The GNSS - TEC analysis of the paroxysmal eruptive activity of Mt. Etna

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The ionosphere

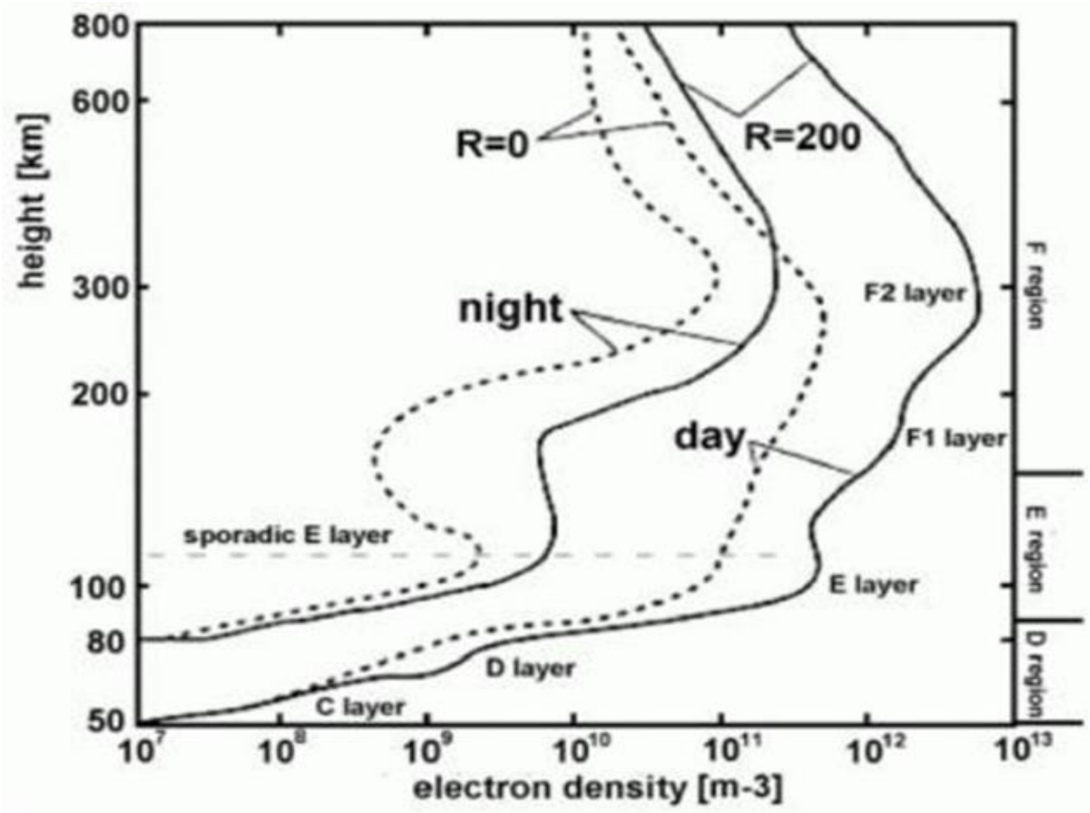


Figure from INGV

- 50 – 1000 km of altitude (mesosphere – termosphere – esosphere)
- **Plasma** composed by free electrons and ions (UV, X solar and cosmic radiations)
- Electron density influenced by solar activity (R) and daytime
- **Dispersive medium** for the GNSS signal

The Total Electron Content (TEC)

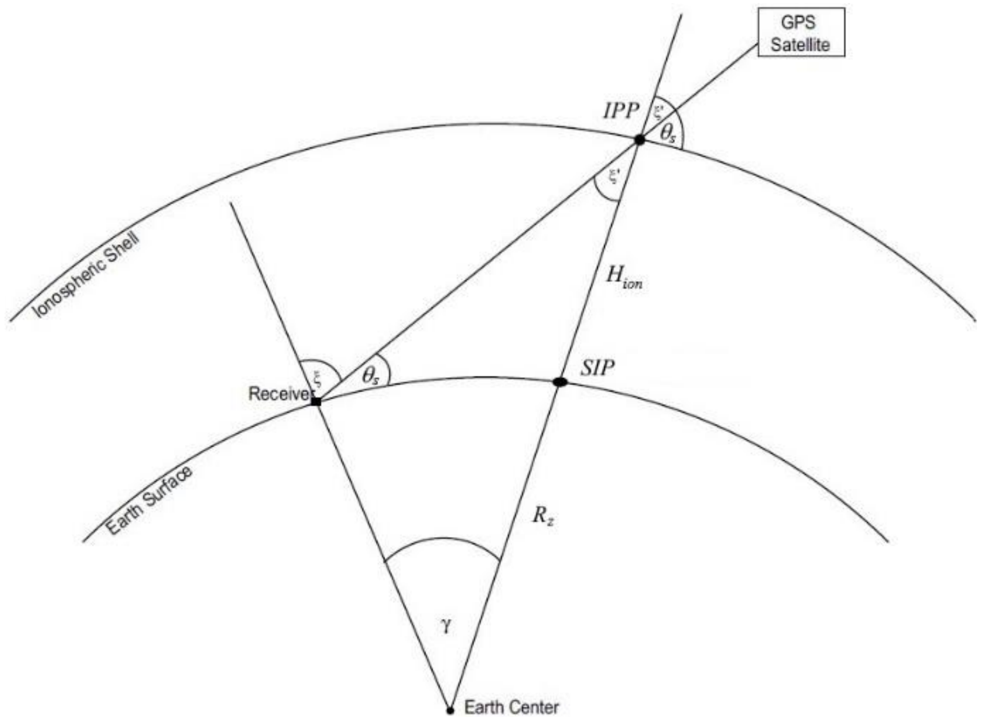


Figure adapted from Dautermann & Calais, 2008

- Integral of the number of electrons along the satellite – receiver line of sight for a **referee ionospheric height H_{ion}** (ionospheric shell)
- 1 TECu (TEC unit) = $1 \cdot 10^{16}$ e^-/m^2
- H_{ion} ~ 300 km of altitude
- IPP (Ionospheric Pierce Point)
- SIP (Sub-ionospheric Pierce Point)
- θ (satellite elevation angle)

Co-Volcanic Ionospheric Disturbances (CVIDs)

Ionospheric electron density oscillations caused by **Acoustic-Gravity Waves** (AGW) propagation from volcanic eruptions

TEC peaks proportional to **VEI (Volcanic Explosivity Index)**

- Velocity ~ 550 - 1200 m/s (AGW – AW – Shock AW)
- T period ~ 12 – 30 min.
- First arrival time to H_{ion} about 10 to 45 min

Acoustic waves: 2 – 10 mHz

Gravity waves: 0.1 – 2 mHz

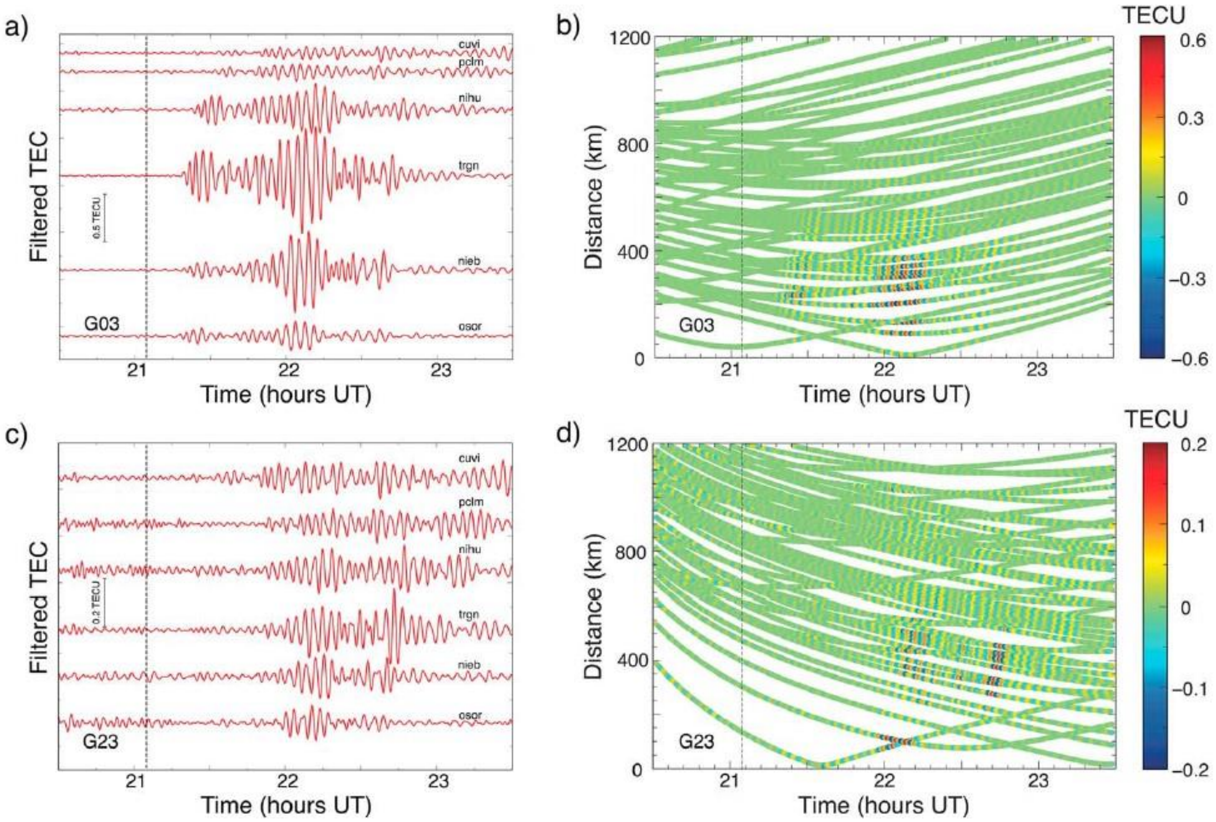
⬇

Upward amplification

⬇

Ionospheric disturbances detectable by GNSS Ionospheric Sounding

Figure adapted from Occhipinti, 2015



Shults et al., 2015

The VARION algorithm

Variometric Approach for Real-time Ionosphere ObservatioN

$$L_{4R}^{S}(t+1) - L_{4R}^{S}(t) = \frac{f_{L1}^{2} - f_{L2}^{2}}{f_{L2}^{2}} \left[I_{1R}^{S}(t+1) - I_{1R}^{S}(t) \right]$$

Single time difference of **geometry-free combinations** of GNSS carrier-phase measurements

- f_1, f_2 (carrier frequencies)
- I (ionospheric delay)

↓

$$\delta sTEC(t+1, t) = \frac{f_L 1^2 f_{L2}^2}{A\left(f_{L1}^2 - f_{L2}^2\right)} \left[L_{4R}^{S}(t+1) - L_{4R}^{S}(t) \right]$$

TEC variation between two epochs

- A (ionospheric constant)

↓

$$\Delta TEC(t_f, t_0) = \int_{t_0}^{t_f} \delta TEC(t)$$

TEC variation over a chosen time range

Ravanelli et al., 2021

Etna – 4 December 2015 (I episode)

Large Scale Lava Fountain (LSLF) eruptive style

- very high, dense eruptive column
- abundant coarse-grained tephra fallout up to the lower slopes
- ash dispersal up to hundreds of kilometeres

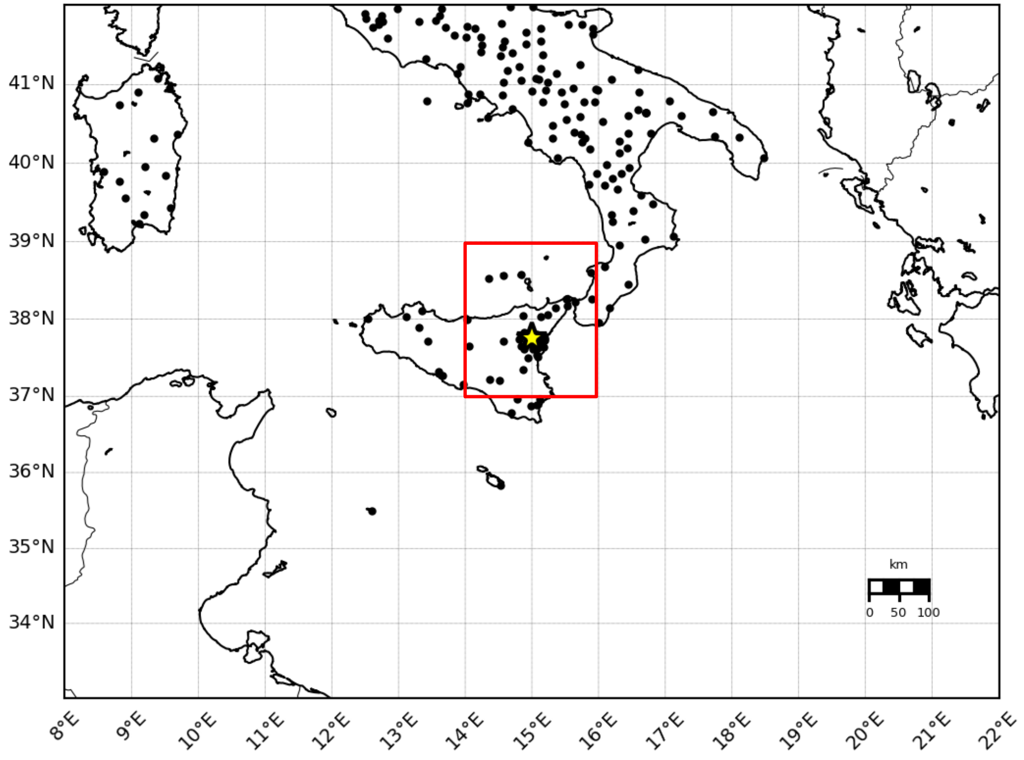
Andronico et al., 2021

Data from Calvari et al. (2018) and from courtesy of Scollo & Mereu***

Crater	Start seismo-acoustic activity (UTC)	End seismo-acoustic activity (UTC)	Mean wind velocity (m/s) **	Mean height fountain (m) *	Max height fountain (m) *	Plume height (km) **	Pyroclastic volume (m^3) *	Max Q_m (kg/s) **	Max RMS_seismic (m/s)	Max RMS_infrasound (Pa)
Voragine	*08:40*	*11:00*	*7.5*	*1264*	*2600*	*13.1*	*2760000*	$1.62 \cdot 10^{6}$	$5.54 \cdot 10^{-5}$	*13.78*

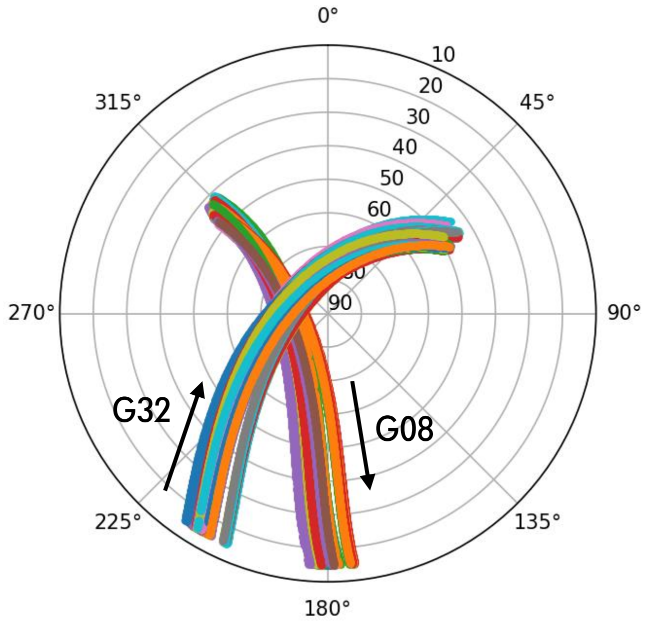
Dataset

RINEX (Receiver INdependent EXchange format) data at 30 s



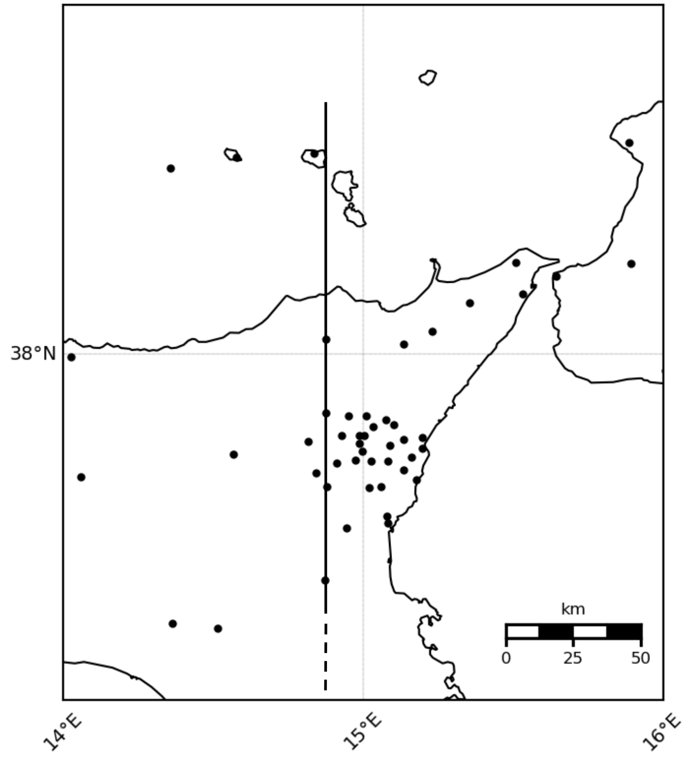
197 receivers

- 28 INGV-OE (GPS)
- 16 ASI (Euref net - GNSS)
- 54 Topcon (GNSS)
- 99 RING (GNSS)



G08 – G32

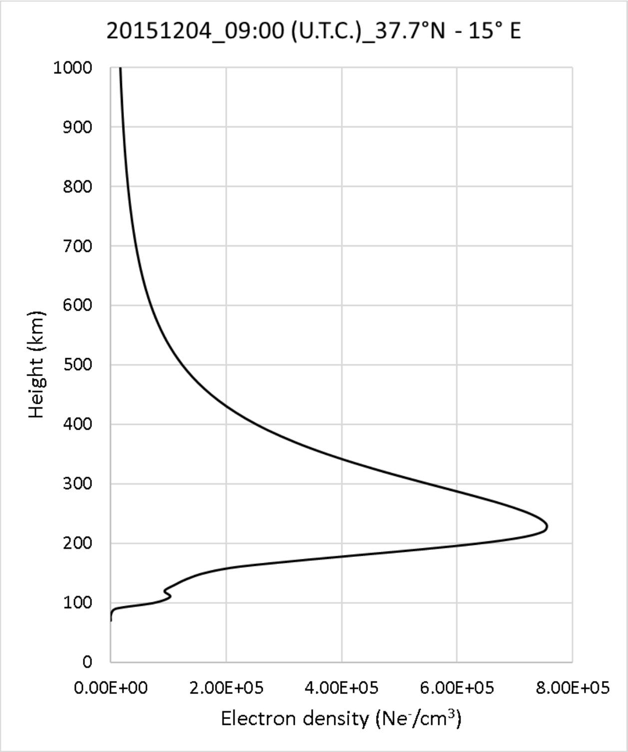
Ionospheric Sounding



North - South profile

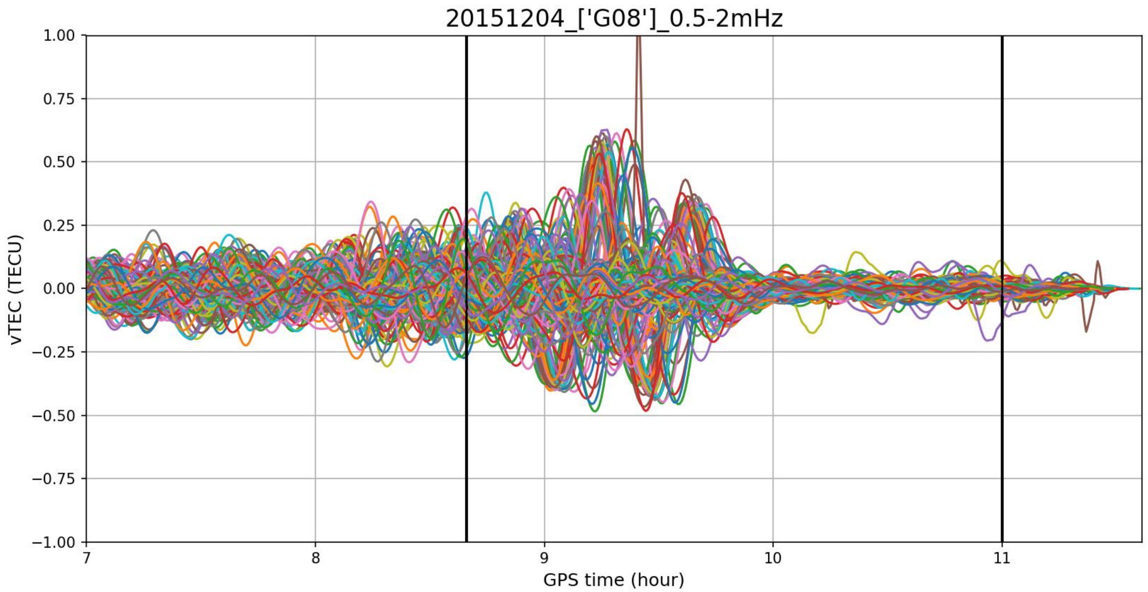
TEC time series

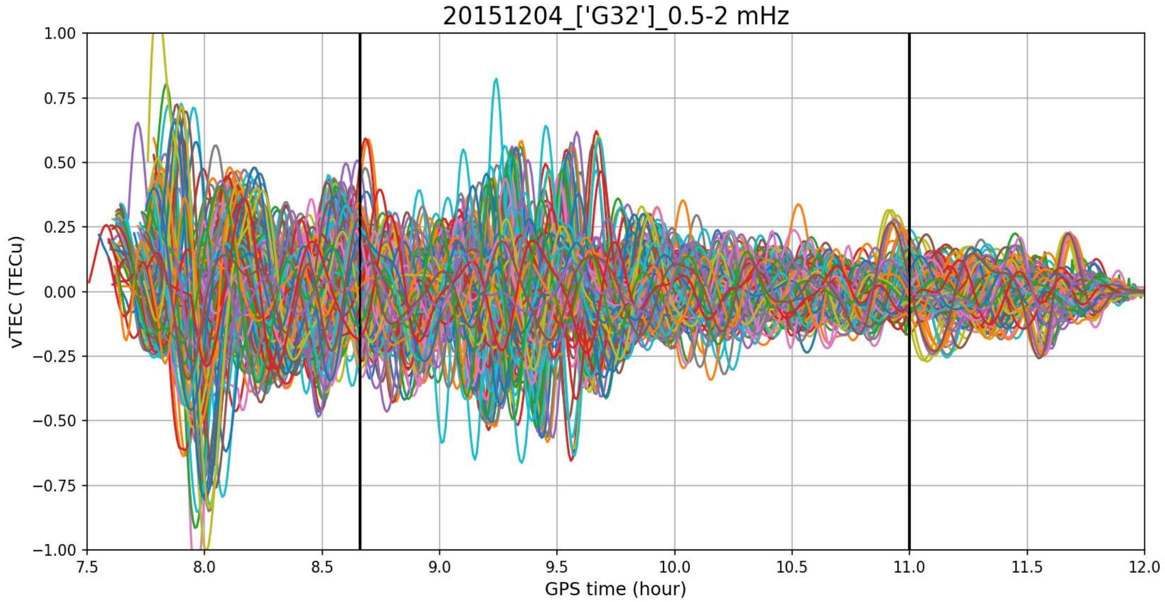
TEC peaks about **0.5 TECu** in 0.5 – 2 mHz frequency range



H_{ion} = 230 km s.l.m.

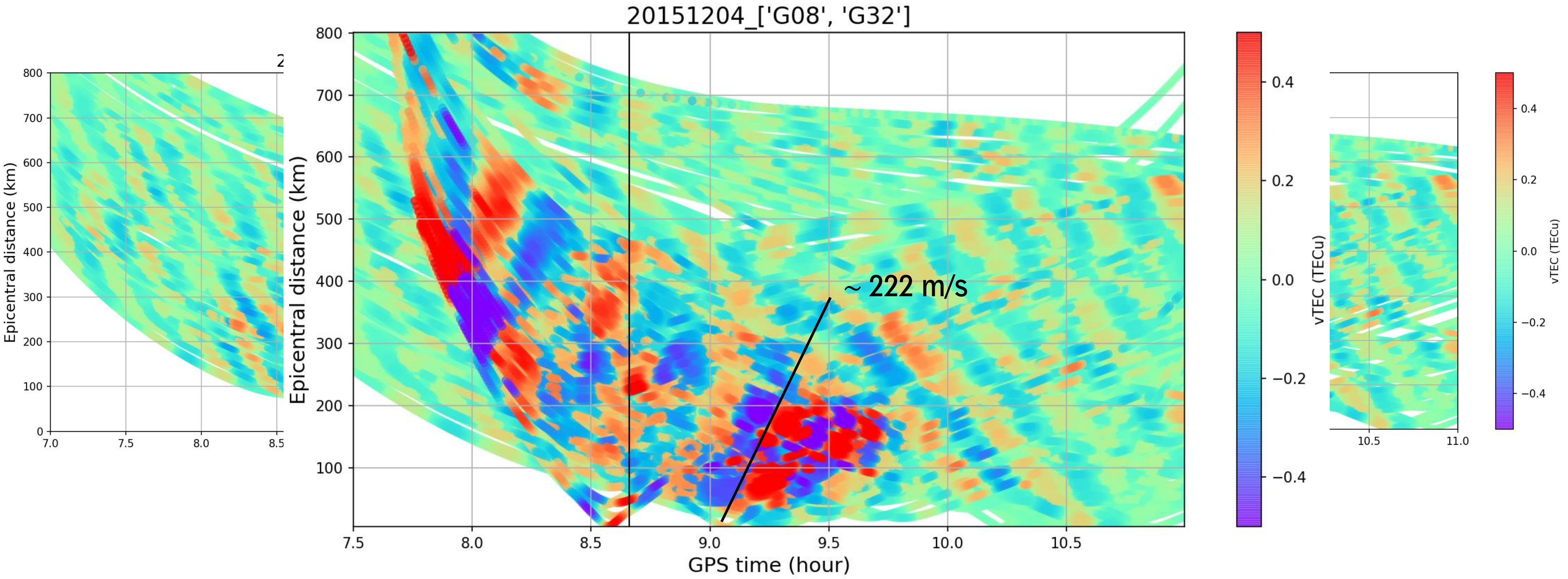
Data from IRI 2016





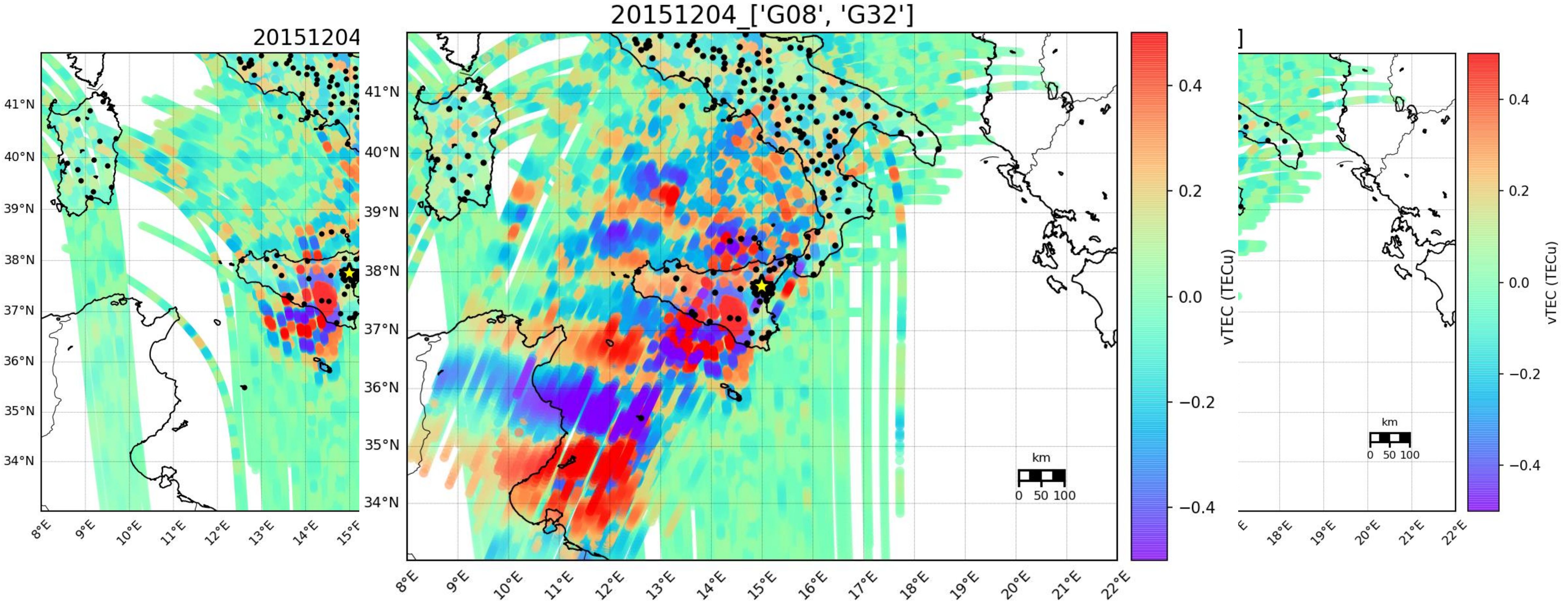
Hodochrones

Apparent horizontal velocity at about 222 m/s



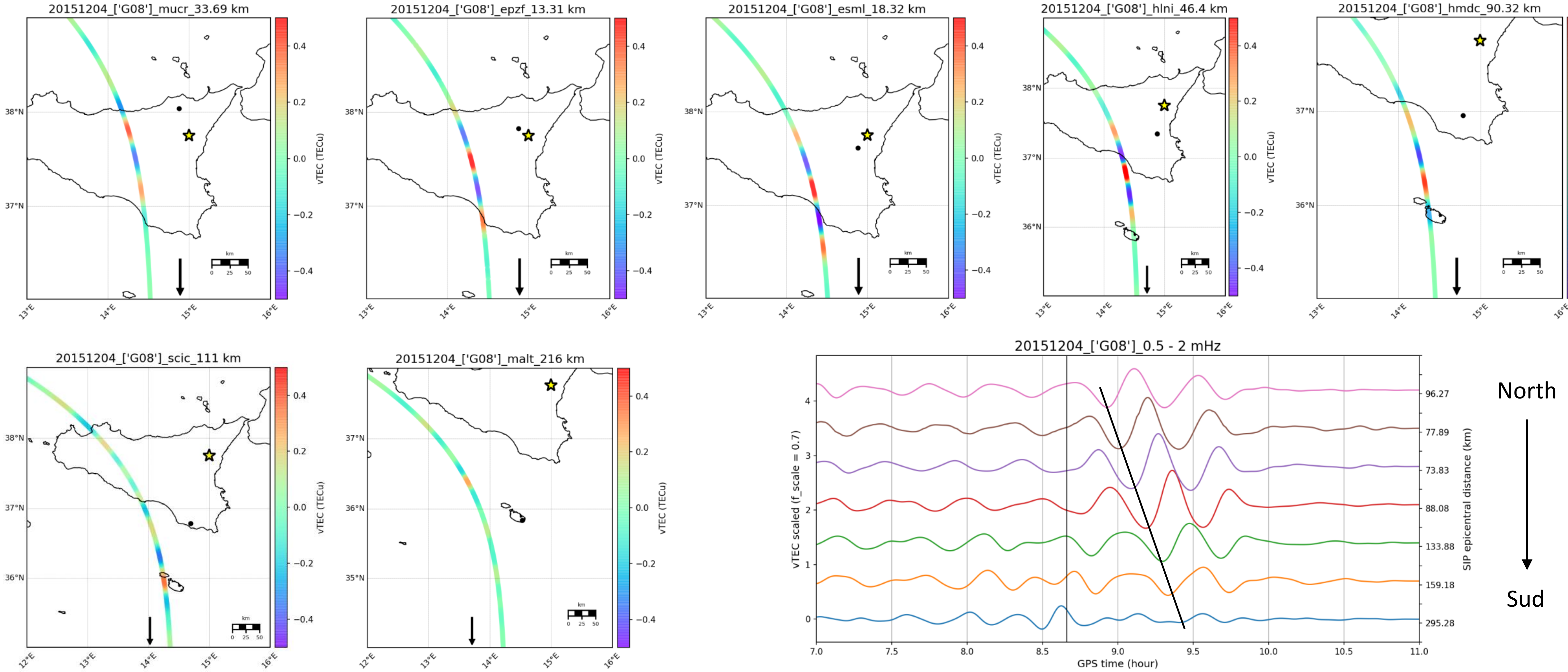
SIP maps

Local vTEC anomalies (0.5 – 2mHz) in the South near field, up to about 200 km from Etna



G08 - SIP trajectories and wave forms

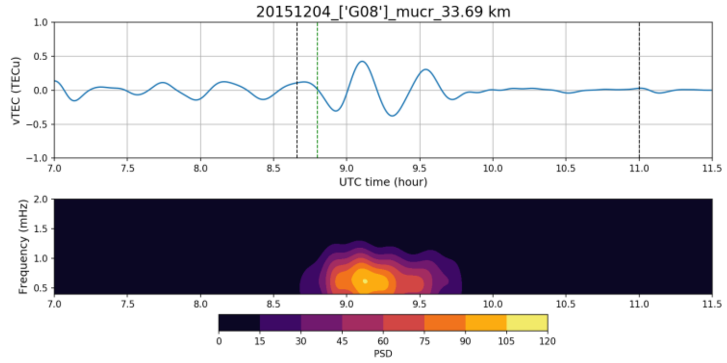
Wave propagation southward for about 30 minutes

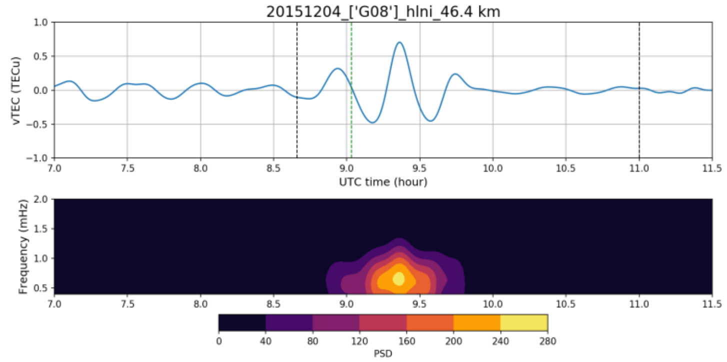


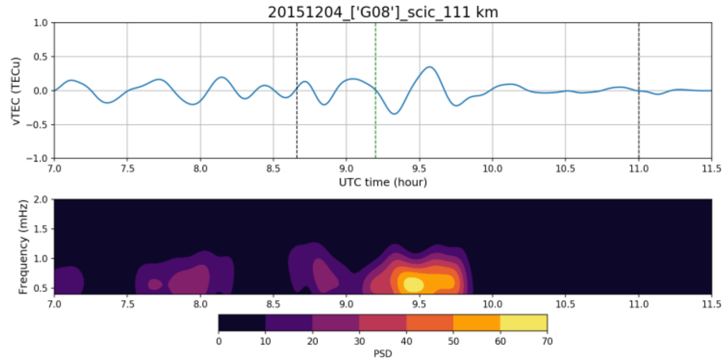
G08 - spectrograms and frequency peaks

Stable frequency content at **0.6 mHz** for vTEC peaks

Station	Picking time (U.T.C.)	SIP epi_distance (km)	vTEC peak (TECu)	Peak frequency (mHz)	PSD peak
MUCR	*08:47:55*	*96.27*	*0.43*	*0.61*	*156.46*
EPZF	*08:53:00*	*77.9*	*0.62*	*0.66*	*192.67*
ESML	*08:56:30*	*73.84*	*0.68*	*0.64*	*226.63*
HLNI	*09:02:04*	*88.09*	*0.7*	*0.66*	*250.04*
HMDC	*09:09:00*	*133.88*	*0.43*	*0.61*	*118.49*
SCIC	*09:12:00*	*159.19*	*0.35*	*0.55*	*66.28*
MALT	*09:28:56*	*294*	*0.12*	*0.67*	*7.38*







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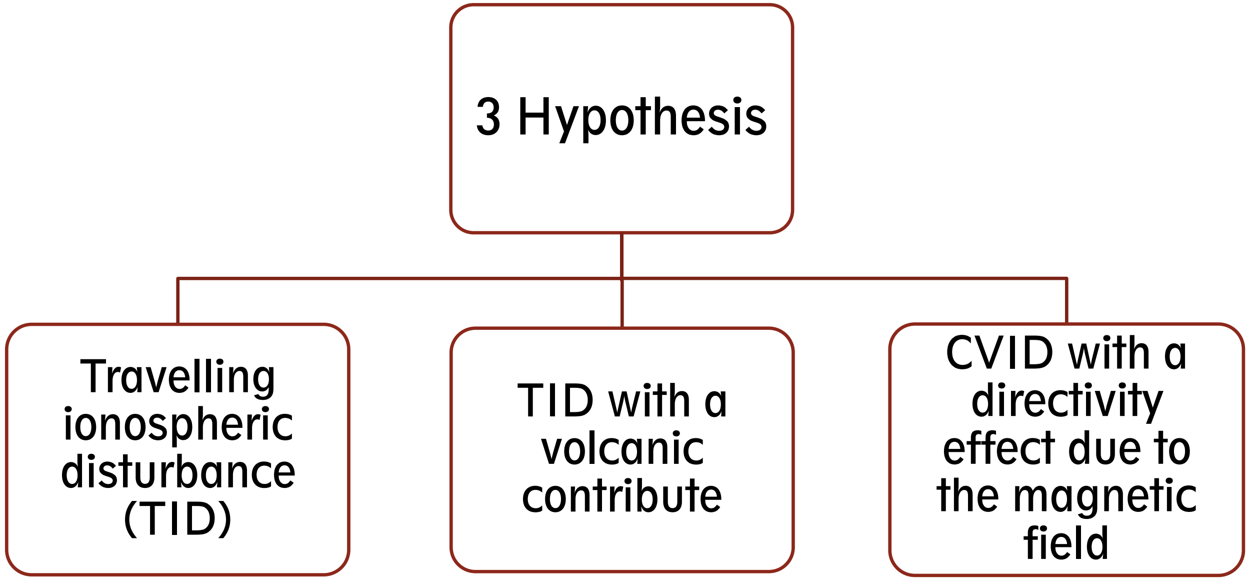
Conclusions and outlook

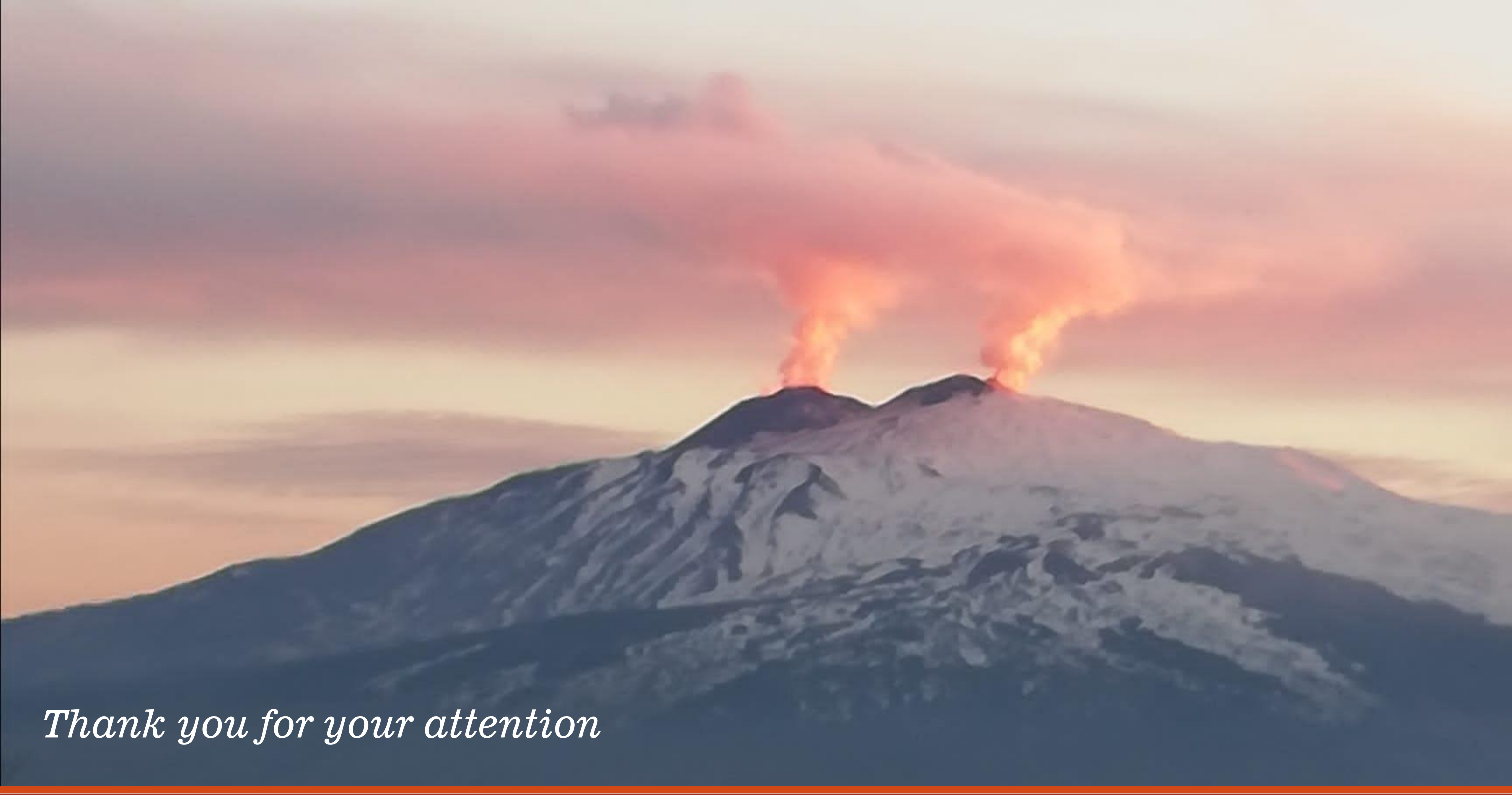
Conclusions:

- **Gravity waves propagation** with most frequency content at 0.6 mHz
- **Directivity** of the vTEC peak towards South-West principally



Outlook:

- Source characterization
- Constellation satellite geometric features
- Directivity effects by geomagnetic field
- Other Etna paroxysmal activities data
- Other ionospheric data
- **Time relation source – ionosphere**



Thank you for your attention

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