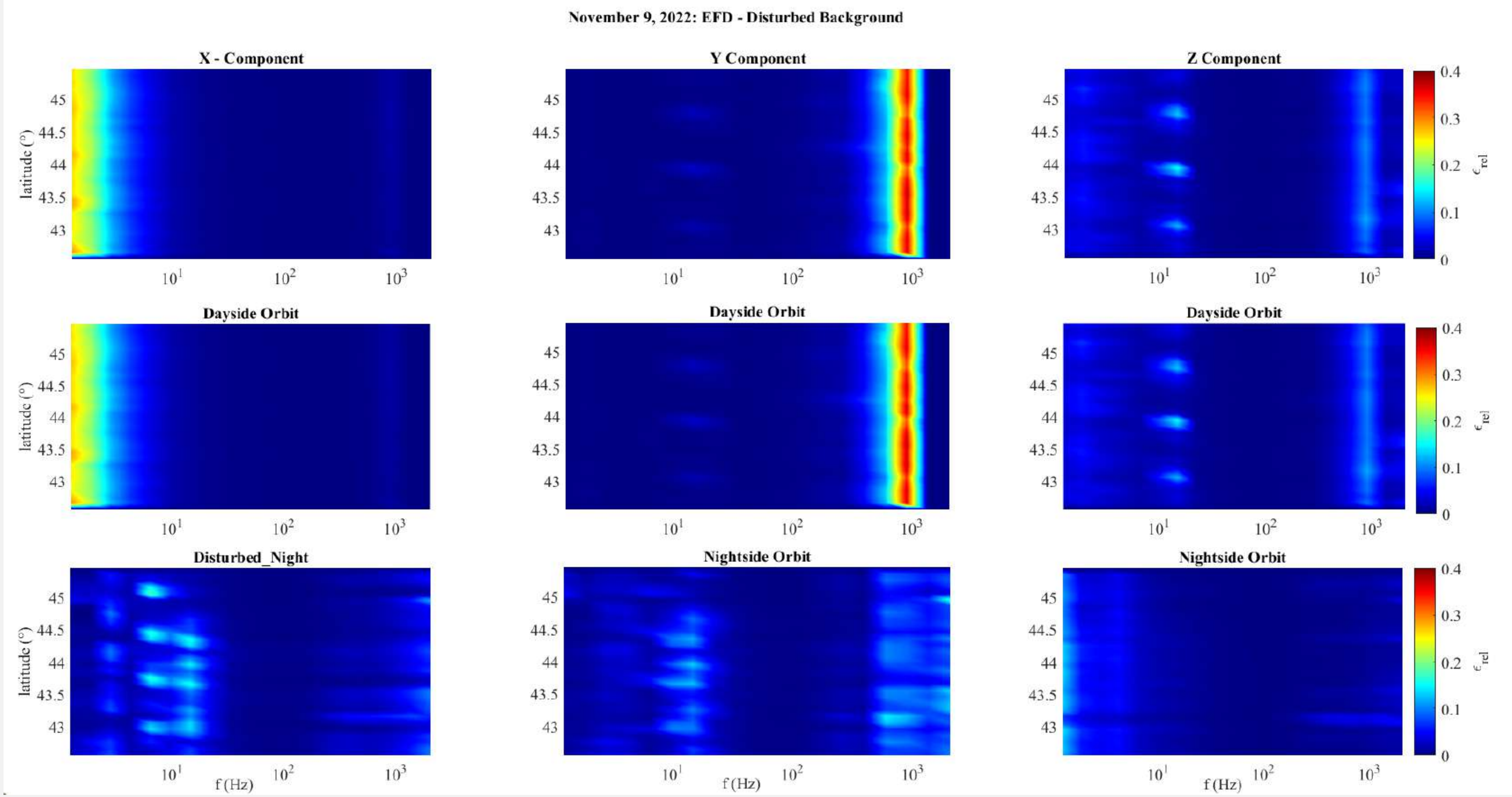
MILC MODEL RESULTS	
T (min)	**K (km)**
0,5	0,8
3	3,5

Italy - FLR

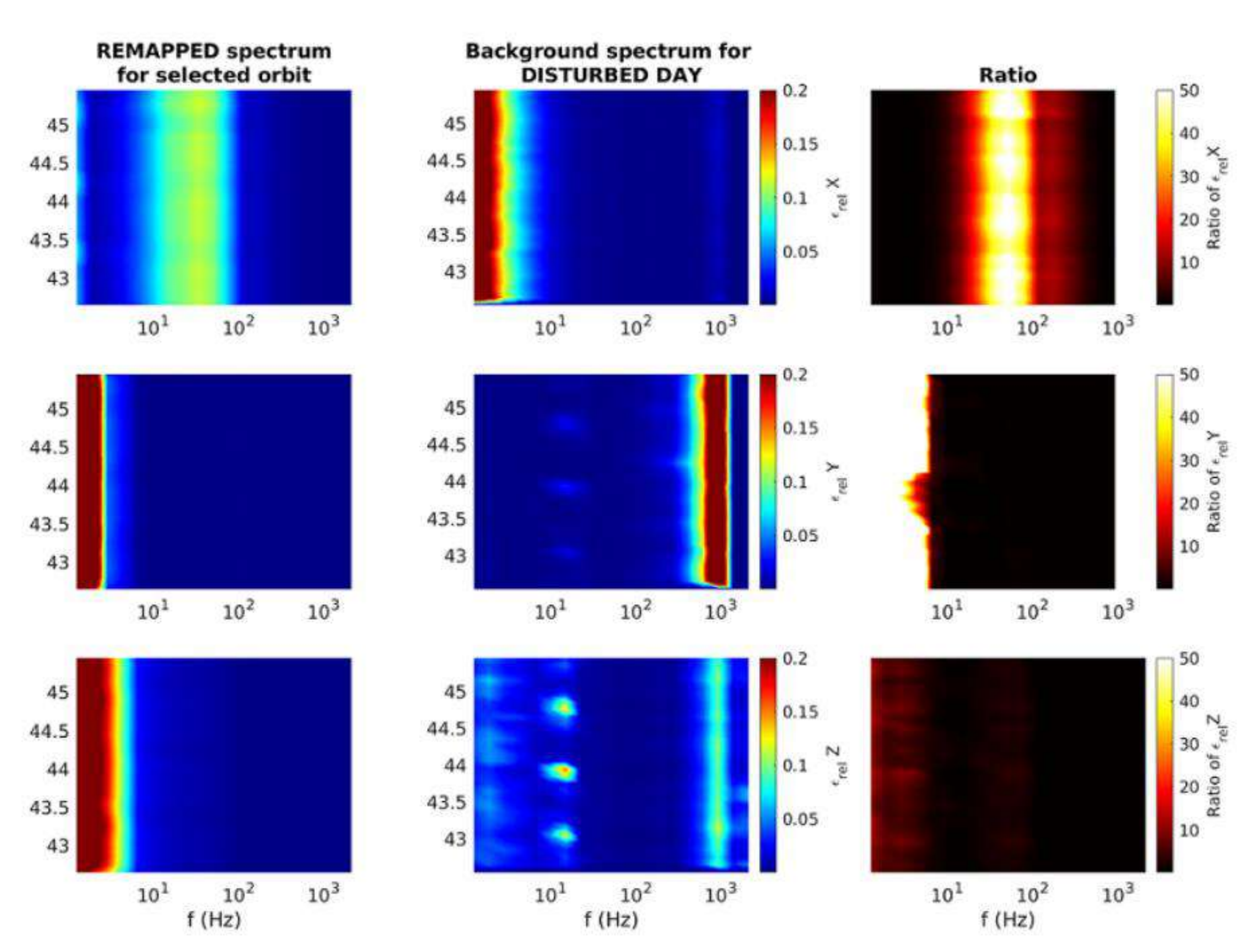


MILC model prevision at λ=43.98°
f (mHz)
100
80
60
40
20
0
2
4
6
8
10
12
14
16
18
20
22
CROSS-Phase Spectrum: 2022/11/09 AQU - CST
f (mHz)
100
80
60
40
20
0
2
4
6
t_{eq}
8
10
12
14
16
18
20
22
UT
150
100
50
0
cross-phase (°)

CSES- Observations



CSES-Observations



The ratio between observations of the selected orbit and the appropriate background immediately tells us if there is an emerging signal. In this case there is a clear signal on the X component at about 77 Hz.

Discussion

1. **The observational scenario can be explained in terms of the M.I.L.C. model**

- According to MILC model, the Italia EQ will excite AGW in the frequency range 3 mHz < ω < 30 mHz and wavevectors 100 m < k < 3000 m.
- **The previsions completely agree with the observed AGWs before and during the EQ occurrence.**

- The frequency range expected by MILC model applied to this EQ for the EM waves propagating from the Ionosphere is [50 – 300] Hz
- **Previsions agree with the observed EM wave detected by CSES satellite.**

- MILC model expected to observe a FLR frequency decrease.
- **Previsions agrees with the observed FLR frequency behaviour**

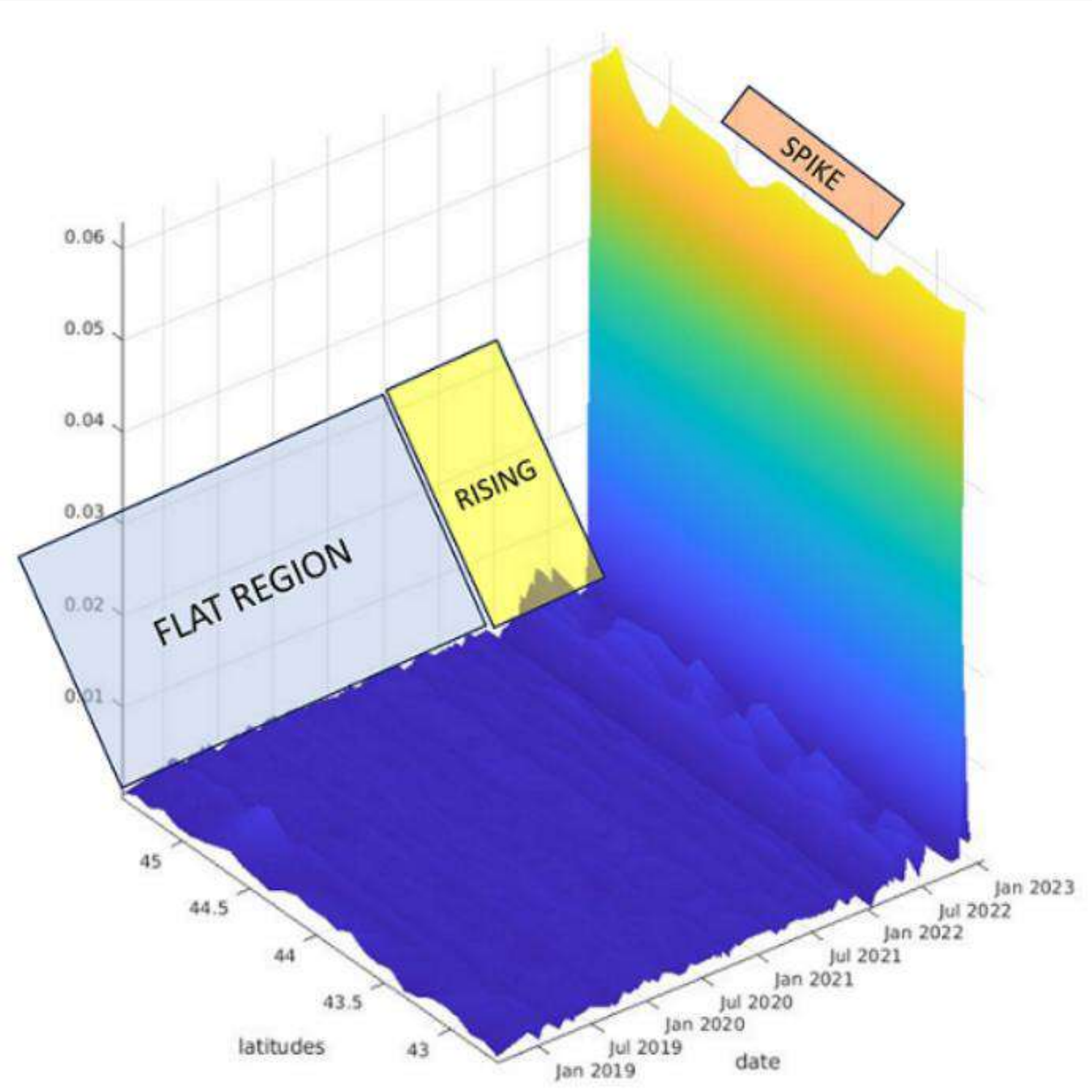
Discussion

- The E.M. signals we found was interesting.
- They are often present in ionosphere from some hours before up to the moment of the EQ occurrence.
- We asked about their temporal behaviour, namely:

1. Are they always presents or are they a sporadic phenomenon?
2. Does it diseapper after the EQ occurrence?
3. What is its time behaviour in terms of amplitude?

- To answer these questions, we made an analysis of the detected E.M. signal as a function of time.

Marche earthquake

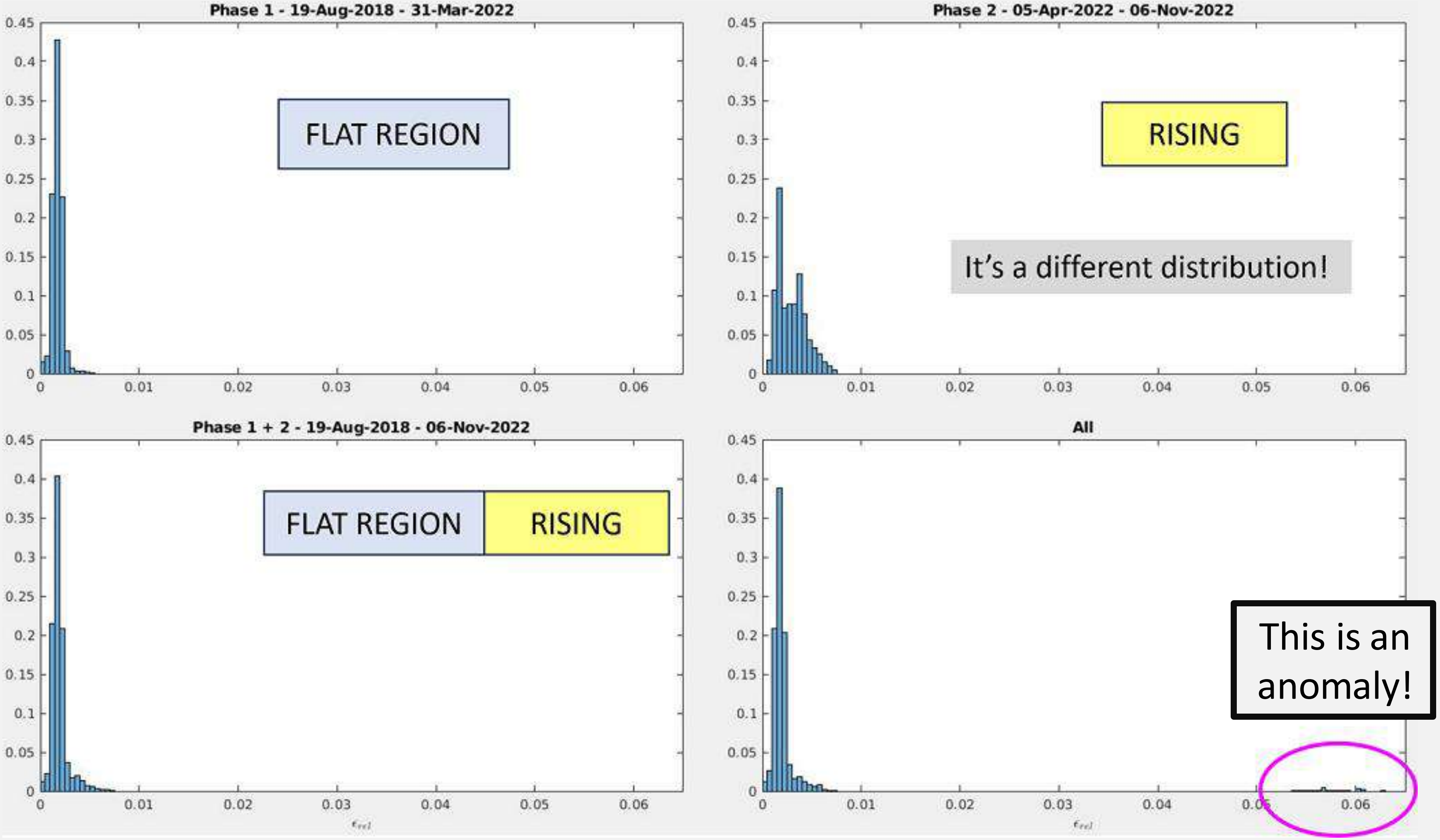


These are the ϵ_{rel} for the 77 Hz frequency for all diurnal orbits during disturbed days.

Three regions can be identified:

- Flat region - from August 2018 to April 2022: ϵ_{rel} values are always very low
- Rising region – from April to November 2002: ϵ_{rel} values are increasing
- Spike: at the end of November 2022, after a series of seismic events occurred from 9 November 2022 in the same point.

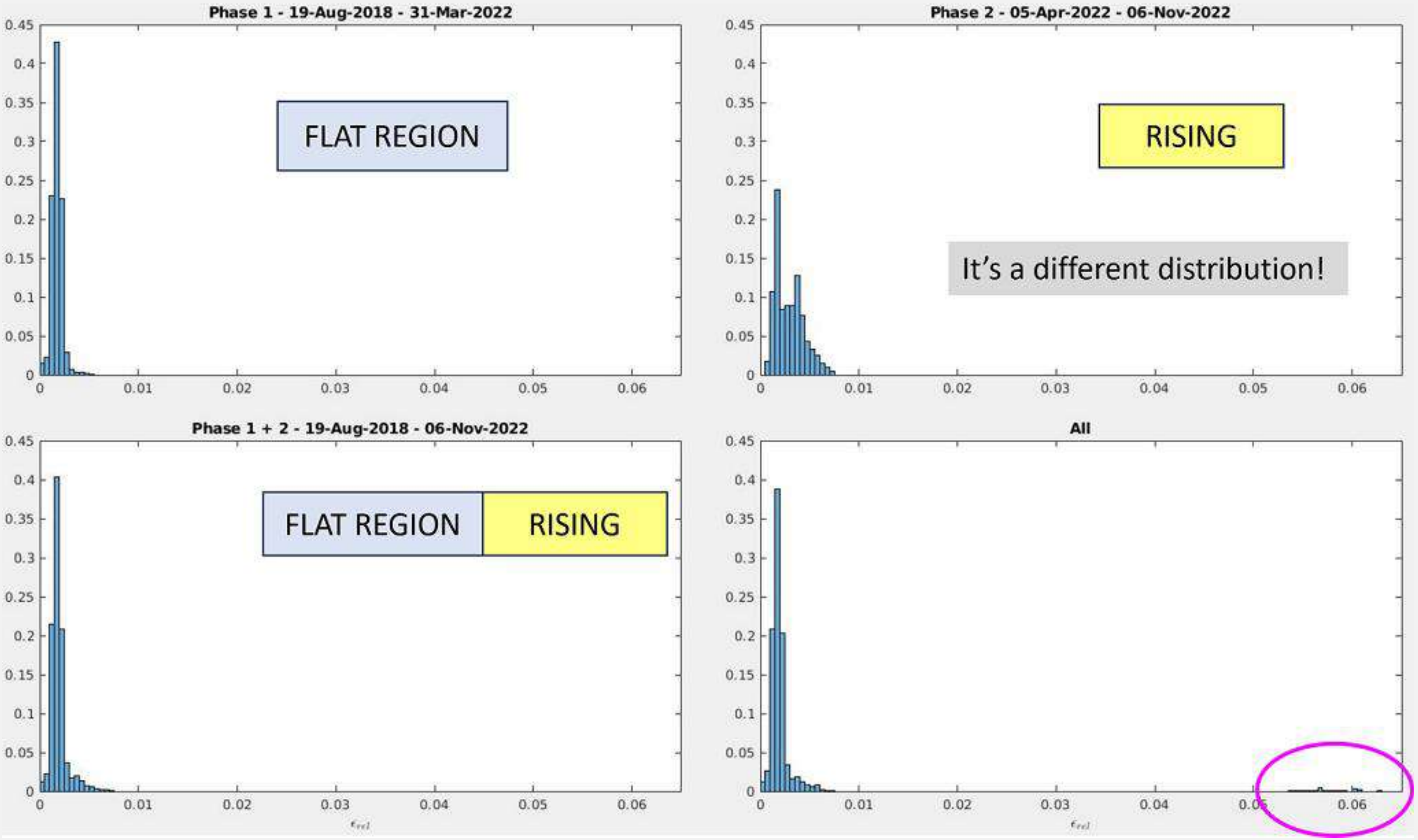
Probability distribution of the ϵ_{rel}



Why now I can say anomaly and not "anomaly"?
Why this plot is so important?

Our previous analysis and several other works based the definition of an anomaly on a threshold with respect to the average (2, 3 or even 5 σ).
However, they can still be rare but not anomalous events.

When the distribution change the underlying physics change!



We are in presence of 3 different distribution for the three regions!
The physics is changing, and both the spike and the rising phase represent **anomalous** events!

Discussion

- We are sure now that the E.M. signals we found was not only interesting but also are deserved to be studied, analyzed and explained.
- Such behaviour happened for all the events (clean in terms of Space Weather and Atmospheric weather) analyzed.
- Interestingly…look at what we found for Vanuata EQ….

M 5.9 - 52 km E of Luganville, Vanuatu

V DYFI | IV ShakeMap | GREEN PAGER

Time	2019-08-07 05:32:40 (UTC)
Location	15.498°S 167.656°E
Depth	124.0 km

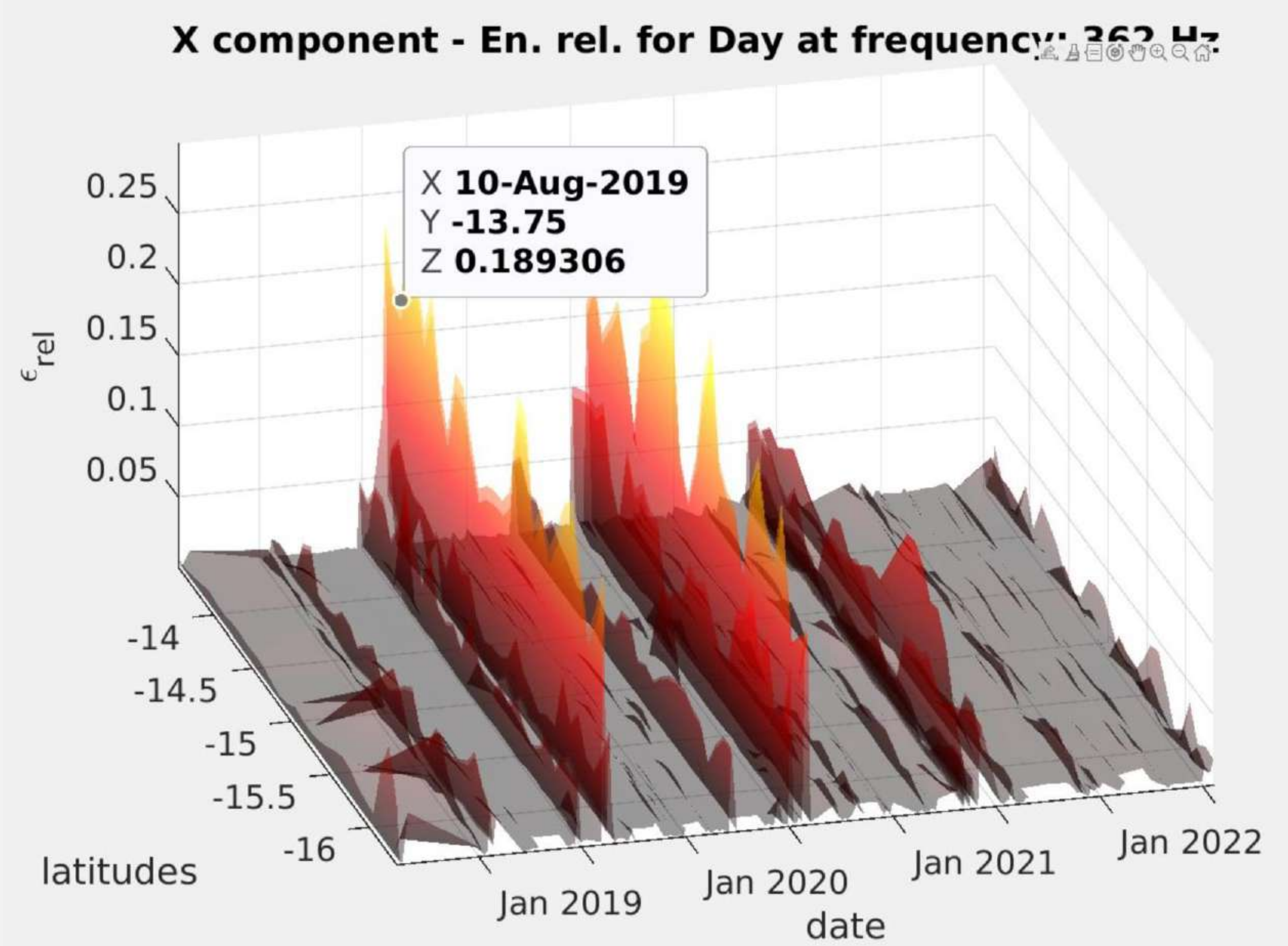
07-08-2019 earthquake

Earthquake from our list of clean events

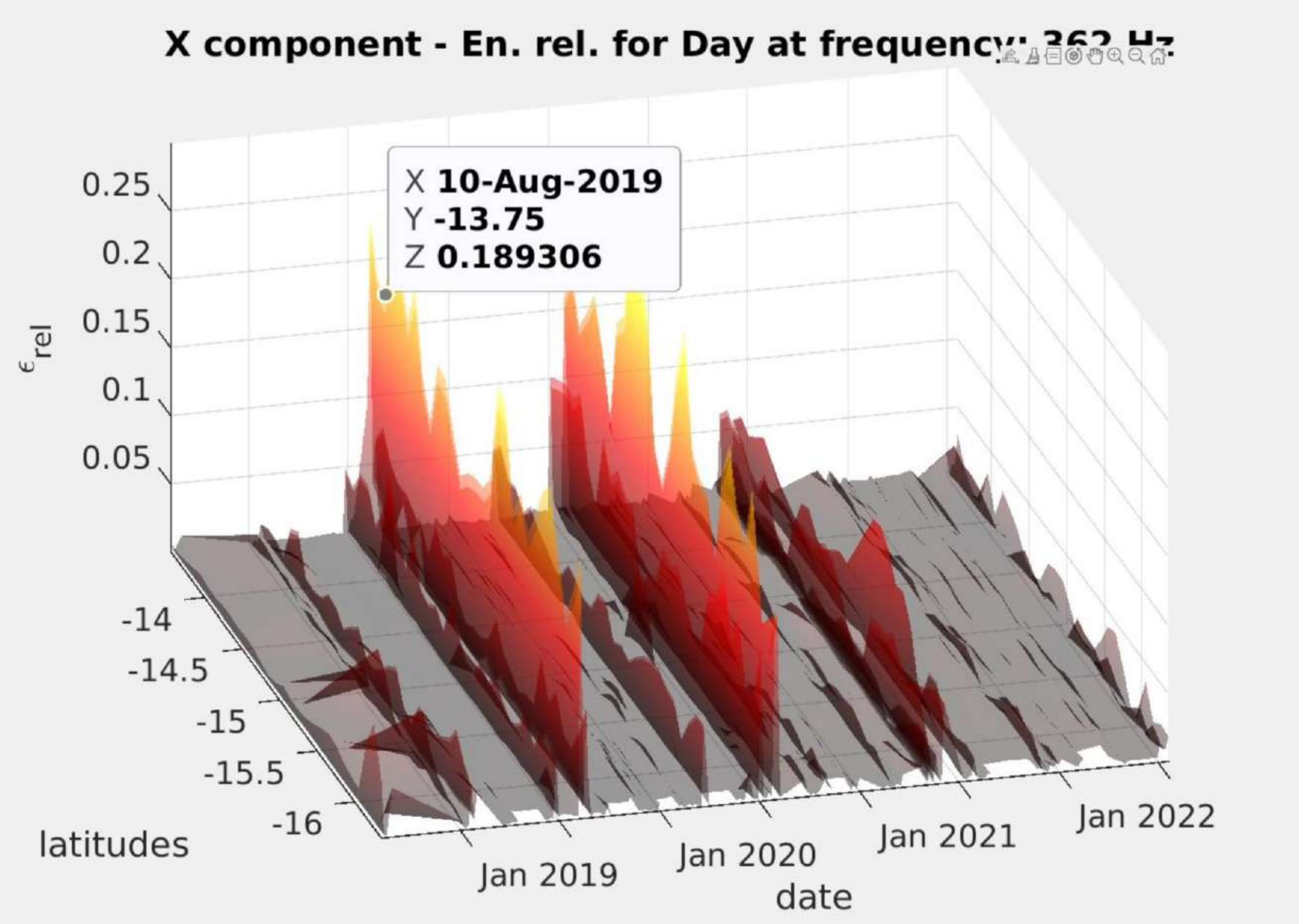
Huge spike for $\approx 360\ Hz$ right after the earthquake
Pre-seismic activity

In our previous analysis we would have designated this as an anomaly. But now we study the distribution of the ϵ_{rel} on the whole time scale.

In this case high value of ϵ_{rel} are observed again a year later and again two years later.



3 anomalous region at summer 2019, 2020, 2021



M 5.9 - 52 km E of Luganville, Vanuatu

V DYFI | IV ShakeMap | GREEN PAGER

Time	2019-08-07 05:32:40 (UTC)
Location	15.498°S 167.656°E
Depth	124.0 km

M 6.4 - 69 km E of Lakatoro, Vanuatu

IV ShakeMap | GREEN PAGER

Time	2020-08-05 12:05:36 (UTC)
Location	16.094°S 168.065°E
Depth	181.9 km

M 6.9 - 17 km N of Port-Olry, Vanuatu

VIII DYFI | VII ShakeMap | GREEN PAGER

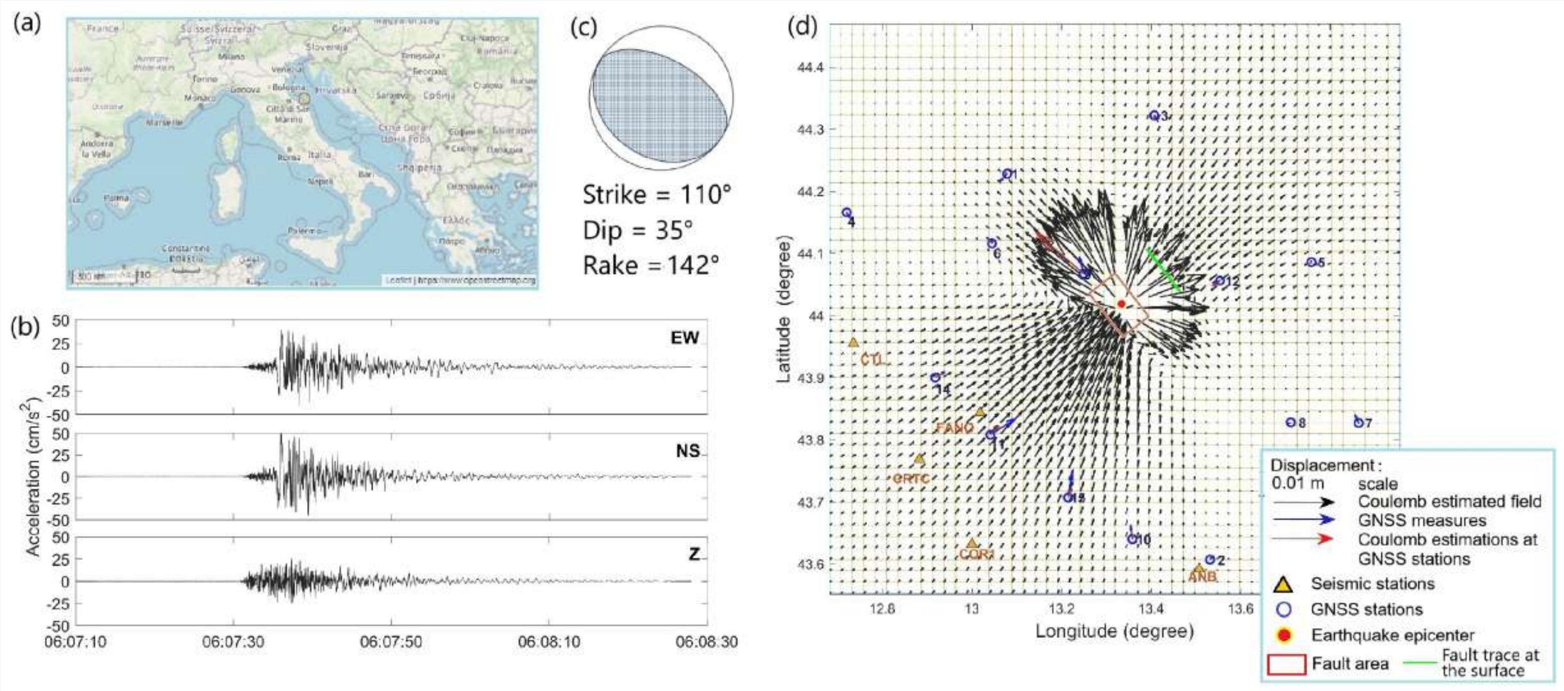
Time	2021-08-18 10:10:05 (UTC)
Location	14.882°S 167.059°E
Depth	93.0 km

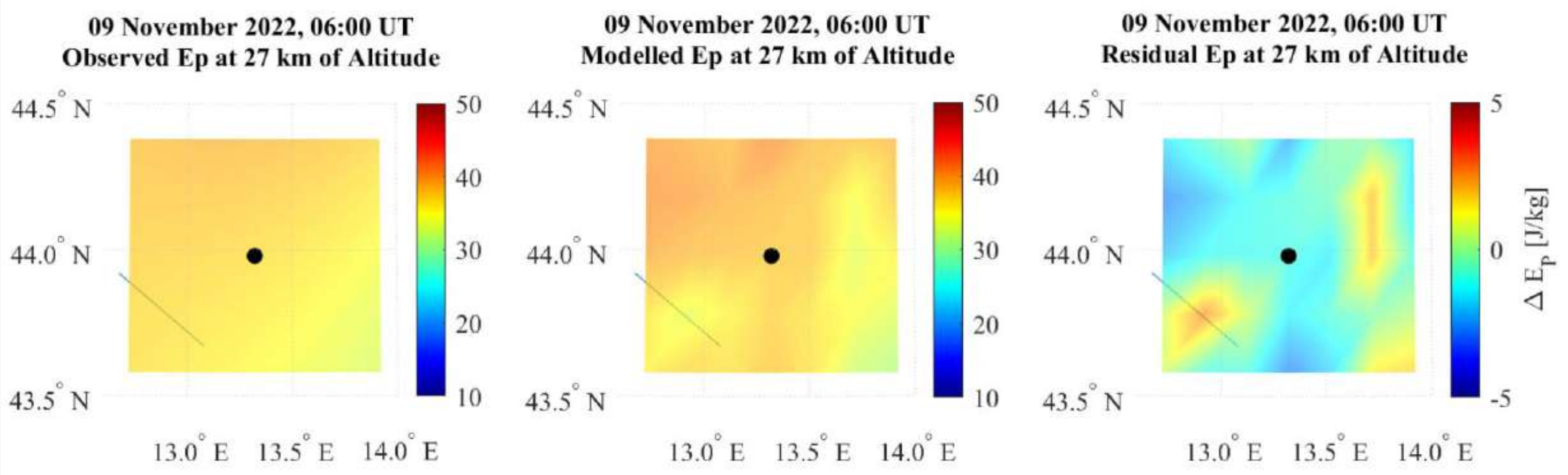
Conclusions an future steps

1. We developed an analytical model 1D of the Lithospere-Atmosphere-Ionosphere-Magnetosphere coupling (MILC) during active seismic condition able to explain and forecast any possible signal injected by the EQ into the atmospheric layers.
2. We analyzed CSES data for selected CLEAR (in terms of Space Weather and Atmospheric Weather) EQs for which we found very interesting EM signals that seems to be produced some months before the seismic event.
3. We developed a statistical approach through which we gave a ROBUST definition of an anomaly, marking the difference between anomalies and rare events.

Conclusions an future steps

We are now working on expanding the MILC model in 2D with the help of INGV and the University of Salerno, and University of Calabria) using data from both simulated and observed ground displacements (seismograms).





Conclusions an future steps

1. We are now developing (together with INGV and the University of Salerno) a new lithospheric electric model through which we will try to explain the emission of E.M. waves (found) before an EQ.
2. We will use both CSES satellites to both increase the statistics about E.M. signals (if any) injected in ionosphere before an EQ and understand the Physics of their origin (amplitude, diurnal/nocturnal pattern, statistical proprieties, spectral characteritics, ecc).
3. We will integrate numerically the MILC model (no linearization) in order to understand also the role played by the small time and spatial scales variations and to increase the reproducibility of the observed atmospheric and ionspheric fluctuations.

Publications

1. Piersanti, M., et al., M. On the Ionosphere–Atmosphere–Lithosphere Coupling During the 9 November 2022 Italian Earthquake. *Geosciences*, 2025
2. Piersanti, M., *et al.* A mathematical model of atmosphere-ionosphere coupling for seismic events, *Nature*, *Sci Rep,* in press, 2025
3. Piersanti, M., et al., Multiscale analysis of the background seismicity: application to Campi Flegrei (Italy), *JGR-Solid Earth*, in press, 2025.
4. De Santis, A., et al., Near-Earth electromagnetic environment and natural hazard disturbances: Volume I, *Front. Environ. Sci.,* 2023.
5. De Santis, A., et al., Near-Earth electromagnetic environment and natural hazard disturbances: Volume II*, Front. Environ. Sci.,* 2023.
6. Carbone, F., M. Piersanti, F. Lepreti, et al. Nonlinear shallow water investigation of atmospheric disturbances generated by strong seismic events, *Physical Review E,* 2023.
7. Recchiuti, D., et al., Detection of electromagnetic anomalies over seismic regions during two strong (MW > 5) earthquakes. *Frontiers in Earth Science*, vol. 11, 2023.
8. D'Angelo, G., et al., Haiti Earthquake (Mw 7.2): Magnetospheric-Ionospheric-Lithospheric Coupling during and after the Main Shock on 14 August 2021, *Remote Sensing*, vol. 14, issue 21, p. 5340, 2022.
9. Piersanti, M., et al., On the Geomagnetic Field Line Resonance Eigenfrequency Variations during Seismic Event. *Remote Sensing* 2021.
10. Carbone, V., *et al.* A mathematical model of lithosphere–atmosphere coupling for seismic events, *Nature*, *Sci Rep* 11, 8682, 2021.
11. Piersanti, M. et al., Magnetospheric–Ionospheric–Lithospheric Coupling Model. 1: Observations during the 5 August 2018 Bayan Earthquake. *Remote Sens.* 2020.
12. Piersanti, M. et al., On the Geomagnetic Field Line Resonance Eigenfrequency Variations during Seismic Event. *Remote Sens.* 2021.

The End – Questions?

Back-up Slides

Acoustic Gravity Waves - Detection

- The common way to indirectly detect an AGW injection is to calculate the total wave energy (E_0)
- E_0 is presented as a sum of kinetic (E_K) and potential energies (E_P), which correspond to the fluctuations in wind fields and temperature, respectively;
- E_0 and E_P energies are proportional to each other (de la Torre et al., 1999; VanZandt, 1985), so that the wave activity can be easily evaluated by one of them;
- **Here we will use the potential energy as a proxy to estimate the wave activity which requires only the vertical temperature profiles.**

Temperature Profile

- The potential energy density is defined as (VanZandt, 1985; Piersanti et al., 2020):

$$E_P = \frac{1}{2}\left(\frac{g}{N}\right)^2 \overline{\left(\frac{T'}{\overline{T}}\right)^2}$$

Where g is the gravitational acceleration (constant), N is the Brunt-Vaisala frequency defined as:

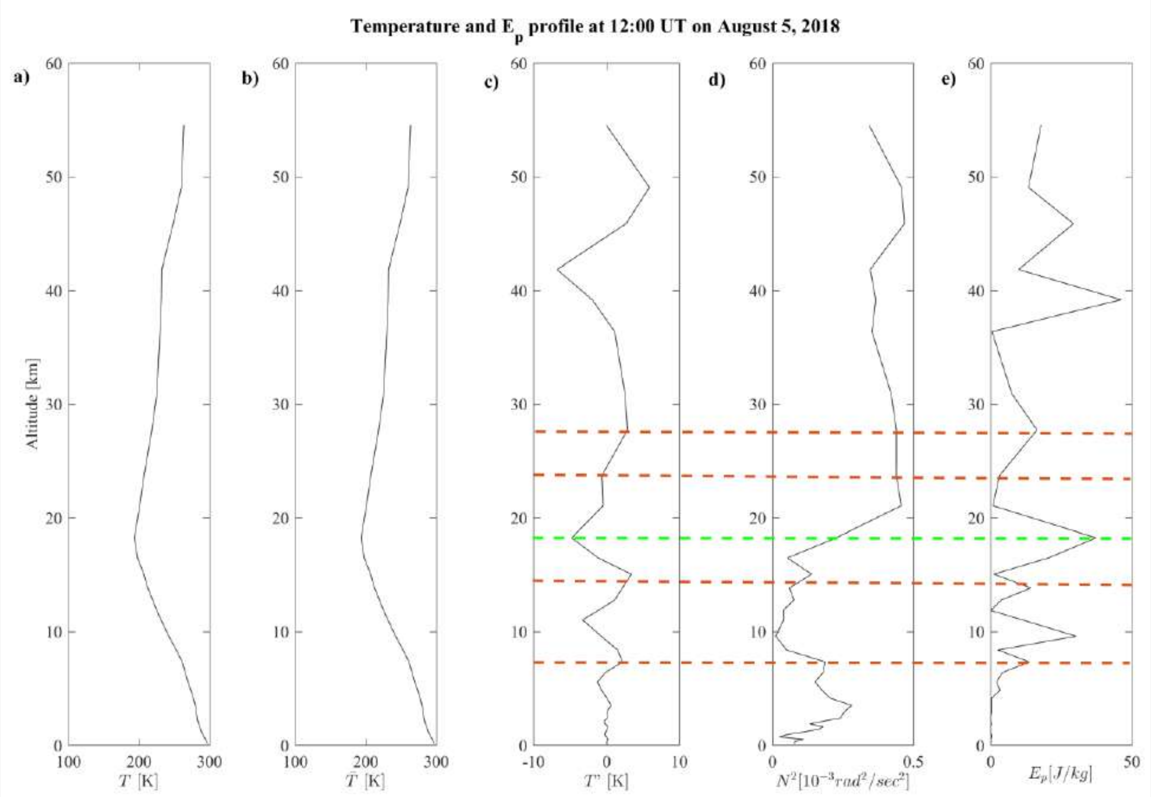
$$N = \sqrt{\frac{g}{\theta}\frac{d\theta}{dz}}$$

where $\theta = T\left(\frac{P_0}{P}\right)^{\frac{R}{cp}}$ is the potential temperature, z is the altitude, P_0 is the standard reference pressure (1 hPa), R is the gas constant of air and c_p is the specific heat capacity at a constant pressure. $R/c_p = 0.286$ for air (Piersanti et al., 2020).

T' is the perturbation deviated from the background temperature $\overline{T}$ that are all function of the altitude. The variance term $\overline{\left({T'}/{\overline{T}}\right)^2}$ is calculated within a layer of 2 km thikness as:

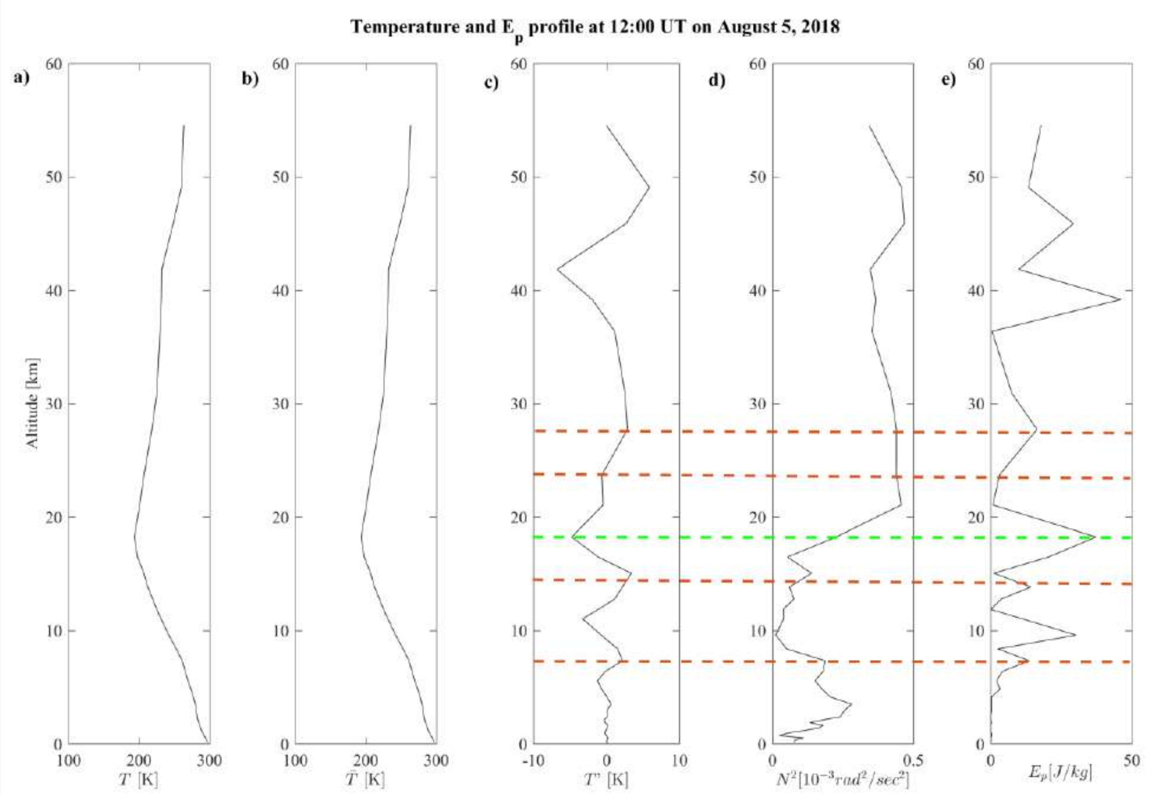
$$\overline{\left(\frac{T'}{\overline{T}}\right)^2} = \frac{1}{z^{max} - z^{min}} \int_{z^{min}}^{z^{max}} \left(\frac{T'}{\overline{T}}\right)^2 dz$$

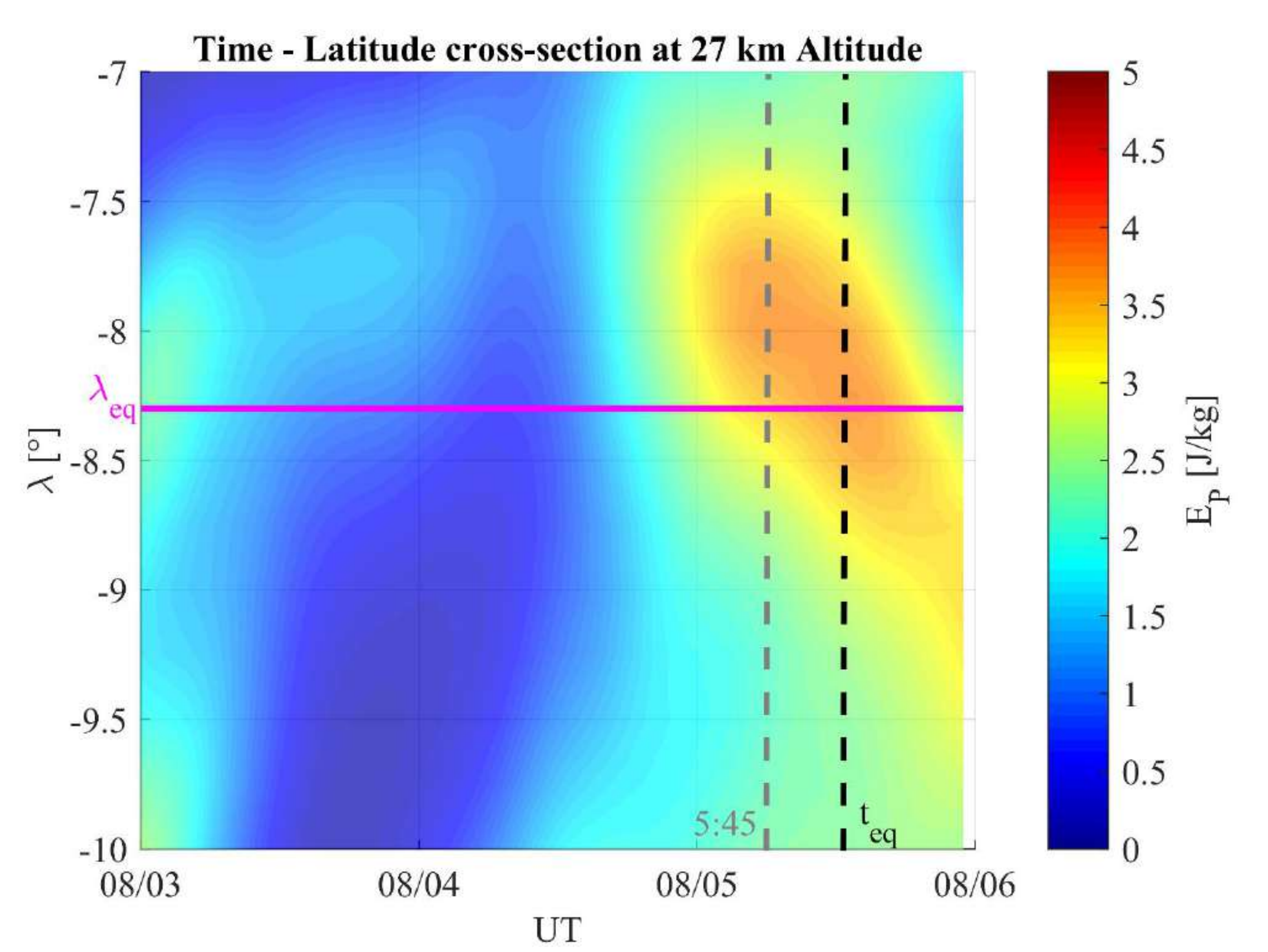
AGW evaluation – results



- The vertical wavelength of stratospheric AGW is about 2–10 km (Tsuda et al., 1994).
- The vertical temperature profile (left) at the EQ epicenter retrieved from ERA5 is hence filtered by a moving average (2 km), to obtain the background temperature profile (second panel from left);
- Then the temperature deviation (third panel) is computed by subtracting the background from the original temperature profile.
- Besides, the squared term of the Brunt-Väisälä frequency (Figure forth panel) can also be derived from the temperature profile. Finally, all the variables are substituted into equation (1),
- and the potential energy is calculated (right panel).
- The *E*P value is absolutely maximum around the altitude of 17 km (the tropopause). The temperature inversion around this altitude is filtered out by the moving average. The similar increase can also be found in Brunt-Vaisala frequency.

- **Gravity waves disturb the temperature profile, and their influence is revealed in the temperature deviation profile (third panel).**
- **The wavelength is thus defined by a full period in the sinusoidal variation in the temperature deviation but not in the EP profile.**

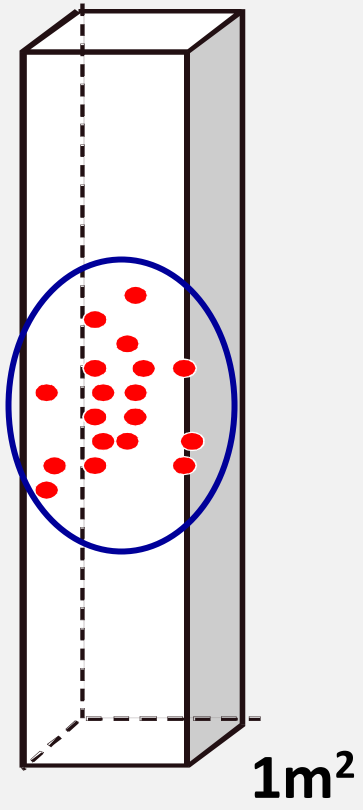




- Four wave crests are found in the temperature deviation profile at the altitudes of 17.8, 27.6, 36.6, and 44.8 km. There exist two sinusoidal periods, and the corresponding vertical wavelengths are 9.8 and 7.2 km, respectively.
- On the other hand, the *E*P profile maximizes only for the first wavelength.

So, there is a AGW of 9.8 km wavelength propagating in the atmosphere .

Total Electron Content (TEC)



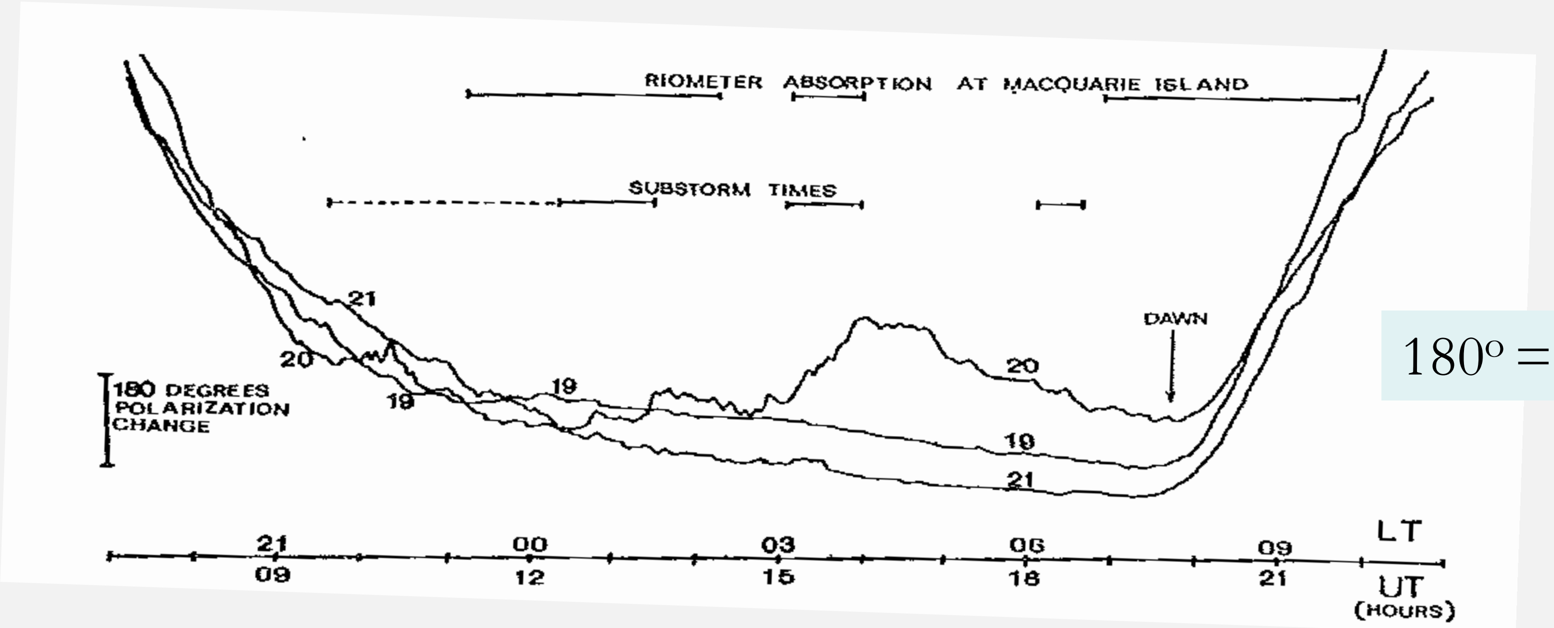
Total number of electrons in a column
with cross section of $1m^2$
(1 TECU = 10^{16} electrons/m^2)

TEC Measurements

- Use Ionospheric effects on radio wave propagation

  - **Faraday rotation** of the polarization angle of a radio wave
    → Require magnitude of the geomagnetic field

TEC from Macquarie Island for 19-21 May, 1970



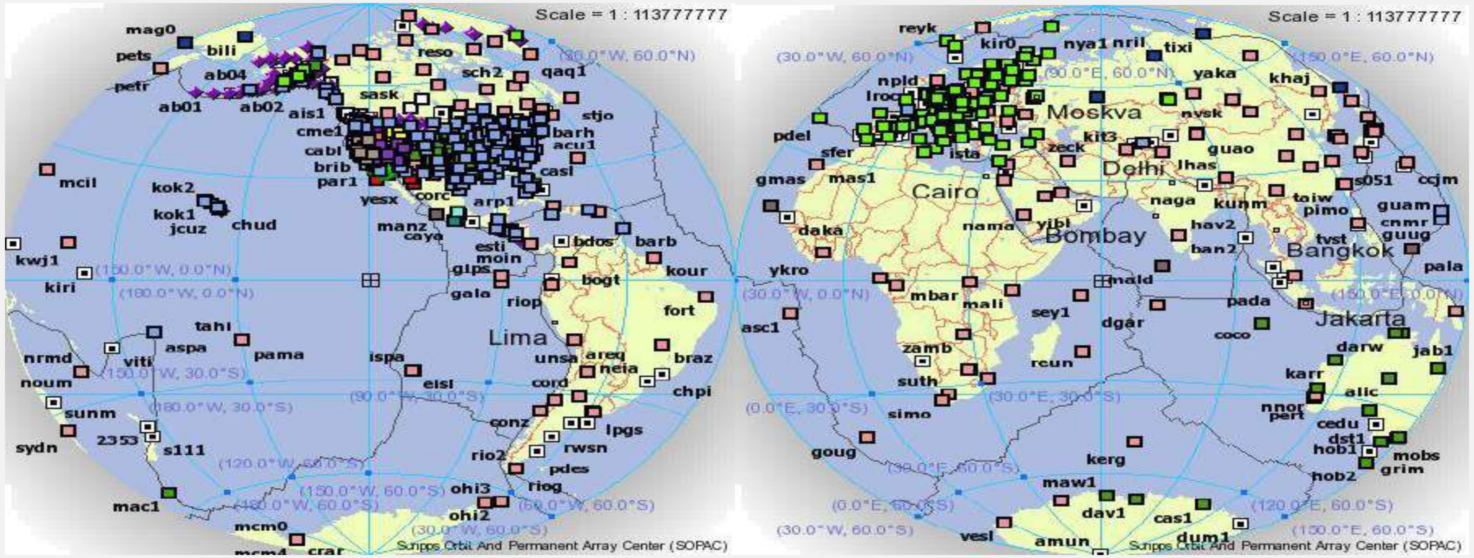
180° = 2.5 TECU

Essex and Watkins, 1973

TEC Measurements

- Use Ionospheric effects on radio wave propagation

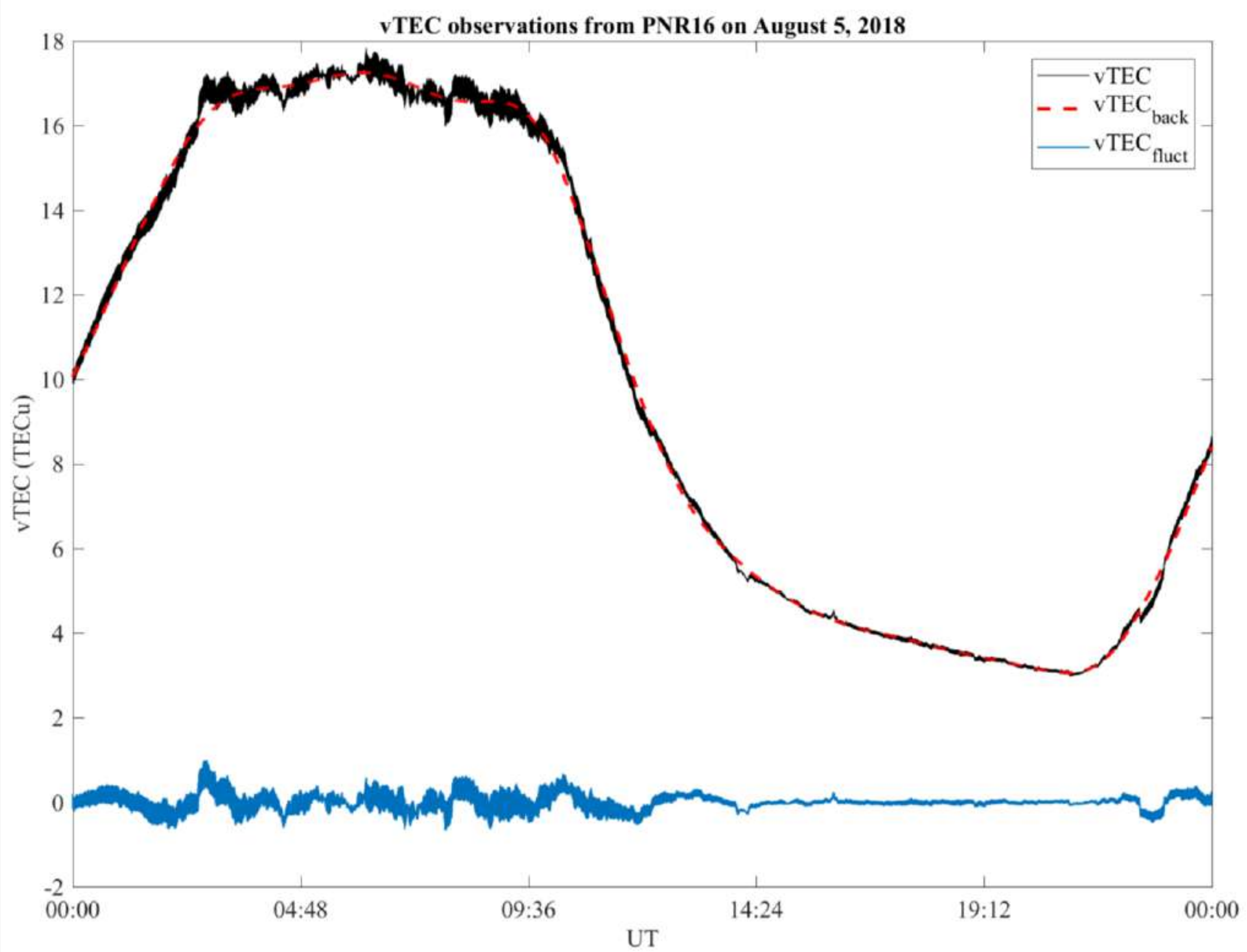
  - **Ionospheric effects on GPS signals**



SOPAC Online Map Interface (http://sopac.ucsd.edu/cgi-bin/smi)

– Time delay of signal
– Phase advance of carrier wave

August , 2018 – vTEC



- To derive both the background and the fluctuation we used a new data-analysis technique called **ALIF**.

A posteriori decomposition method useful for nonlinear and non-stationary datasets [Piersanti et al. 2017];

$$s(t) = \sum_{j=1}^{m} c_j(t) + r(t)$$

$c_j(t)$ is called Intrinsic Mode Component (IMC) and $r(t)$ is the residue of the decomposition;

Through the Hilbert Transform, it is possible to write:

$c_j(t) = A_j(t) \cdot \cos[\varphi_j(t)]$;

Instantaneous frequency can be derived as $\omega_j(t) = d\varphi_j(t)/dt$.

For each IMC, we can obtain a characteristic mean period as:

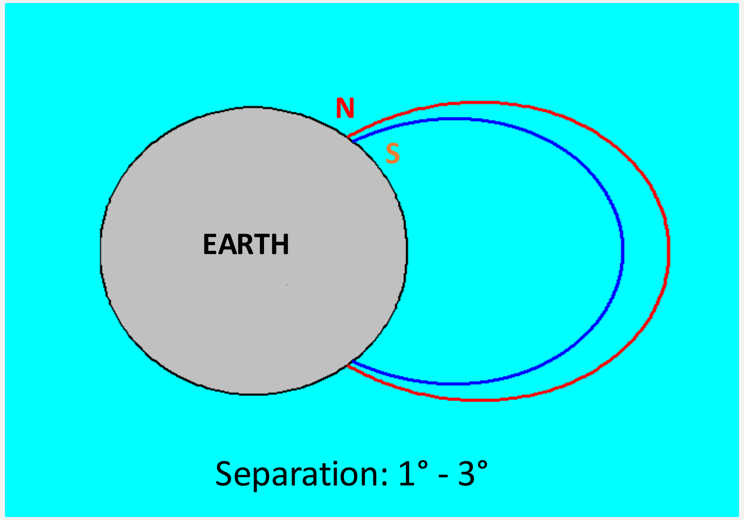
$T_j = \frac{2\pi}{\langle \omega_j(t) \rangle}$;

The set of *m* IMCs (or empirical modes) is local, complete and orthogonal in all practical sense.

For each IMF we evaluated the relative energy (Flandrin[1998]; Materassi et al., [2017]; Piersanti et al., [2018]) defined as:

$$\epsilon_{rel} = \frac{\int_s |IMF_k(t)|^2 dt}{\int_s |s(t)^2| dt}$$

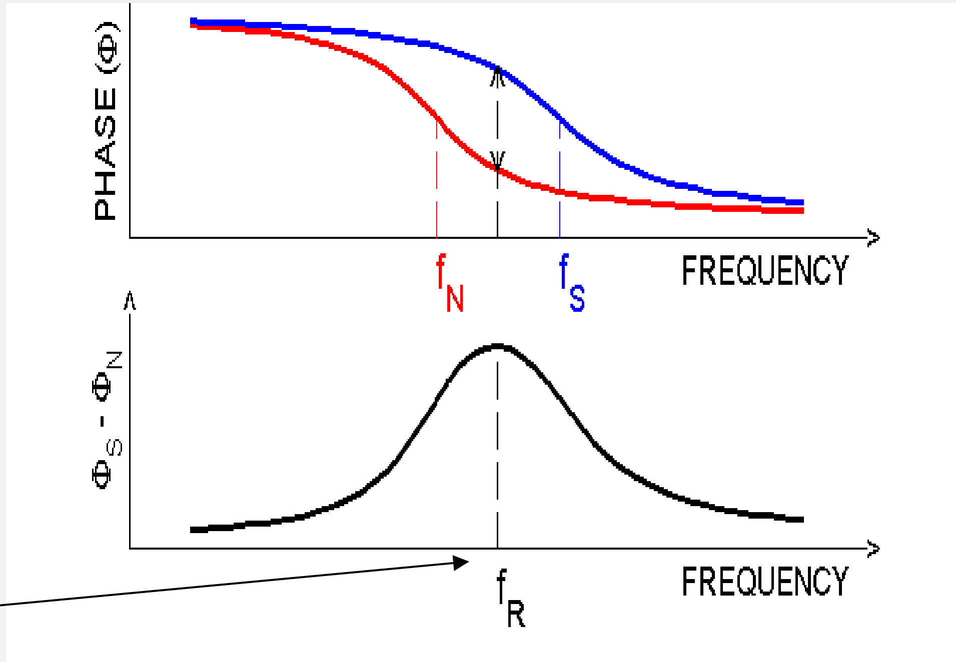
Gradient method for detecting FLR from ground-based ulf measurements



Higher latitude field line → Lower resonance frequency (f_N)

Lower latitude field line → Higher resonance frequency (f_S)

FREQUENCY RESPONSE OF TWO OSCILLATORS



CROSS-PHASE TECHNIQUE

Resonance frequency at the middle point.
Identified by a maximum in the phase difference

The LAIC model: Lithosphere -Atmosphere

$$\begin{cases} \frac{\partial \eta}{\partial t} = -\frac{\partial}{\partial x}[(H + \eta - \beta)u] \\ \frac{\partial u}{\partial t} = -\frac{\partial}{\partial x}\left(\frac{u^2}{2} + g\eta\right) \end{cases}$$

- $\eta(x,t)$ is the fluctuation amplitude and $u(x,t)$ is the horizonthal velocity
- H is the hight of the layer;
- β is the batimetry that can be easily extracted from the seismogram.
- Assuming $\beta(x,t) = \beta_0 f(x,t) w(t)$, *f(x,t)* being the contribution of the seismic surface waves and *w(t)* is the decay time of the seismic event.
- We modelled $w(t) = te^{-\alpha t^2}$, $\alpha^{-1/2}$ is the Strong Motion Duration (SMD) of the seismic event.
- $f(x,t) \sim e^{i(k_s x - \omega_s t)}$ describes a waveform where ${}^{\omega_s}/_{k_s} = v_s$ is the phase speed of Love or Reylaigh surface wave.

STEP 1

- A seismic event manifests itself through surface waves detected by seismograms, whose dispersion relation is described by Love-Reynolds.
- the dynamics of the upper part of the layer (ground) can be roughly described within the shallow water approach

The solution of the system 1 (via linearization) gives the surface perturbation at the first atmospheric layer H*, and the dispersion relation for the perturbation

The LAIC model – STEP 1 – AGW injection

$$
\begin{cases}
\dfrac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}) = 0 \\[2ex]
\rho \left\{ \dfrac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \boldsymbol{\nabla}) \boldsymbol{v} \right\} + \boldsymbol{\nabla} \mathrm{p} = \rho \boldsymbol{g} \\[2ex]
\boldsymbol{\nabla} p_0 = \rho_0 \boldsymbol{g} \\[2ex]
\rho_0 {c_s}^2 = \gamma p_0
\end{cases}
$$

We solved this sistem through a linearization process, obtaining the following equation for the pressure:

$$\boldsymbol{\frac{\partial^2 p}{\partial t^2} - {c_s}^2\, \nabla^2 p + A \cdot p = 0} \qquad \textbf{2)}$$

Where c_0 is the sound speed, $A = {}^{\gamma g^2}/_{c_0}$ and γ is the adiabatic index.

Putting $p = p_0 + \rho g \omega$ in 2), the condition for not-evanescent AGW propagating towards the ionosphere can be extracted, i.e. $\omega^2 > {}^{c^2{}_0}/_{4h^2}$ where $h = {}^{RT}/_{Mg}$ is the scale height of atmosphere and M=0.089 is the mean mass of one mol of atmospheric particles

STEP 1

- Once the fluctuations have been generated at H*, a pressure fluctuation is generated.
- We started from fluid equations propagating in a neutral atmosphere with gravity $\boldsymbol{g}$ to obtain the equation of the pressure propagation.
- It is needed because we have to perturbate the ionospheric plasma with a pressure gradient.

The LAIC model – STEP 2

$$
\begin{cases}
\dfrac{\partial \rho_m}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}) = 0 \\[2ex]
\rho_m \left\{ \dfrac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \boldsymbol{\nabla}) \boldsymbol{v} \right\} + \boldsymbol{\nabla} \left(p + \dfrac{B^2}{2\mu_0} \right) = \dfrac{(\boldsymbol{B} \cdot \boldsymbol{\nabla}) \boldsymbol{B}}{\mu_0} \\[2ex]
\boldsymbol{\nabla} \cdot \boldsymbol{B} = 0 \\[2ex]
\dfrac{\partial \boldsymbol{B}}{\partial t} = -\boldsymbol{\nabla} \times (\boldsymbol{v} \times \boldsymbol{B}) \\[2ex]
\rho_m \dfrac{d({\rho_m}^{\gamma}\, p)}{dt} = 0
\end{cases}
$$

STEP 2.

- We started from MHD equations related to a EM wave propagating through the ionosphere.
- It is needed because we need to know the k-ω relation of the EM wave couming out from the Ionosphere.

At now, we solved the system numerically imposing $\boldsymbol{p}$ as the solution of the wave equation in step 1.
Also in this case we used the linear approximation to solve the system obtaining an EM wave.
The dispersion relation of the solution gives a frequency band estimation: ***100 Hz < f < 400 Hz***

The LAIC model – STEP 3

$$\begin{cases} \dfrac{\partial^2 \boldsymbol{E}}{\partial t^2} = K^2 \nabla^2 \boldsymbol{E} \\ K = \dfrac{B}{\sqrt{\mu_0 \rho}} \\ \boldsymbol{B} = -\dfrac{i}{\omega} \boldsymbol{\nabla} \times \boldsymbol{E} \end{cases}$$

1. We linearized and considered a stationary condition (string).
2. We rotated into field aligned coordinate system

$$\frac{\partial^2 \xi}{\partial x^2} + p(x) \frac{\partial \xi}{\partial x} + \lambda \left[\frac{V_a(eq)}{V_a(x)} \right]^2 \xi = 0$$

STEP 3.

- We started from MHD equations related to stationary EM wave (FLR theory) to obtain the equation ruling the magnetospheric field line eigen-frequency.
- It is needed to evaluate the variation of the FLR eigen-frequency under an EM wave perturbation.

where ξ is proportional to the electric field and x is the curvilinear coordinate moving along the field line.

ω * is proportional to λ: $\omega^* = \dfrac{B_0^2}{\mu_0 \rho_0} \cdot \dfrac{\lambda^{1/2}}{l}$, where *l* is the length of the field line.

What garantee would all these observations be caused by other sources than the EQ?

Despite the event described above fits very well with the model here presented, many issues are still opened and need a careful inspection.

We need to exclude that atmospheric weather and space weather did not invalidate our analysis….

Discussion – Weather Reports

1. **The direct association of AGWs to an EQ phenomena is not trivial.**

- AGW are generally induced by weather systems, by synoptic-scale atmospheric systems and circulations and so on;
- At middle and low latitudes AGWs are meteorologically excited by convective activities around the cold fronts;
- We examined the weather reports (https://www.accuweather.com/) for the August 5, 2018 and we found:
  - a tropical cyclone passing the Indonesia around the 12:00 UT, whose cold fronts was located over the Brunei region (far from the EE).
  - In addition, a thunderstorms occurred over EQ epicenter on 7 and 12 August.

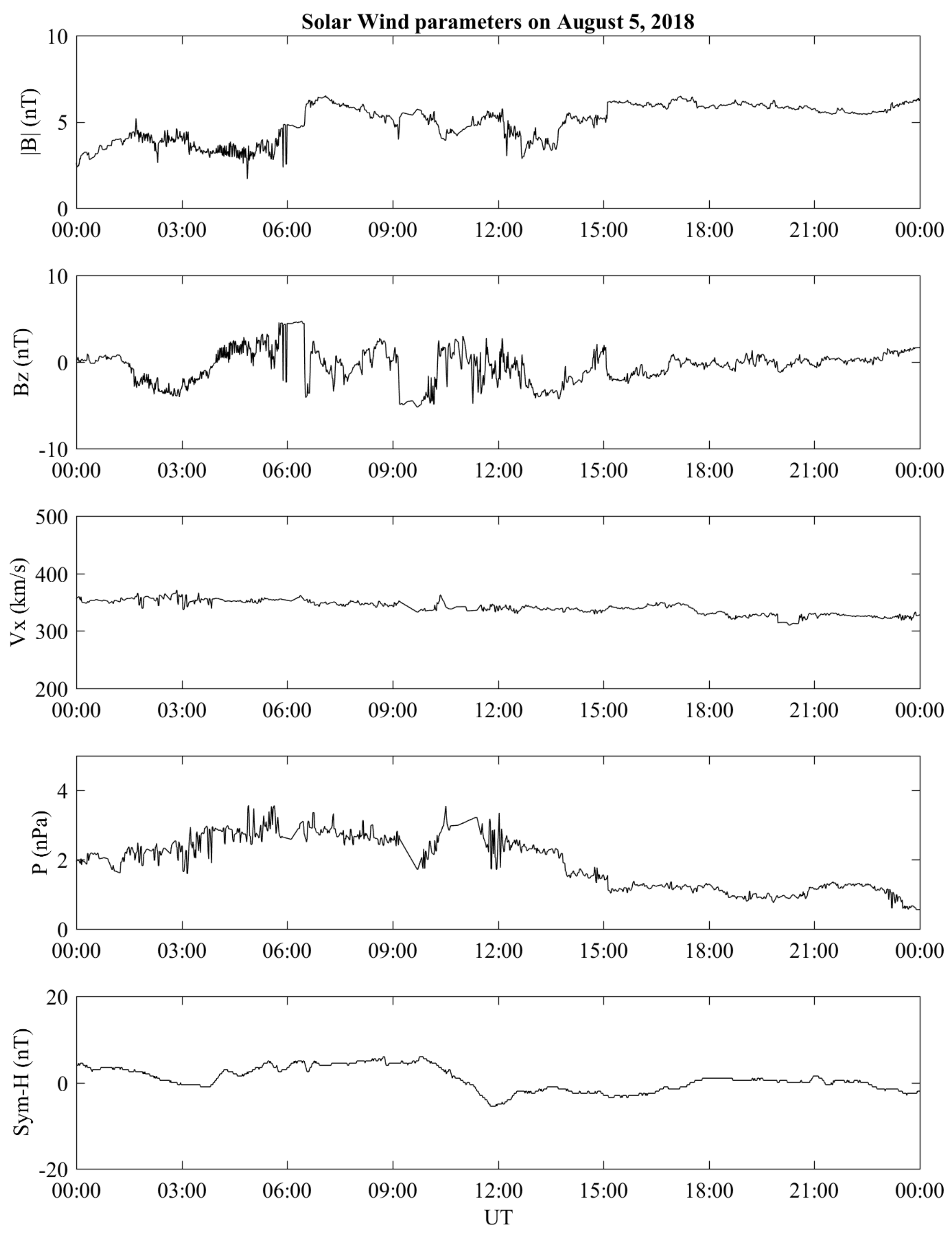
- **So, we are confident that both the AGWs detected at 6:00 UT and at 12:00 UT can be associated to the seismic activity.**

Discussion – Space Weather

- **Discrimination between ionospheric plasma density variations induced by internal and external origin sources is crucial**
- In general, both vTEC and plasma density irregularities are directly driven by the solar activity…
- The solar wind (SW) parameters and the geomagnetic indices (i.e., Sym-H) confirms that the August 5, 2018 was a super-solar quiet day;
  - ➢ Absence of any structure coming from the Sun;
  - ➢ Low geomagnetic activity (Sym-H = [-5 nT ; 6 nT])

vTEC variations observed are not driven by the Sun and can be reasonably associated to the earthquake activity.

FLR frequency variation and the EM activity detected by CSES-01 satellite are linked to the seismic activity.



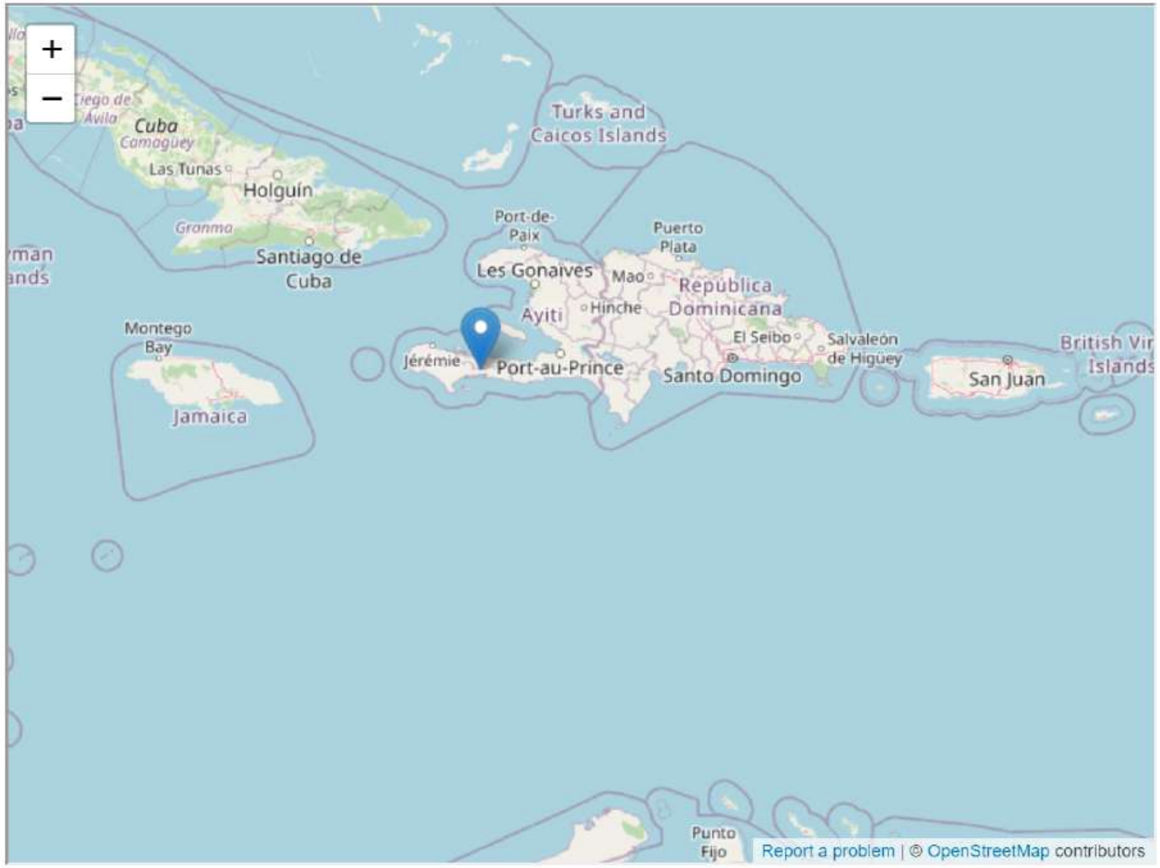
The Haiti Earthquake

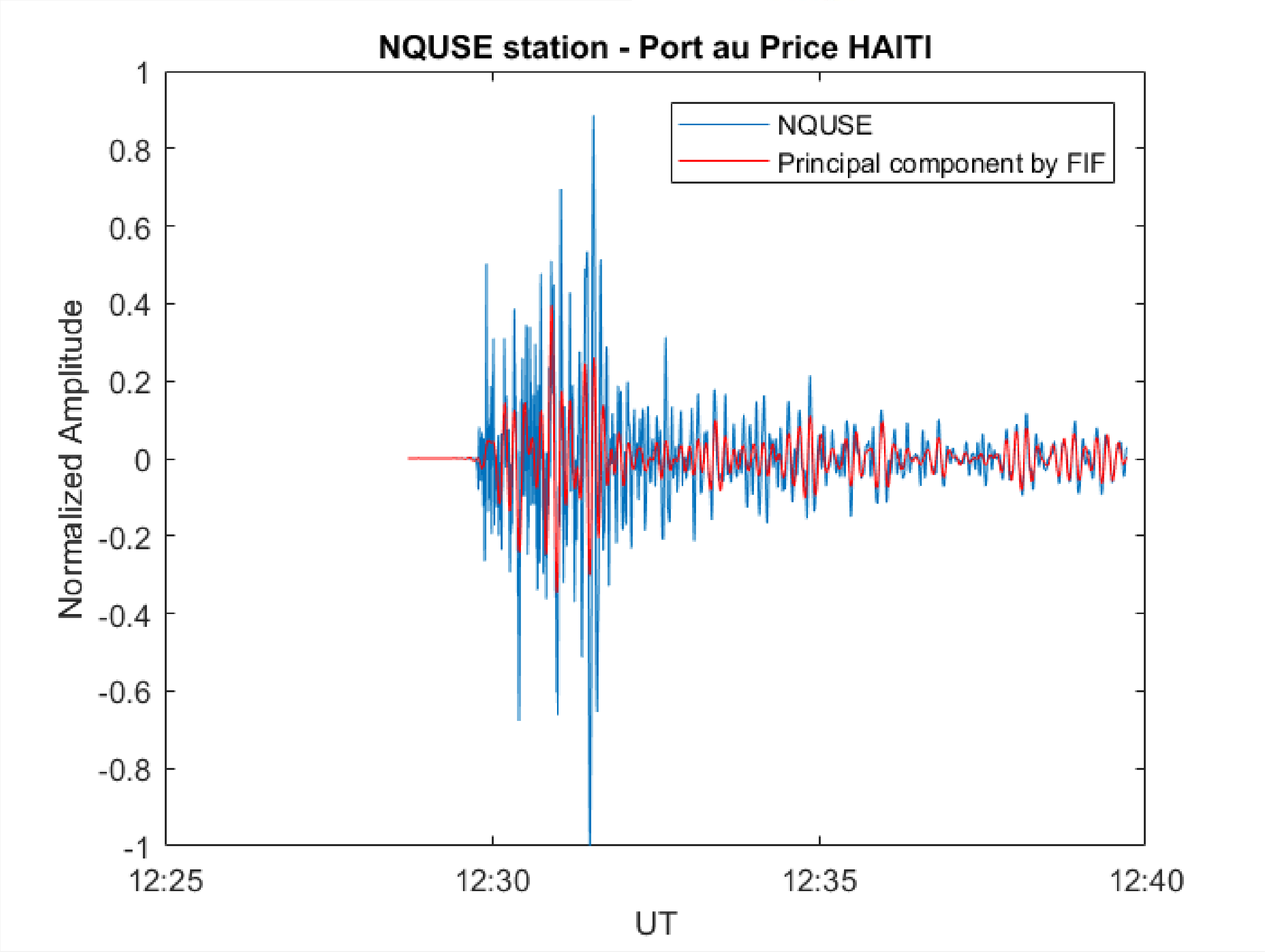
Terremoto di magnitudo **Mwpd 7.5** del 14-08-2021 ore 14:29:10 (Italia) in zona: **Haiti region [Land: Haiti]**

Dati Evento | Sismicità e Pericolosità | Impatto | Localizzazioni e Magnitudo | Meccanismo di sorgente sismica | Download

Un terremoto di magnitudo **Mwpd 7.5** è avvenuto nella zona: **Haiti region [Land: Haiti]**, il

- 14-08-2021 12:29:10 (UTC) 7 mesi fa
- **14-08-2021 14:29:10 (UTC +02:00) ora italiana**
- 14-08-2021 08:29:10 (UTC -04:00) orario locale nella zona del terremoto (America/Port-au-Prince)





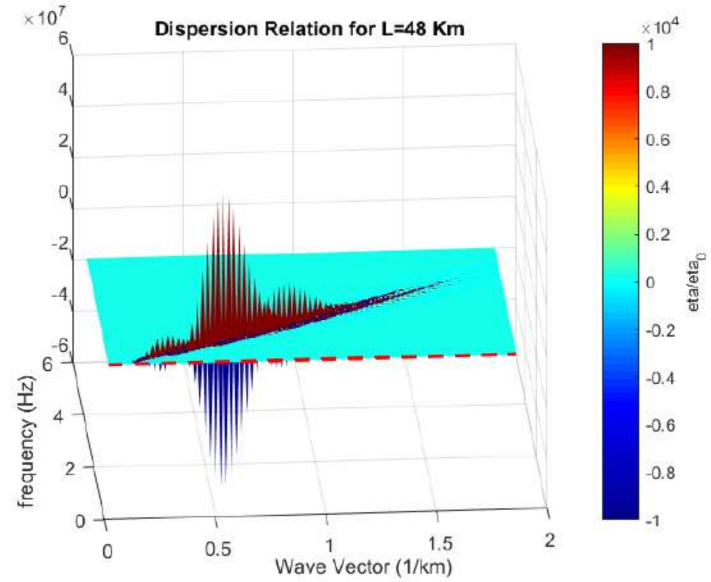
- August 14th, 2021
- Mw= 7.5;
- λ=18.32 °N φ= -73.458 °E;
- UT=12:29:10.

The MILC model

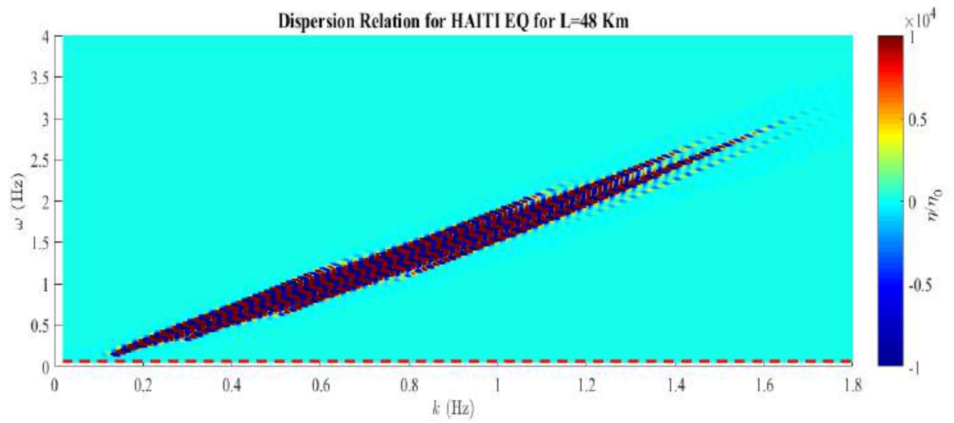
To confirm the seismic origin of the observed AGW we compared observation with MILC model predictions

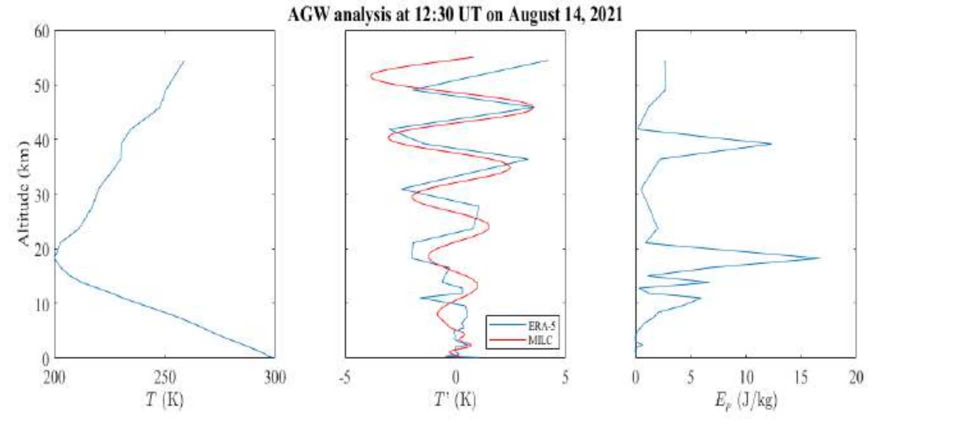
- If the principal characteristics of an earthquake are known, the AGW propagation can be easily predicted.
- What we need is:

1. L: length of the fault;
2. ω_S: decay time of the seismic event;
3. β_0: the Peak Ground Acceleration;
4. α: the time duration of the seismic event;
5. v_s: ground speed of the earthquake;



Dispersion Relation evaluated for the Haiti Earthquake using the parameters in the Table below (USGS website). The dashed line represents the parameter c0/2h (ω=0.2).





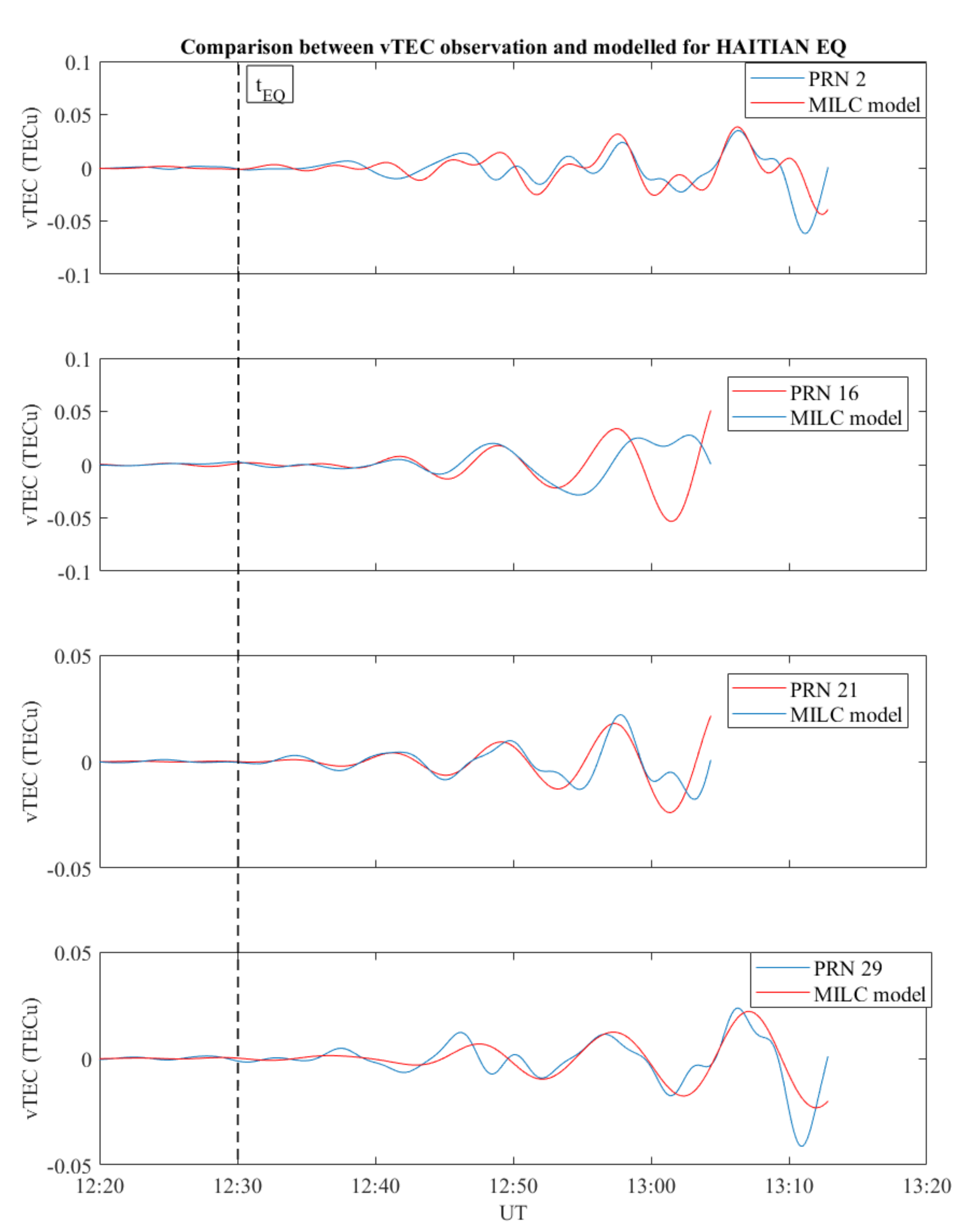
Temperature fluctuations predicted by MILC agree very well with the observations (RMSE = 0.8 K ϱ_{corr} = 0.86). In addition, the χ2 test gives 47.3, suggesting that our model is able to reproduce the observations with 85% probability.

EQ	M	L (km)	ω_S (Hz)	PGA (g)	α (1/s^2)	v_s (m/s)
Haiti	7.5	48	0.041	0.78	0.0043	1,8 10^3

In case of the Haiti Earthquake, the dispersion relation confirms the injection of AGW propagating till the ionosphere with periods between 5 and 9 min.

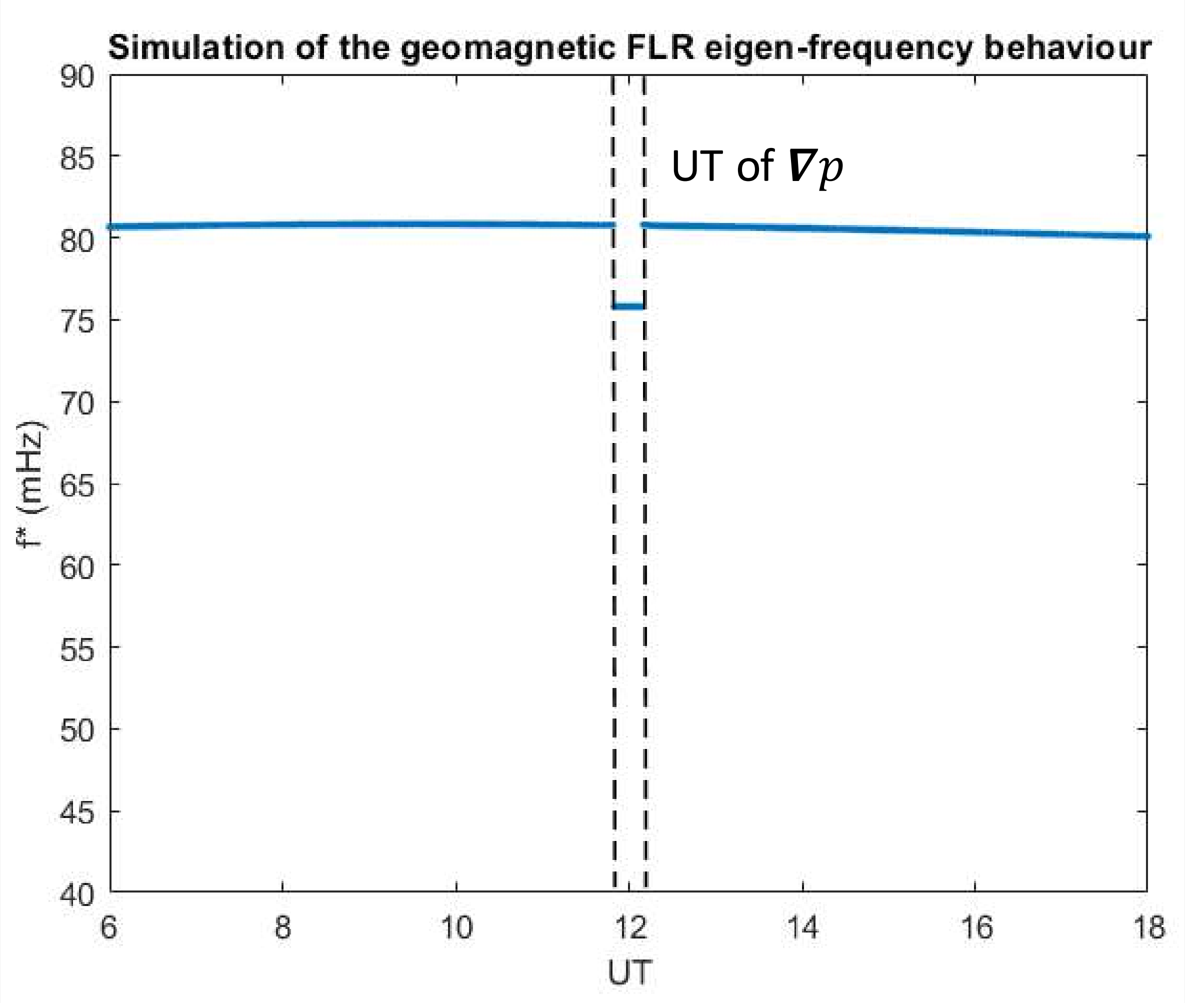
TID – MILC model results

- The MILC model expects a plasma wave (TID) caused by the AGW injected by the EQ;
- The comparison between the observations and the model results is very good;
- **The χ2 test gives a 87% probability of our model to reproduce the observed signal.**



FLR – MILC model results

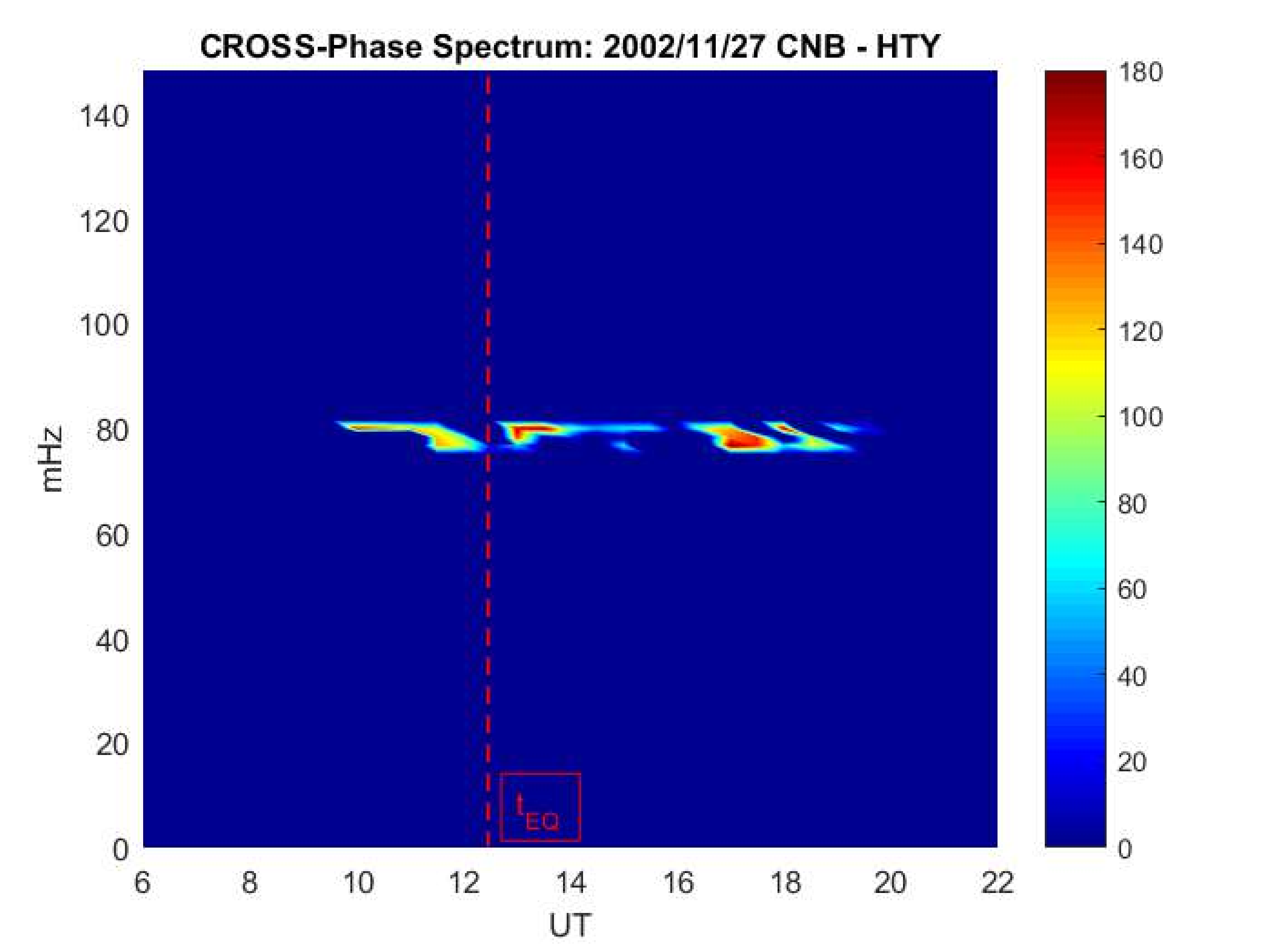
- The result of the modeled **eigen-frequency** variation of a field line footprinted at λ=20°, under the assumption of real Earth's magnetic field, associated to a pressure gradient driven by the Haitian earthquake is reported in right figure.



A clear decrease of ω is visible in coincidence to the pressure gradient (∇p) driven by the AGW injected by the earthquake.

FLR evaluation over the EQ location

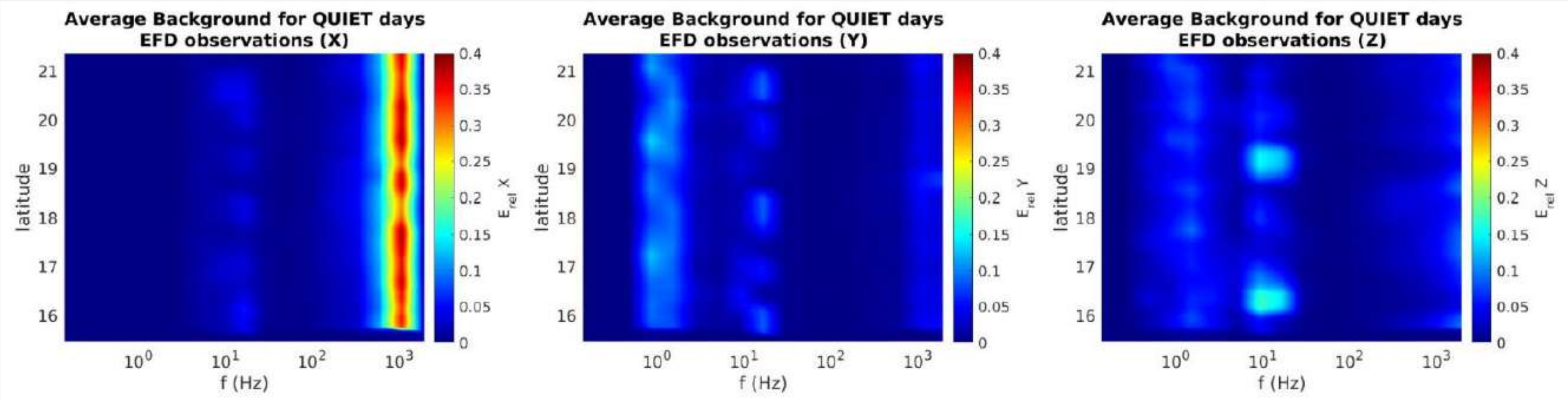
- As expected, the eigen-frequency ***(f)*** is around 80 mHz (close equatorial station).
- A clear decrease of the eigenfrequency detected at the moment of the EQ occurrence.
- df=7 ± 2 mHz;
- dt=32 ± 6 mins;

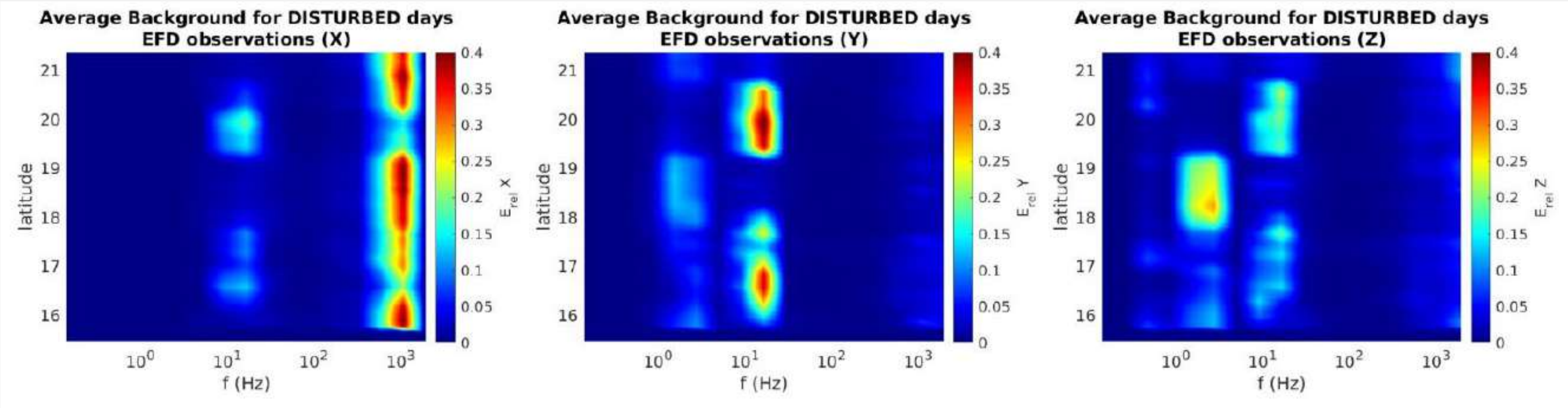


CSES Observations

Quiet and disturbed spectra reveal activity in the same frequency band. Not surprisingly, the energetic content of the disturbed is higher.

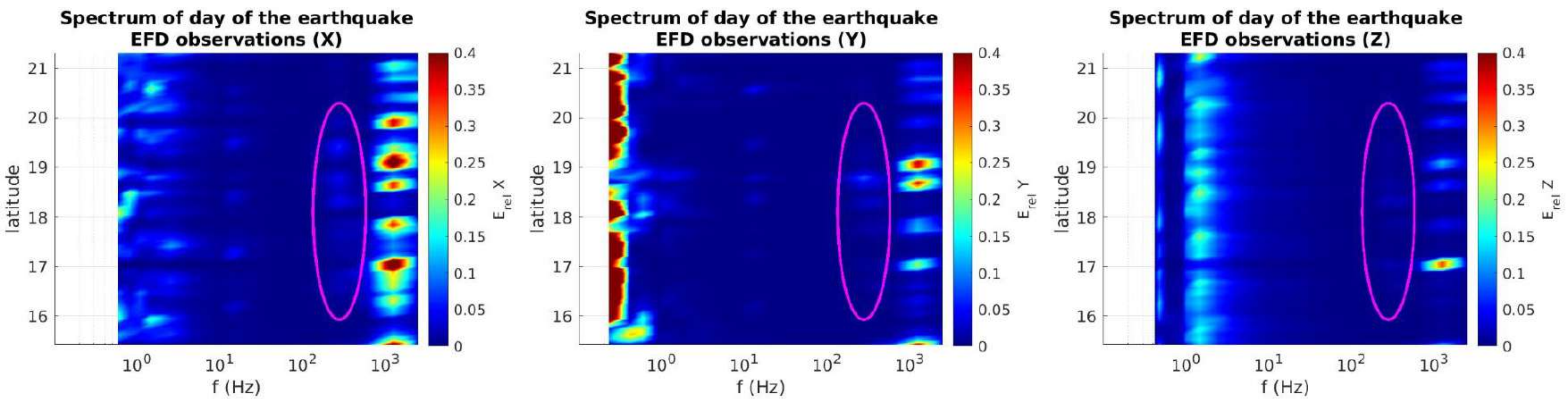
- **$\approx 2\,Hz$ (3 components): due to the $\boldsymbol{v} \times \boldsymbol{B}$ electric field present in the ELF band, caused by satellite's motion into a magnetic field**
- **≈ 8 and $\approx 15\,Hz$ (3 components): first and second Schumann ionospheric resonance at CSES orbit**
- **$\approx 1\,kHz$ (E_x): signature of the plasmaspheric hiss.**





Example: August 14, 2021 Haiti

CSES fly over the EE ≈6 hours before the earthquake



Anomalous signal with respect to the background is detected at ≈ 280 *Hz* along all the 3 components

Discussion

1. The observational scenario can be explained in terms of the M.I.L.C. model

- According to MILC model, the Haitian EQ will excite AGW in the frequency range 3 mHz $< \omega <$ 50 mHz and wavevectors 600 m $< k <$ 3000 m.
- **The previsions completely agree with the observed AGWs before and during the EQ occurrence.**

- The frequency range expected by MILC model applied to this EQ for the EM waves propagating from the Ionosphere is [100 – 400] Hz. In addition the MILC model expected a plasma wave in with frequency in the range 3 mHz $< \omega p <$ 7 mHz.
- **Previsions agree with the observed EM wave detected by CSES satellite and TID pbserved with GNSS.**

- MILC model expected to observe a FLR frequency decrease.
- **Previsions agrees with the observed FLR frequency behaviour**

- Again, this appear as a diurnal phenomenon.

- A possible pre-seismic behaviour is present. It is less clear than the Marche.

- However, the Marche cell was a ”lucky” one, because we have an high density of observations. Could this be essential to correctly see the pre-seismic behaviour?