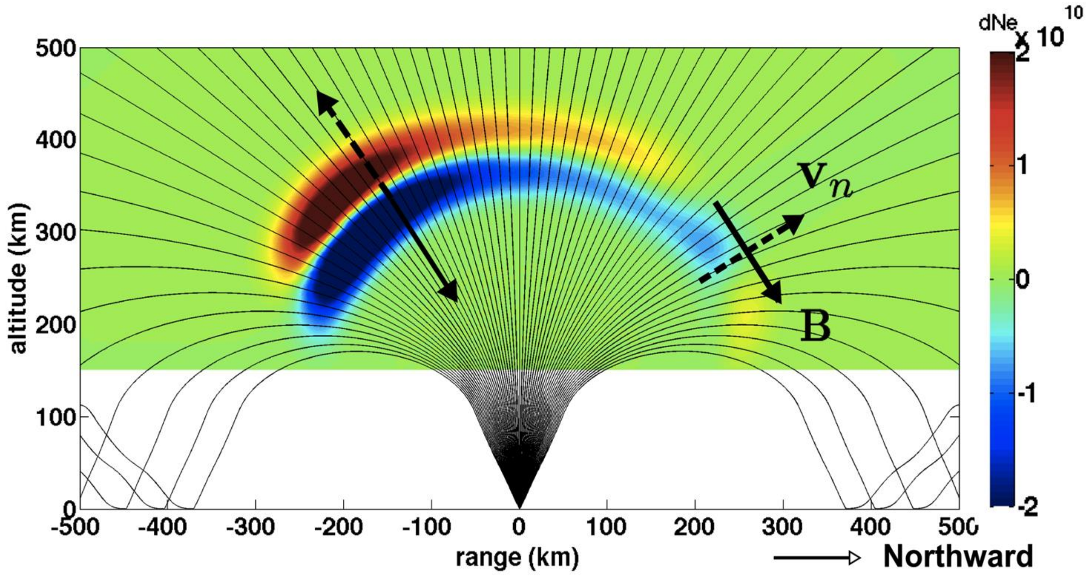
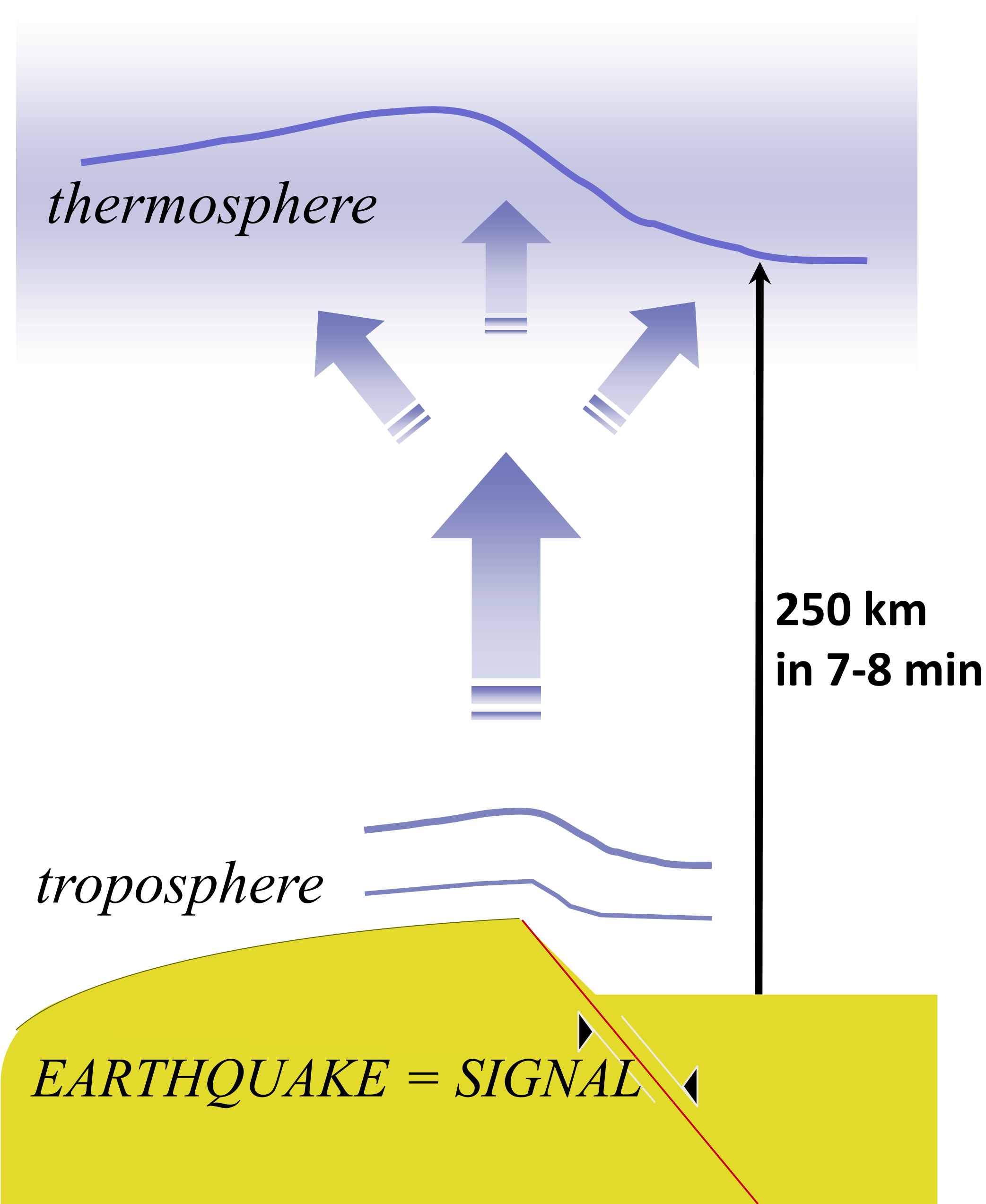
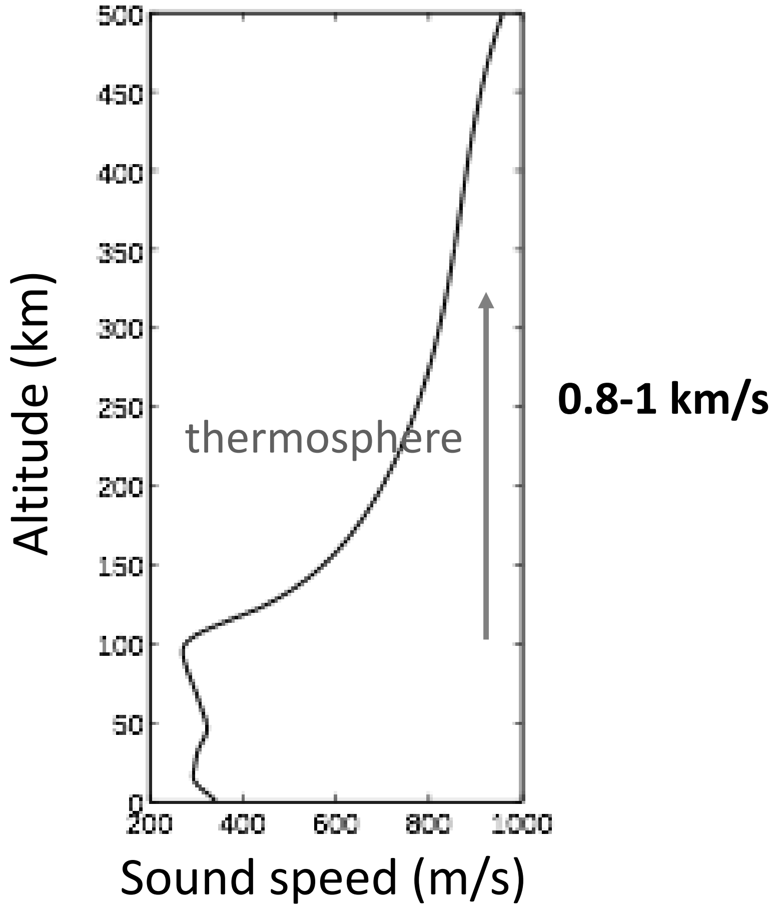
Observation and modeling of the acoustic response of the ionosphere to earthquakes and volcano eruptions

L. Rolland, D. Mikesell, E. Munaibari, F. Zedek, P. Lognonné, E. Astafyeva
and ITEC team (Q. Bletery, P. Coïsson, B. Delouis, D. Rivet, P. Sakic, A. Sladen, C. Twardzik, M. Vidal)

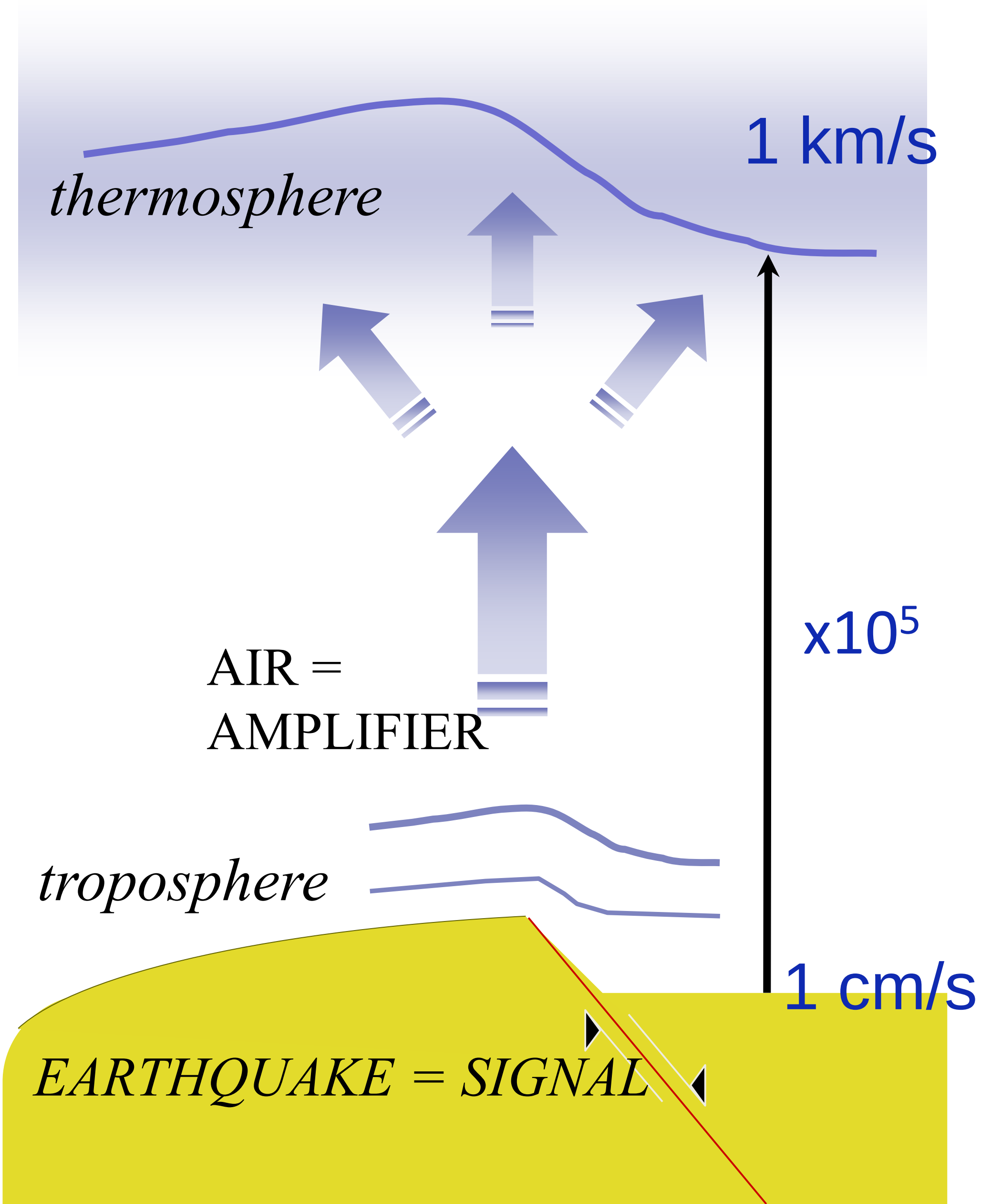


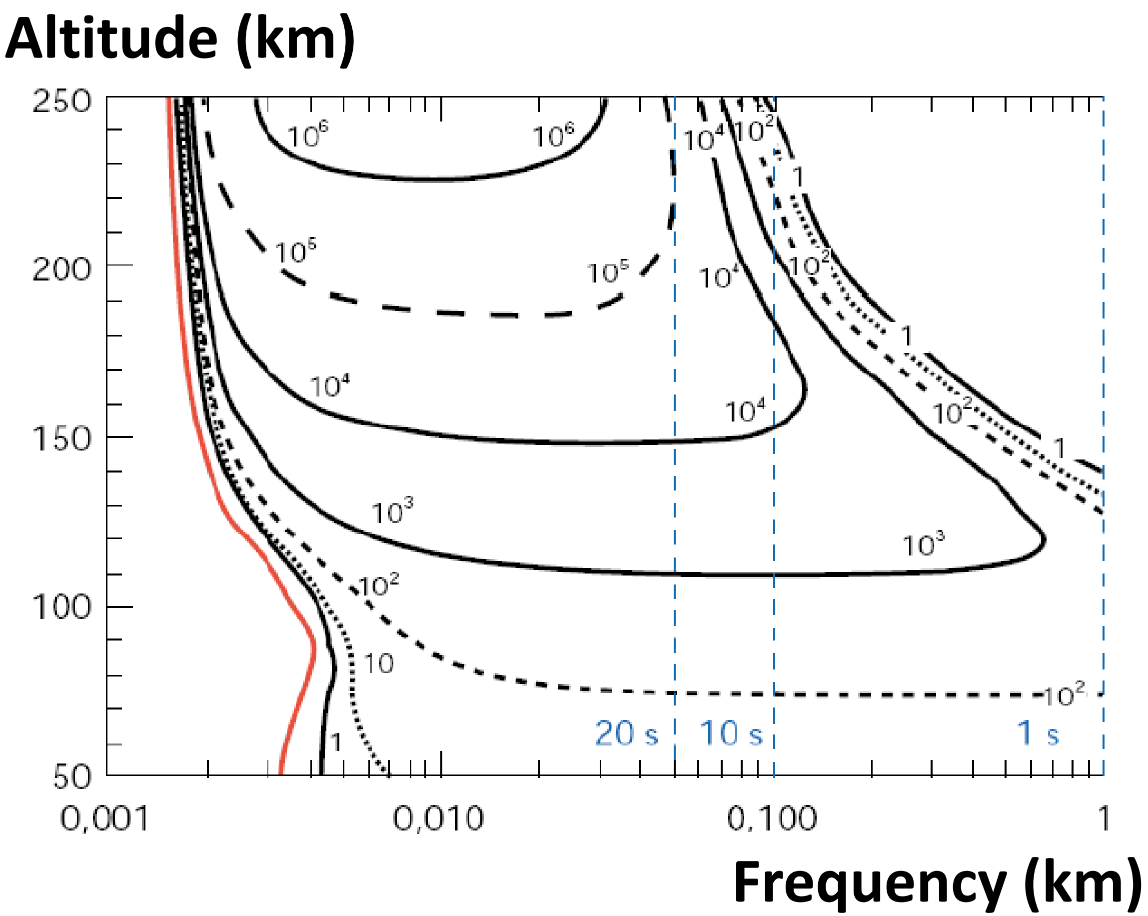
The atmosphere is sensitive to ground shaking





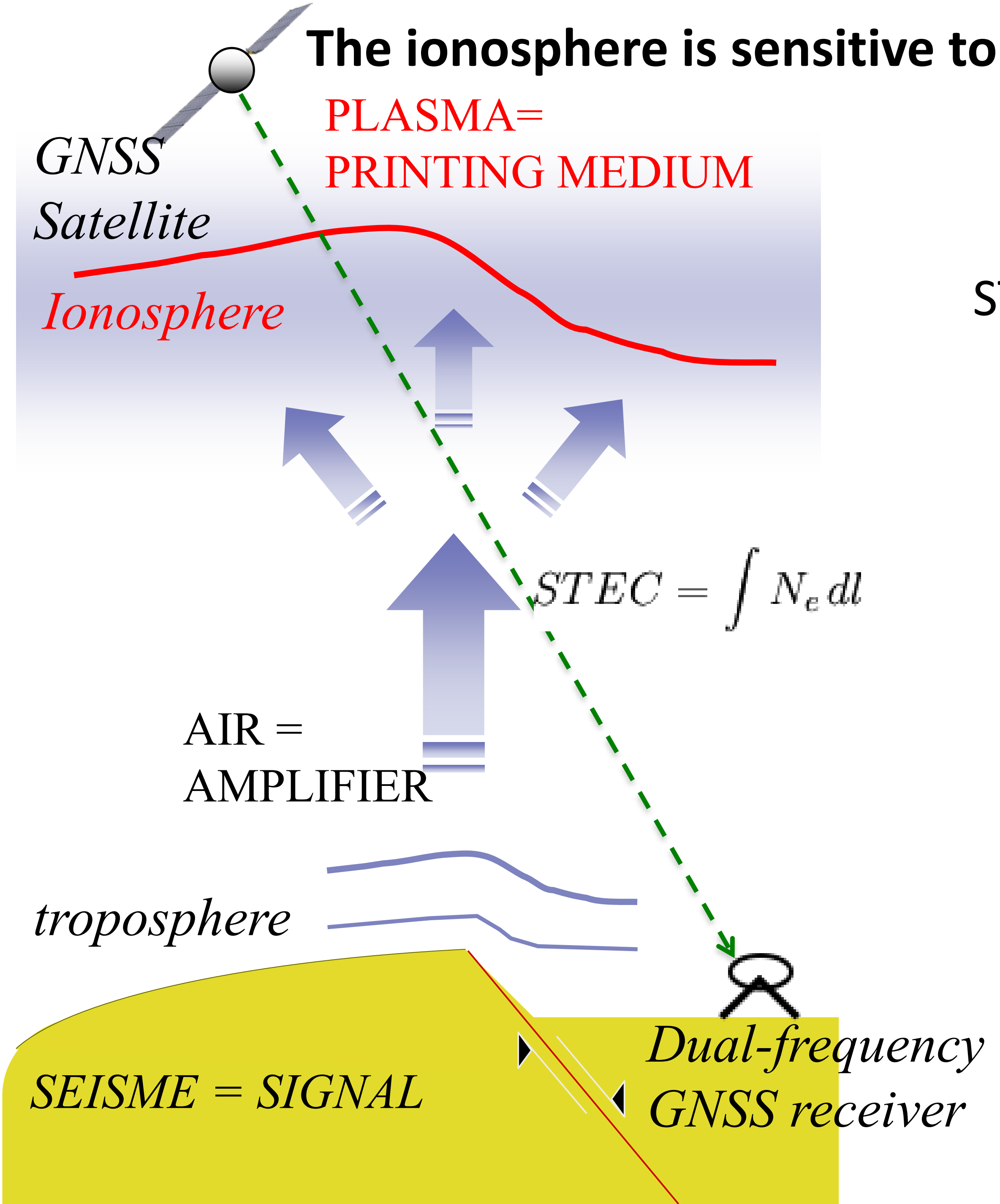
The thermosphere is sensitive to ground shaking





Farges et al. (2022)

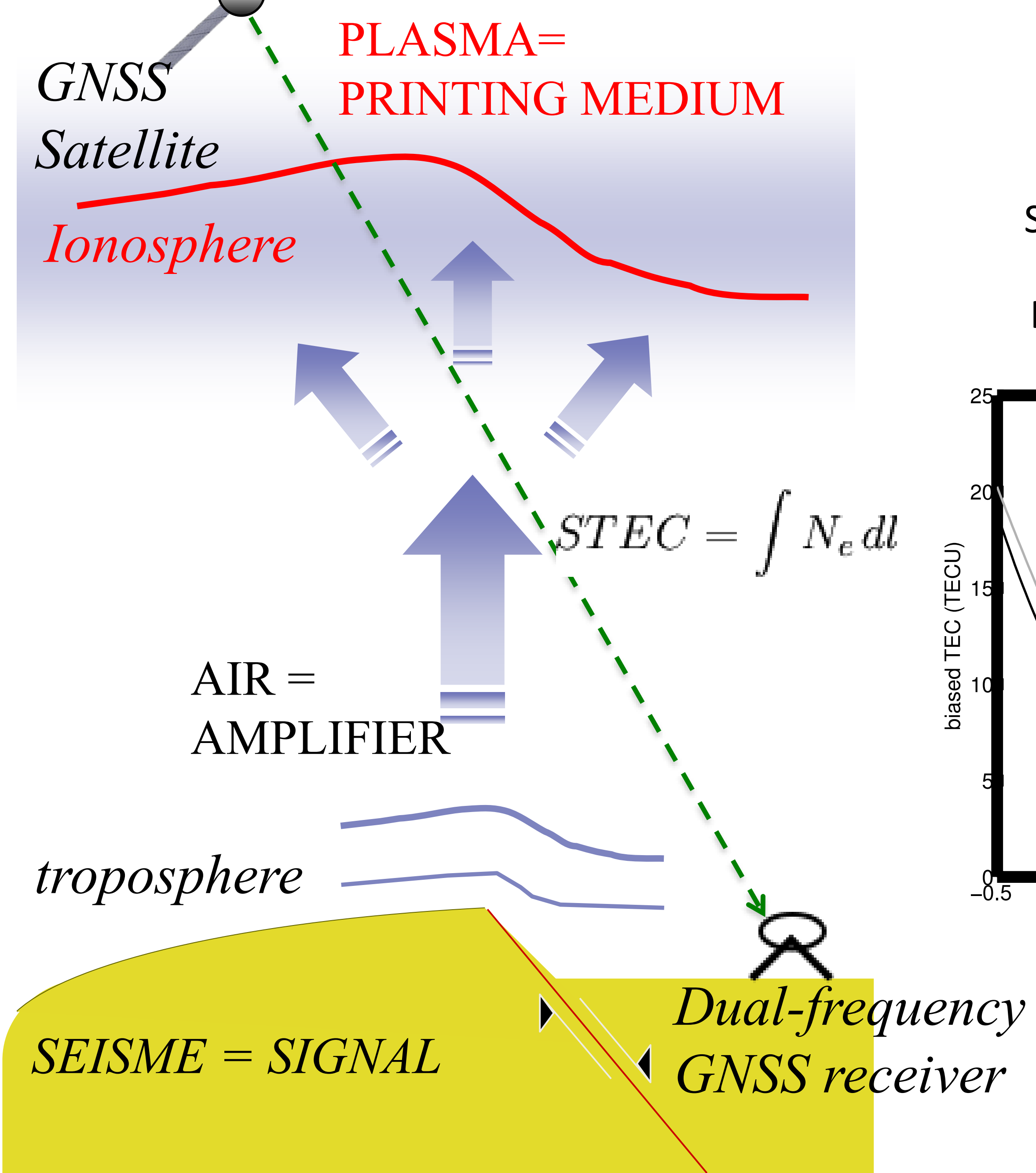
The ionosphere is sensitive to ground shaking



$$\Delta^{iono}_{gr,f} = \frac{40.3}{f^2} STEC$$

STEC : Slant Total Electron Content

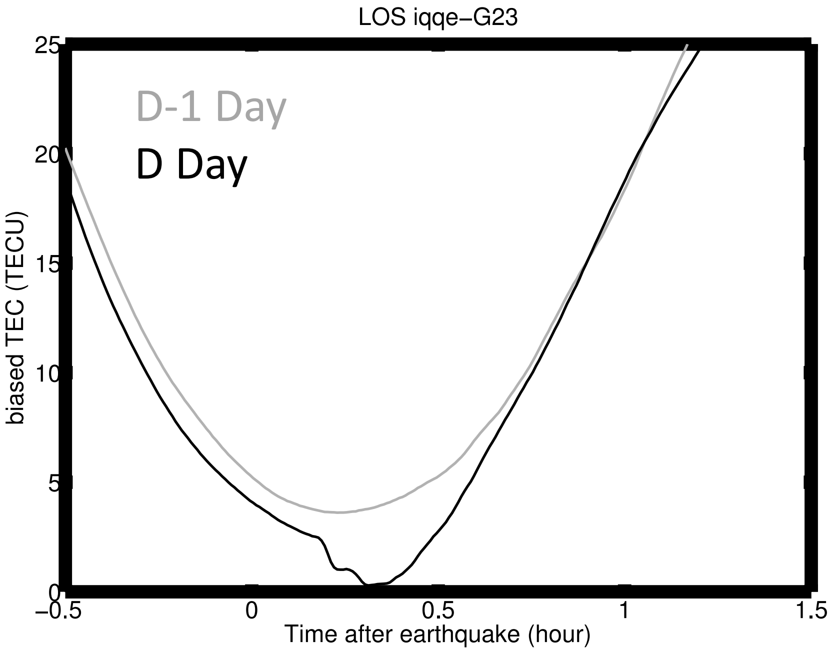
The ionosphere is sensitive to ground shaking



$$\Delta^{iono}_{gr,f} = \frac{40.3}{f^2} STEC$$

STEC : Slant Total Electron Content

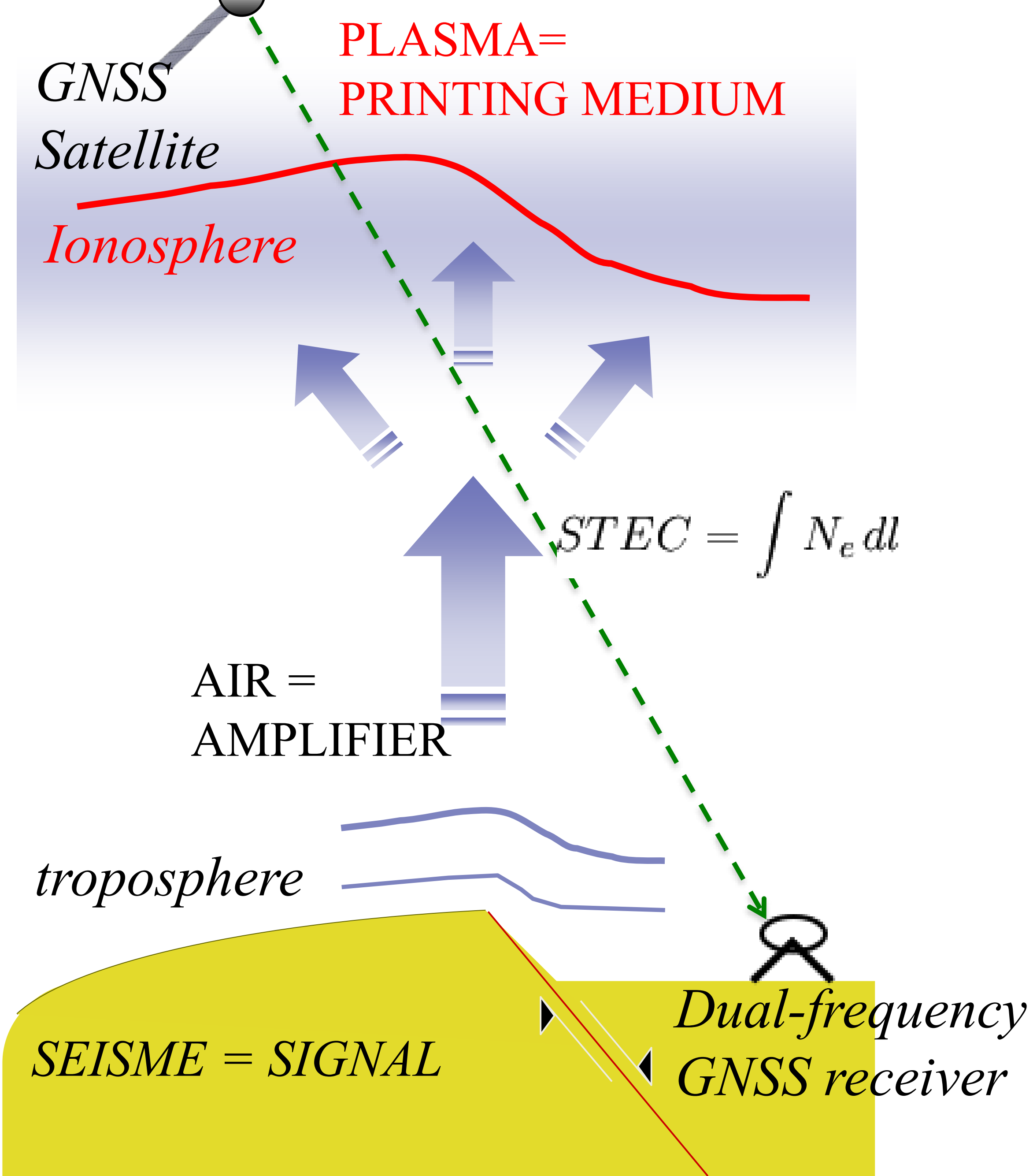
Iquique earthquake (Avril 1st 2014)

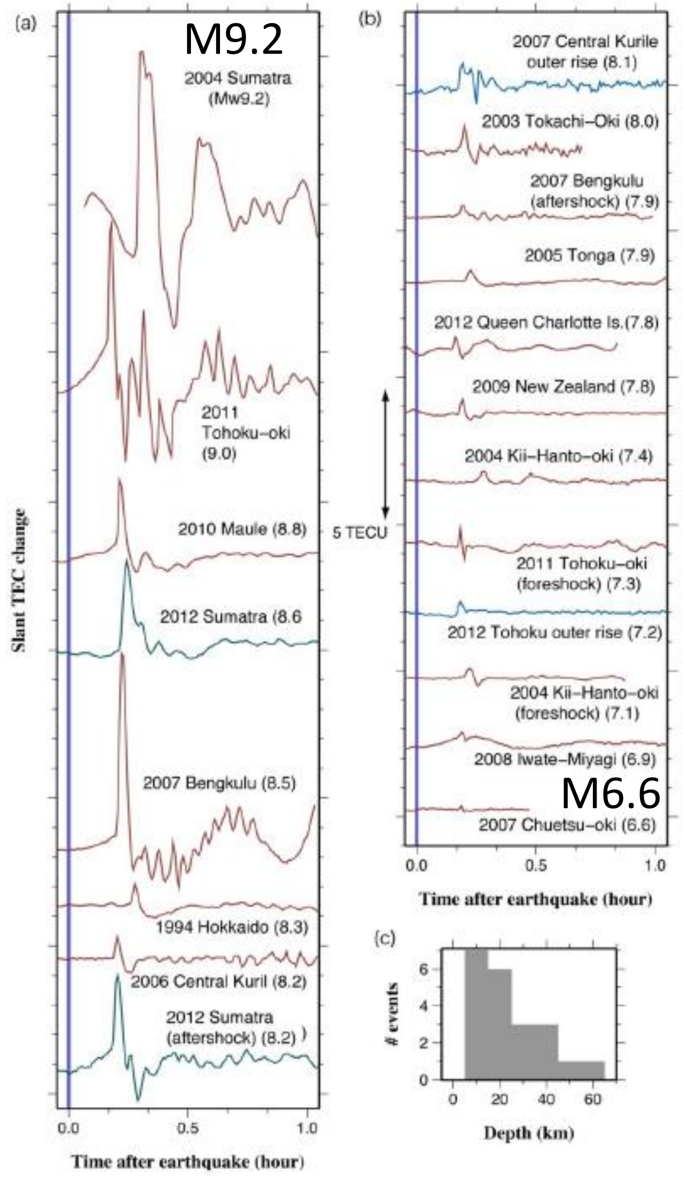


TEC Unit (TECU)
= 1e16 electrons/m2

16 cm on L1
27 cm on L2

The ionosphere is sensitive to ground shaking

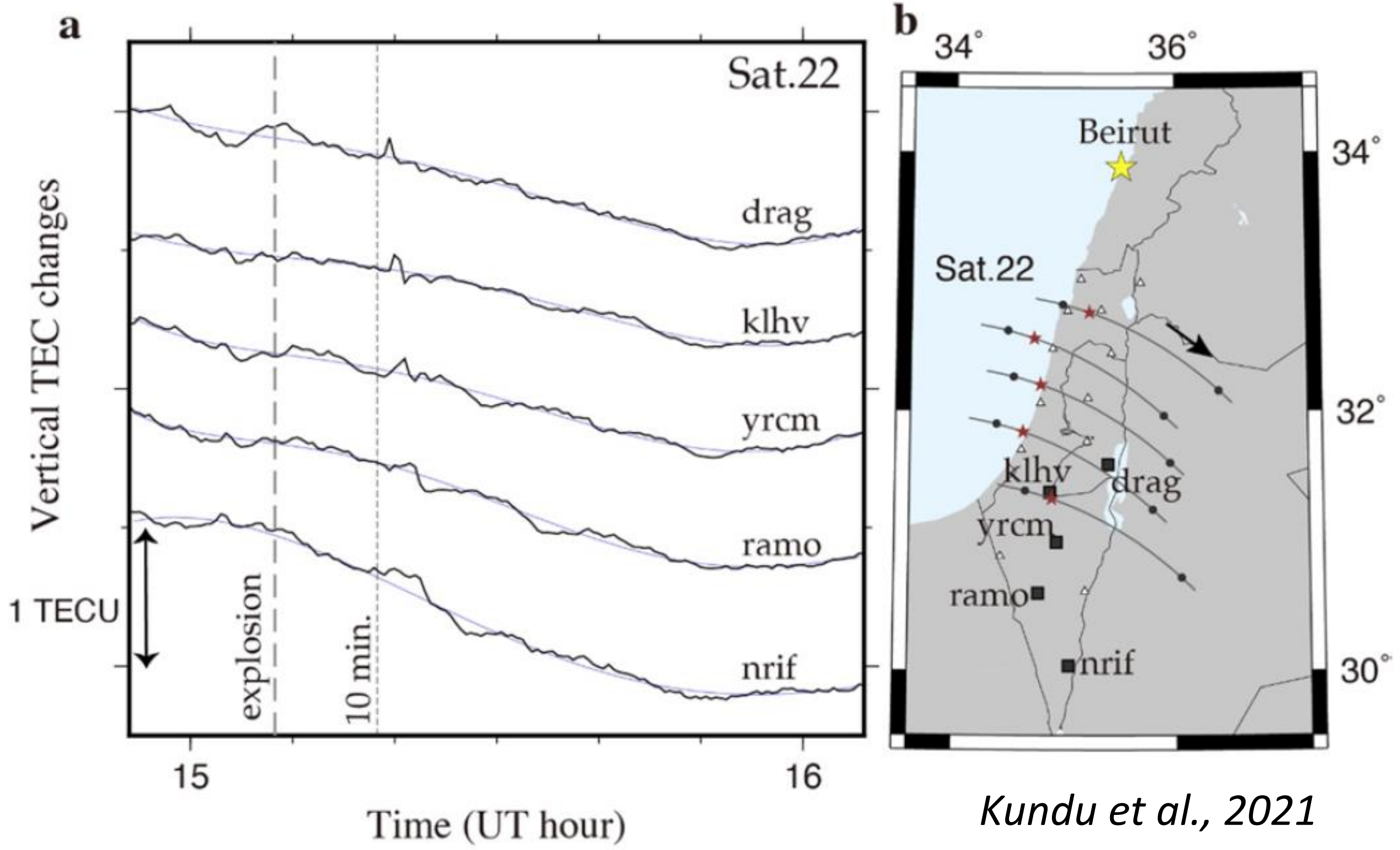




Cahyadi and Heki (GJI, 2014)

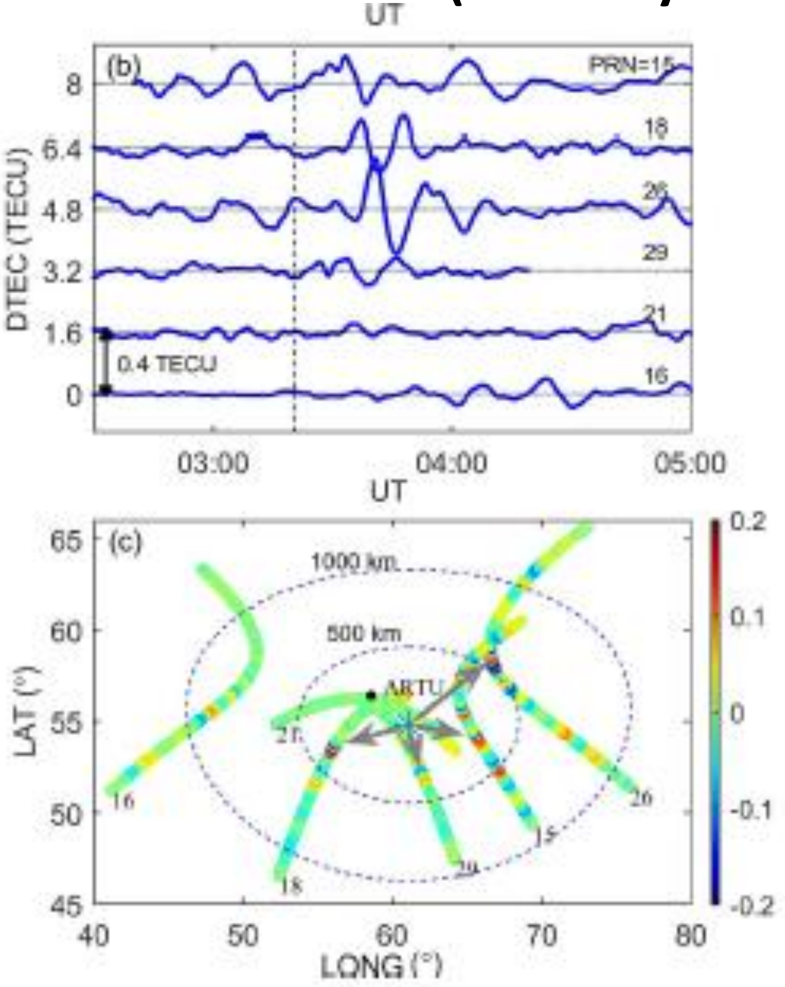
Other sources that generate similar N-wave signatures

Beirut anthropogenic explosion (August 2020)



Kundu et al., 2021

Chelyabinsk meteor airburst (February 2013)

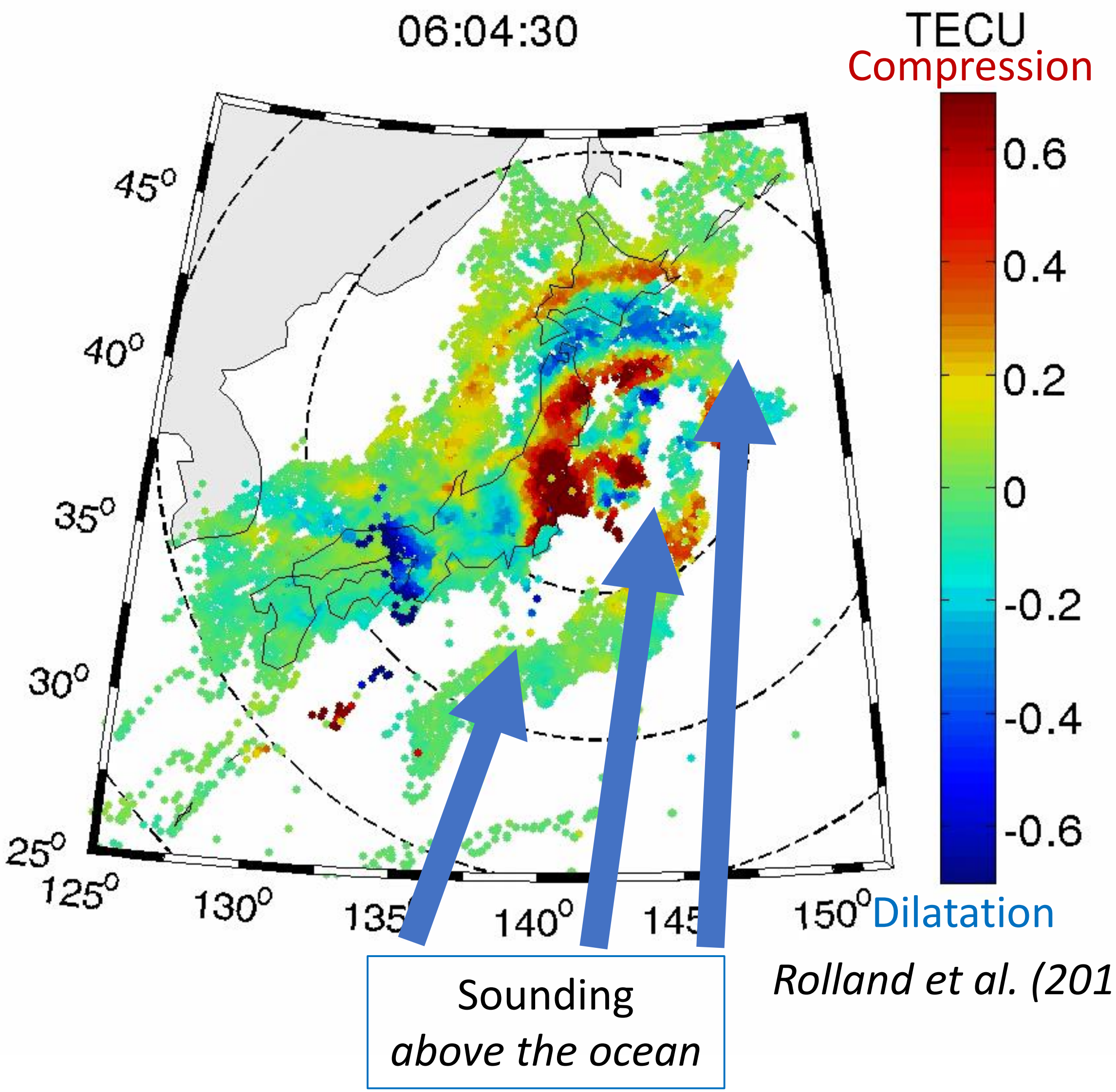


Ding et al., 2016

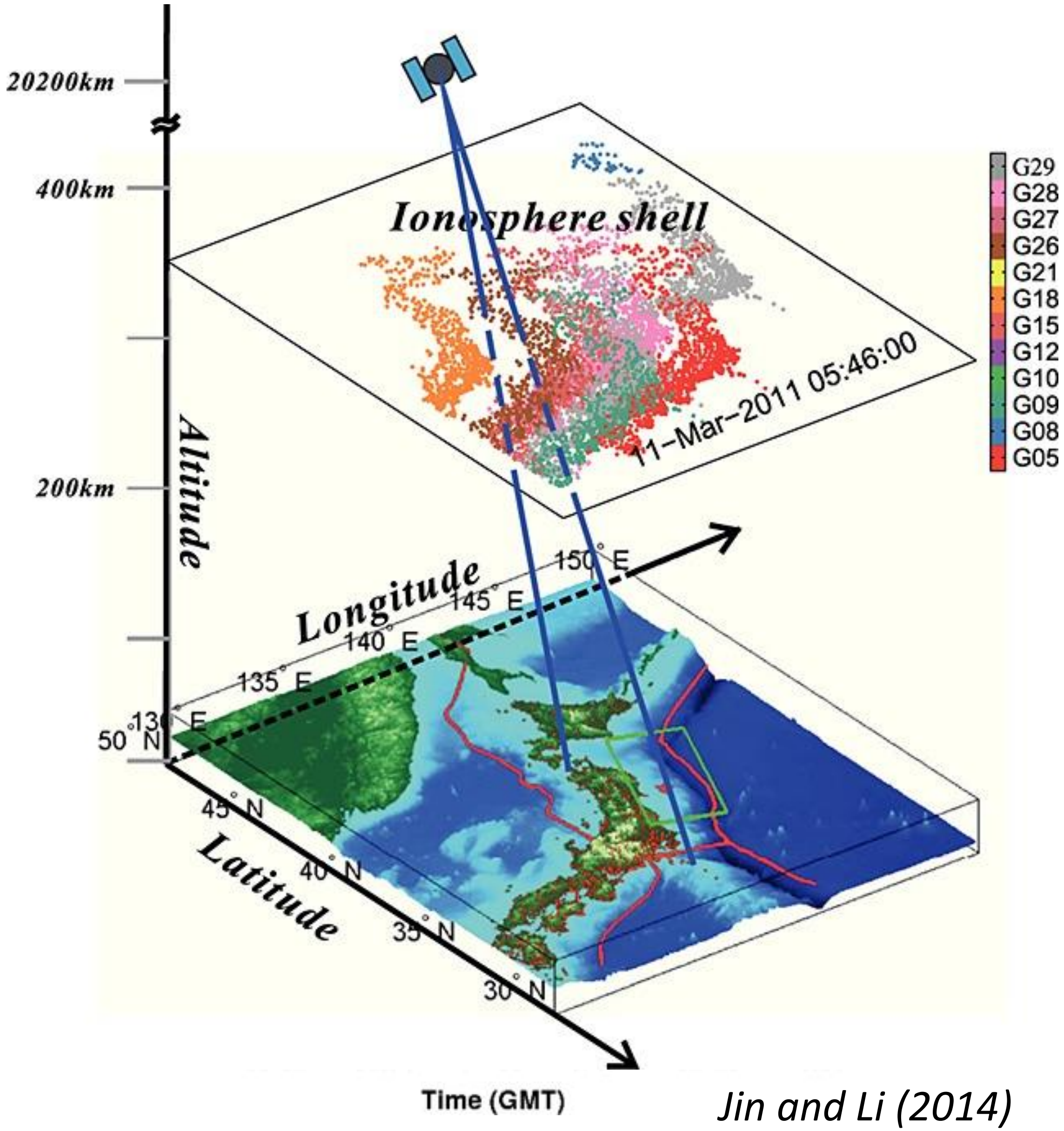
+ explosive volcano eruptions

Imaging the ionospheric imprint of an earthquake

TEC perturbations observed during the 2011 Japan earthquake

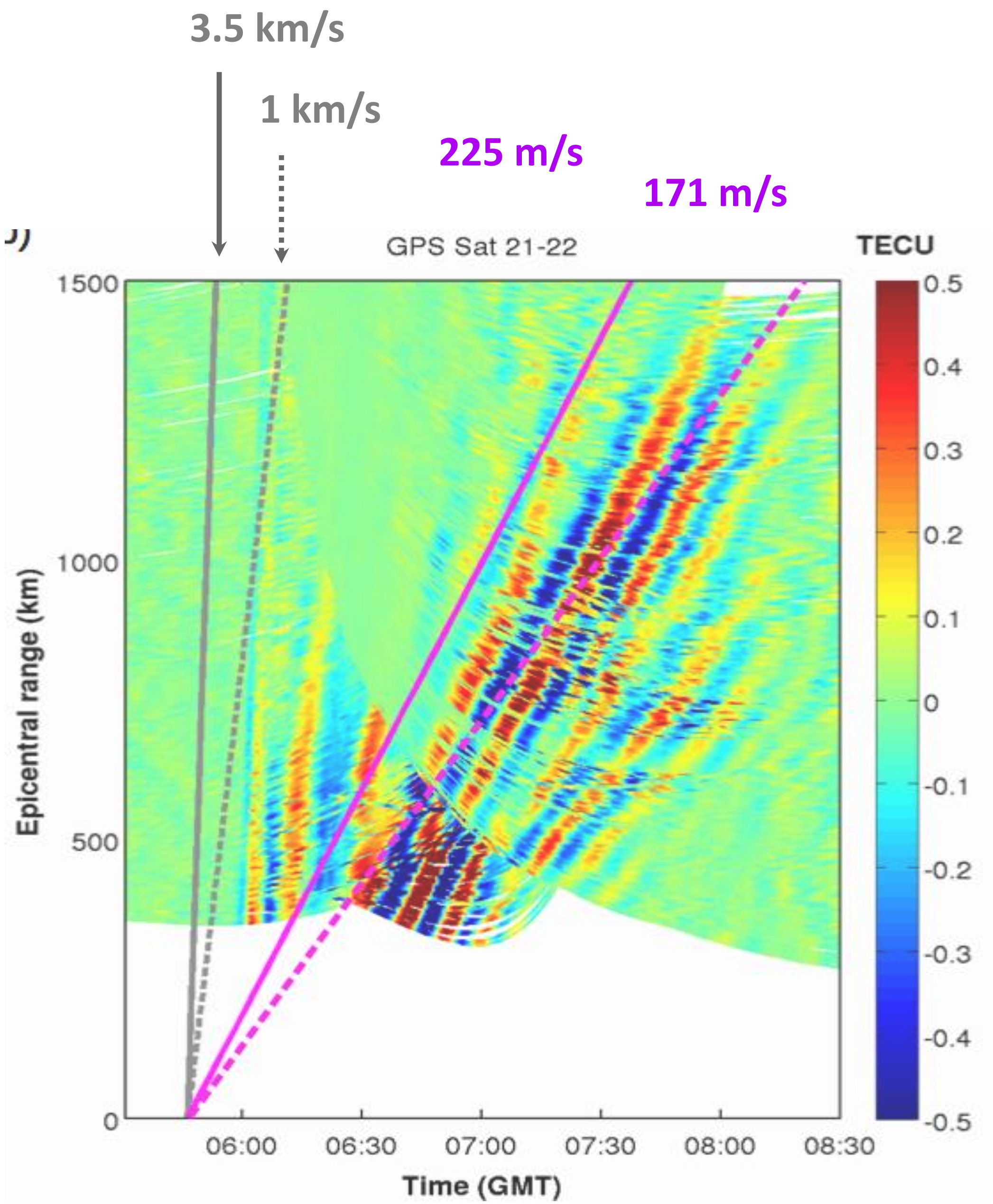


Rolland et al. (2011)



Jin and Li (2014)

Large earthquake, multi-modes signals



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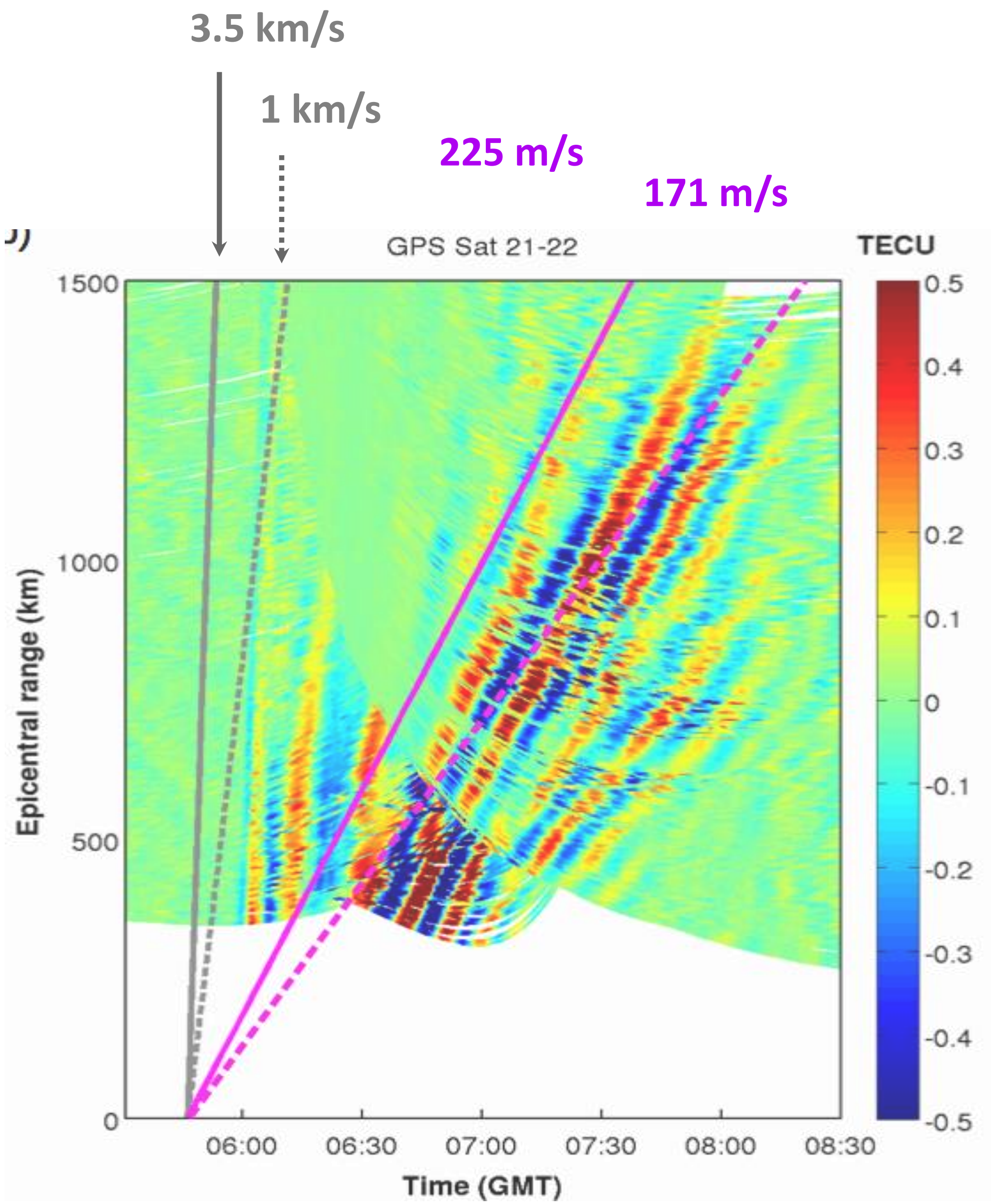
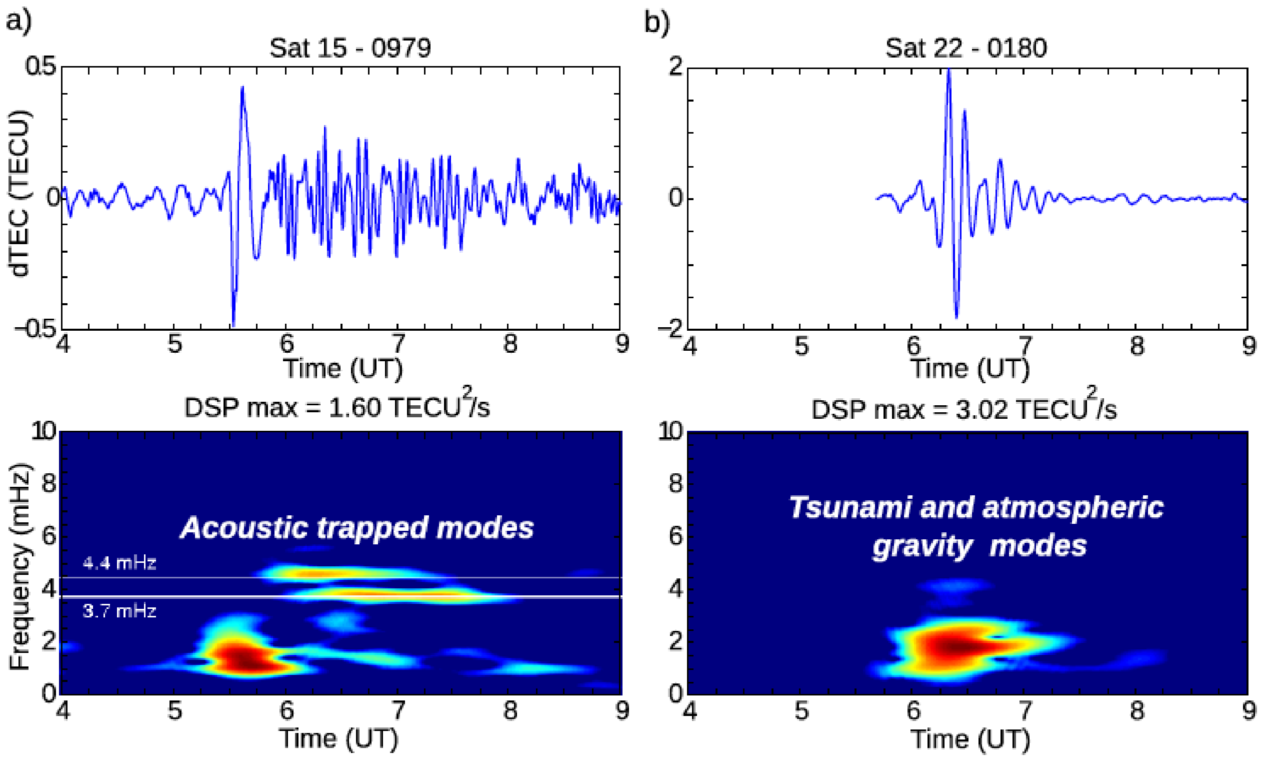
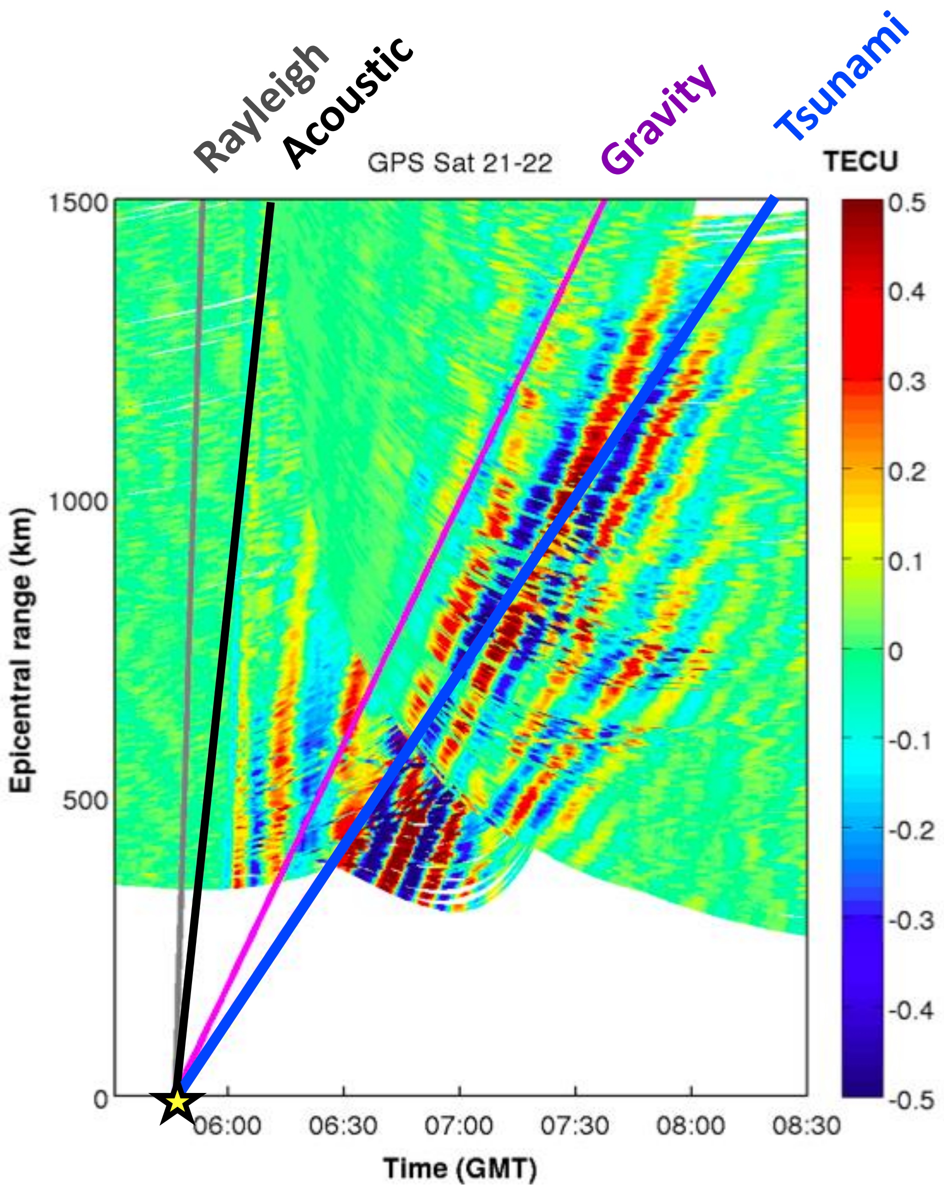


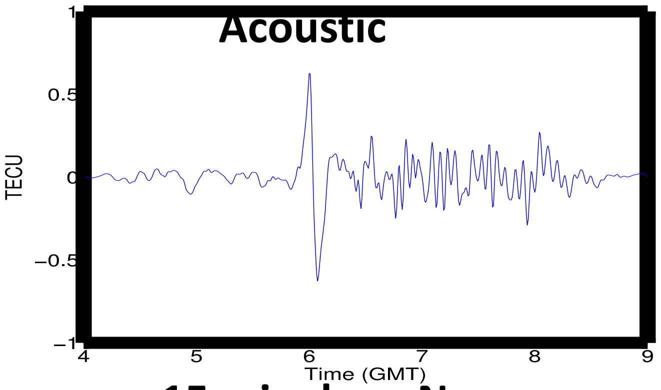


Rolland et al., 2011b

A classification of the ionospheric coseismic signals

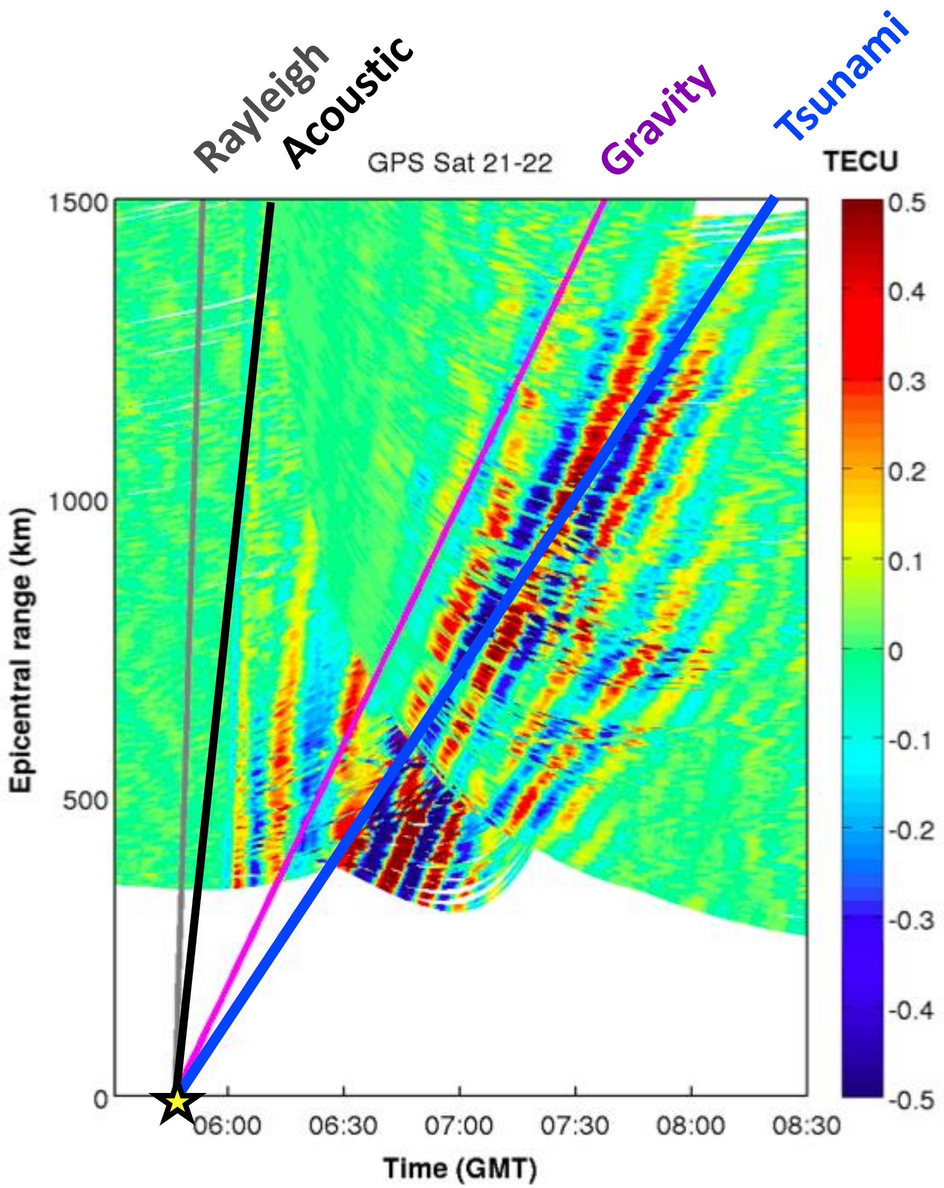


400 km from epicenter

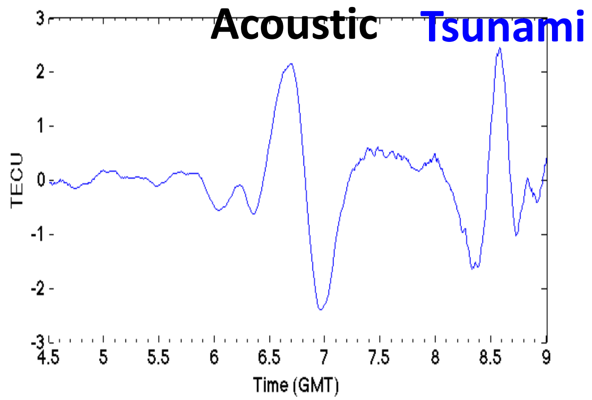


15 min. long N-wave

A classification of the ionospheric coseismic signals

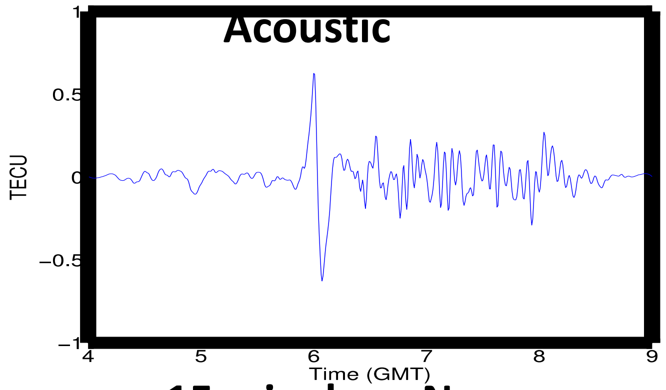


2000 km from epicenter



1 hour long N-wave

400 km from epicenter



15 min. long N-wave

Forward modeling of the GNSS-TEC acoustic response

Current state of research works

Generic scheme

Step 0- Ground motion simulations and coupling with atmosphere *This Spring School*

Step 1- Atmospheric propagation

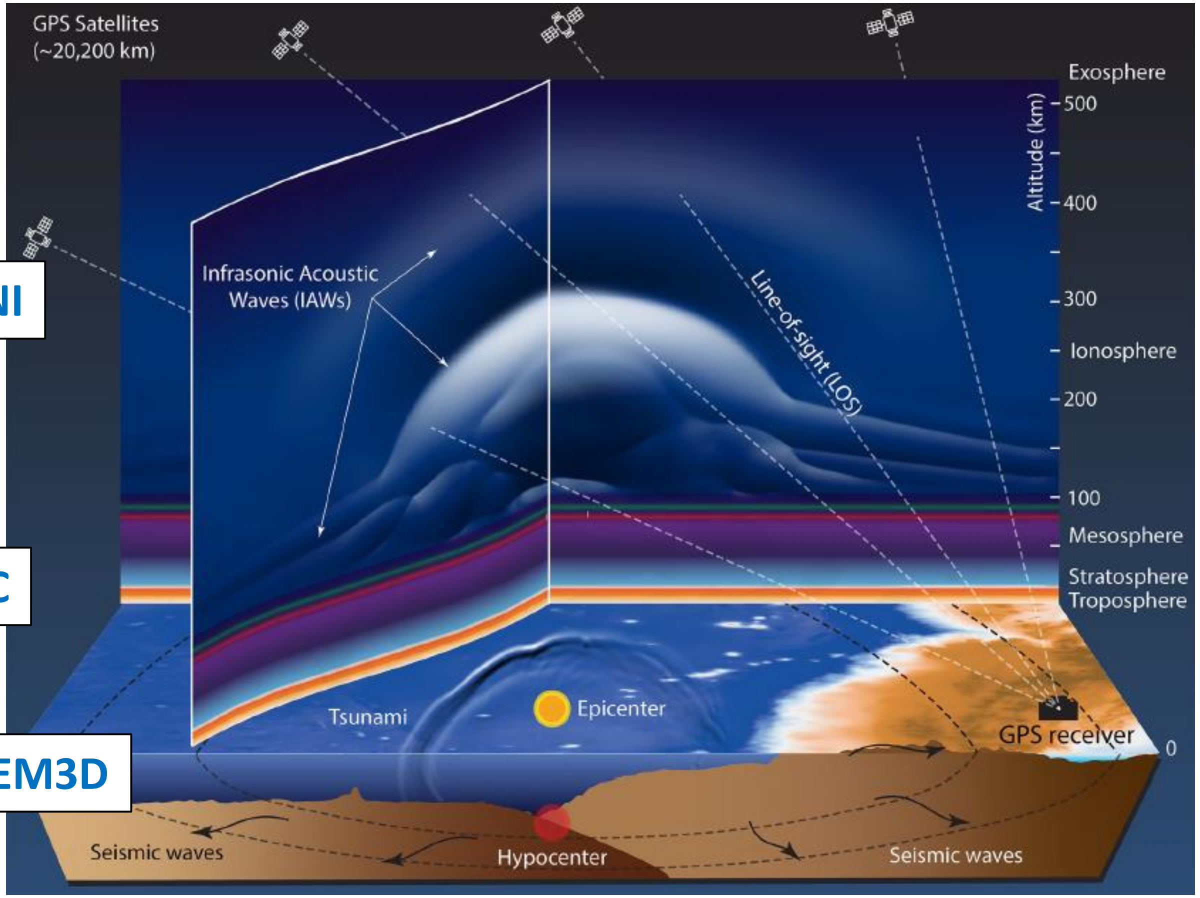
Step 2- Neutral atmosphere/ionosphere coupling

Step 3- integration GPS satellites -> GPS receivers

3: GEMINI

1: MAGIC

0: SPECFEM3D



Inchin et al. (2021)

Forward modeling of the GNSS-TEC acoustic response

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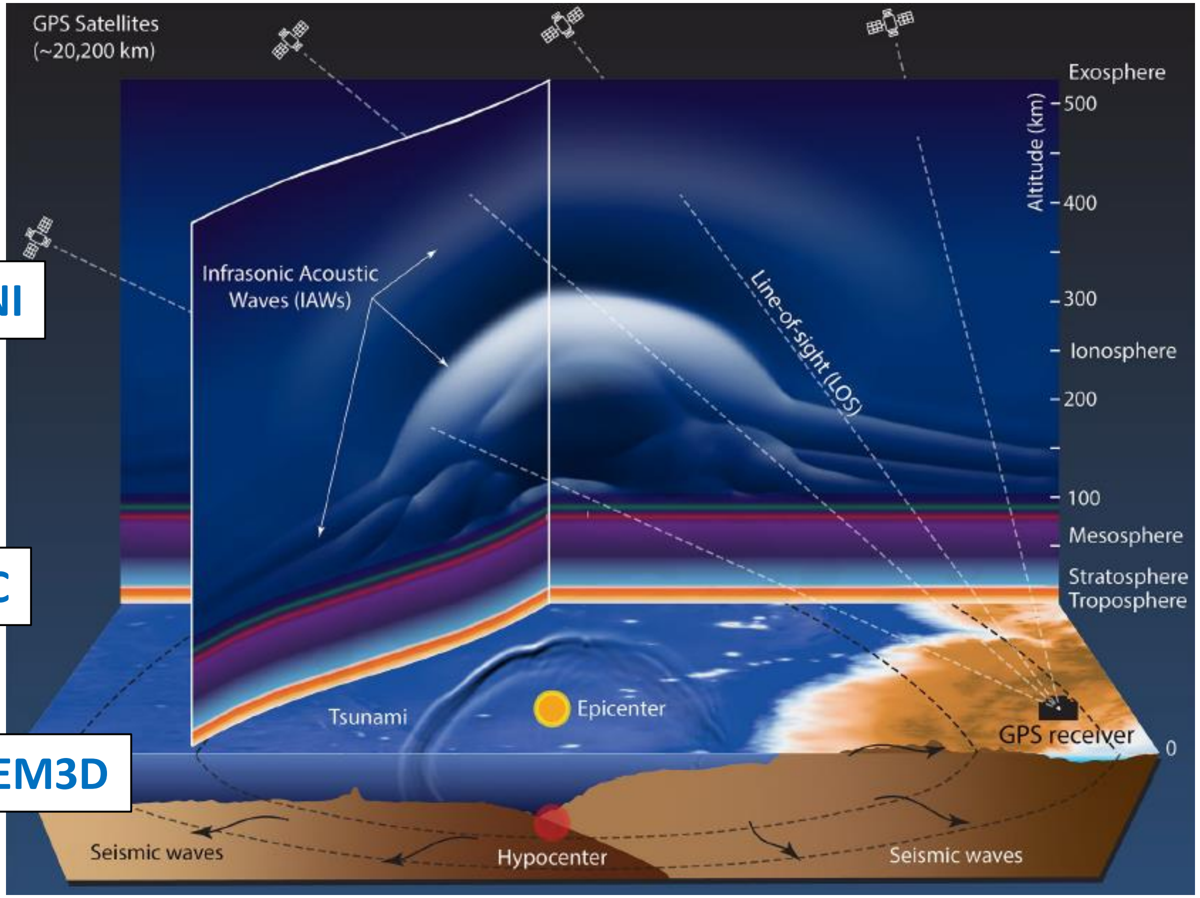
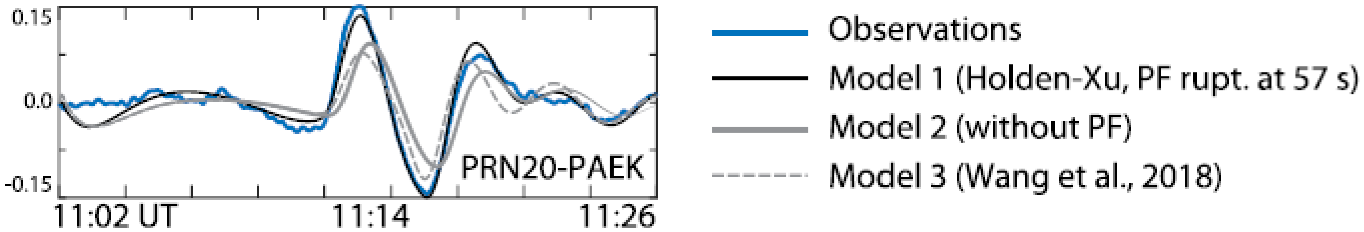


Inchin et al. (2021)

GNSS-TEC is sensitive to the earthquake rupture complexities



Forward modeling of the GNSS-TEC acoustic response

A simple model adapted to rapid characterization

Step 1- Atmospheric propagation

of a pulse in all directions from Earth's surface
-> 3D acoustic ray tracing (*Dessa et al., 2005*)
-> ad-hoc modeling of dissipation terms for amplitude and pulse period lengthening after *Dautermann et al. (2009)*
-> allows proper timing and 3D geometry

Step 2- Simplified neutral atmosphere/ionosphere coupling:

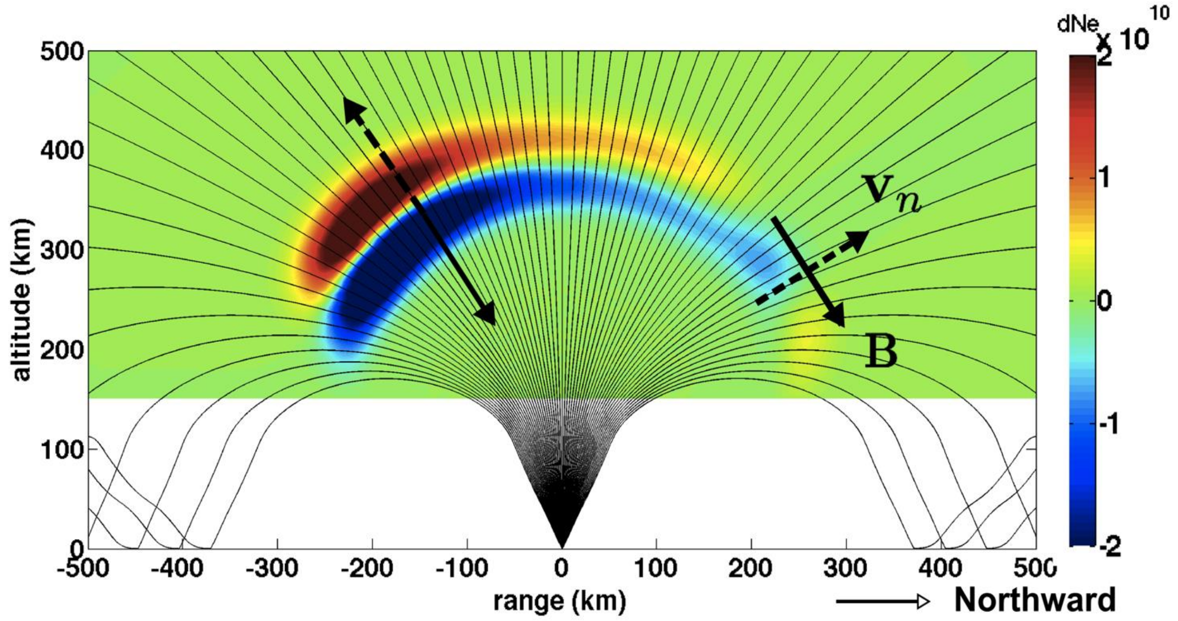
$$\mathbf{v}_i = (\mathbf{v}_n \cdot \mathbf{1}_B)\mathbf{1}_B$$

Linearized continuity equation (dNe << Ne0) numerically solved (FD)

Step 3- integration GPS satellites -> GPS receivers

1D Background atmosphere: NRLMSISE 2.0, wind possible
3D Background ionosphere: IRI2014

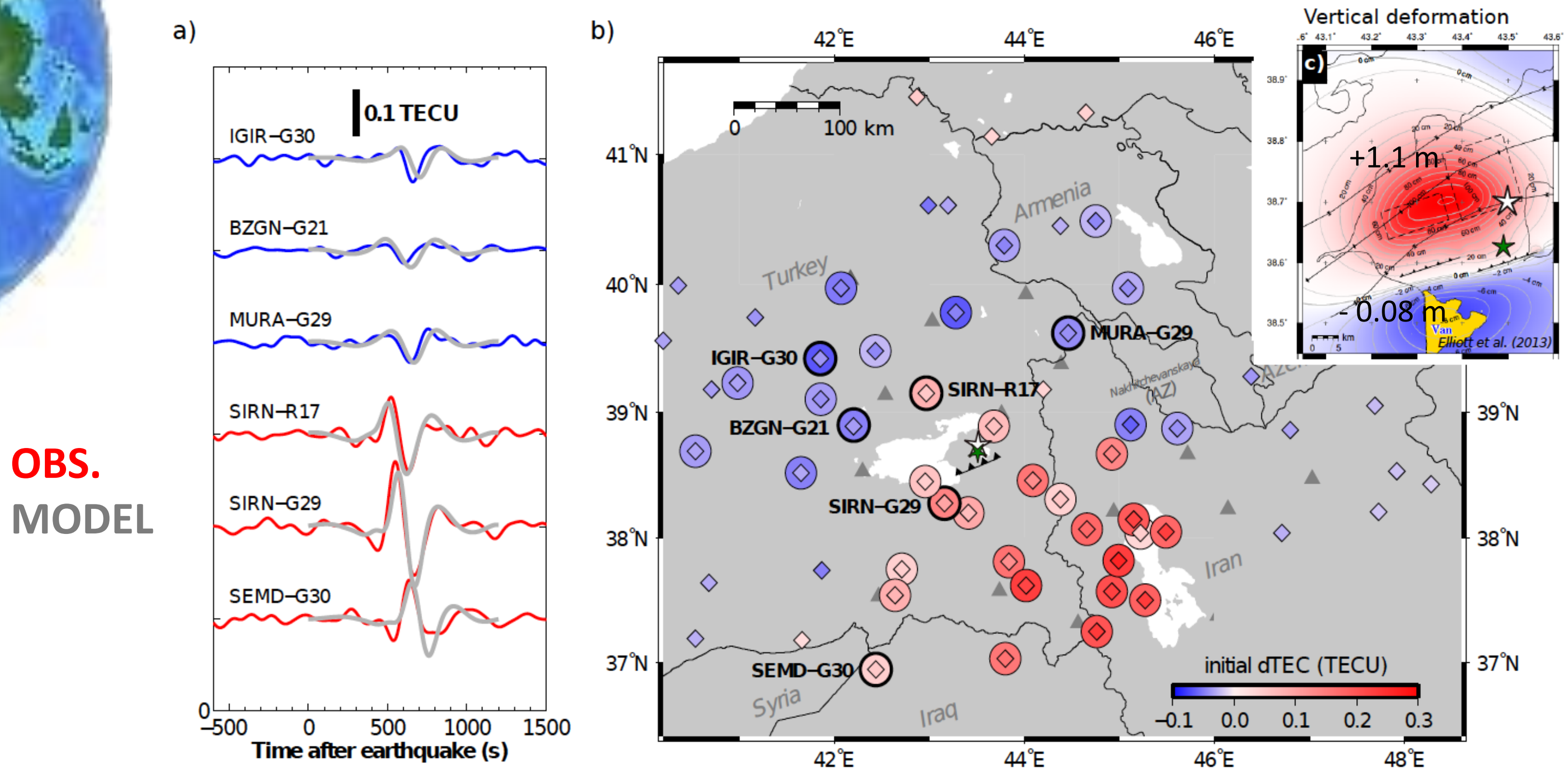
Last developments: Mikesell et al. (2019)



Rolland et al. (2013)

Modeling the near-field coseismic response

The case of the 2011 Mw 7.1 Van earthquake (Eastern Turkey)



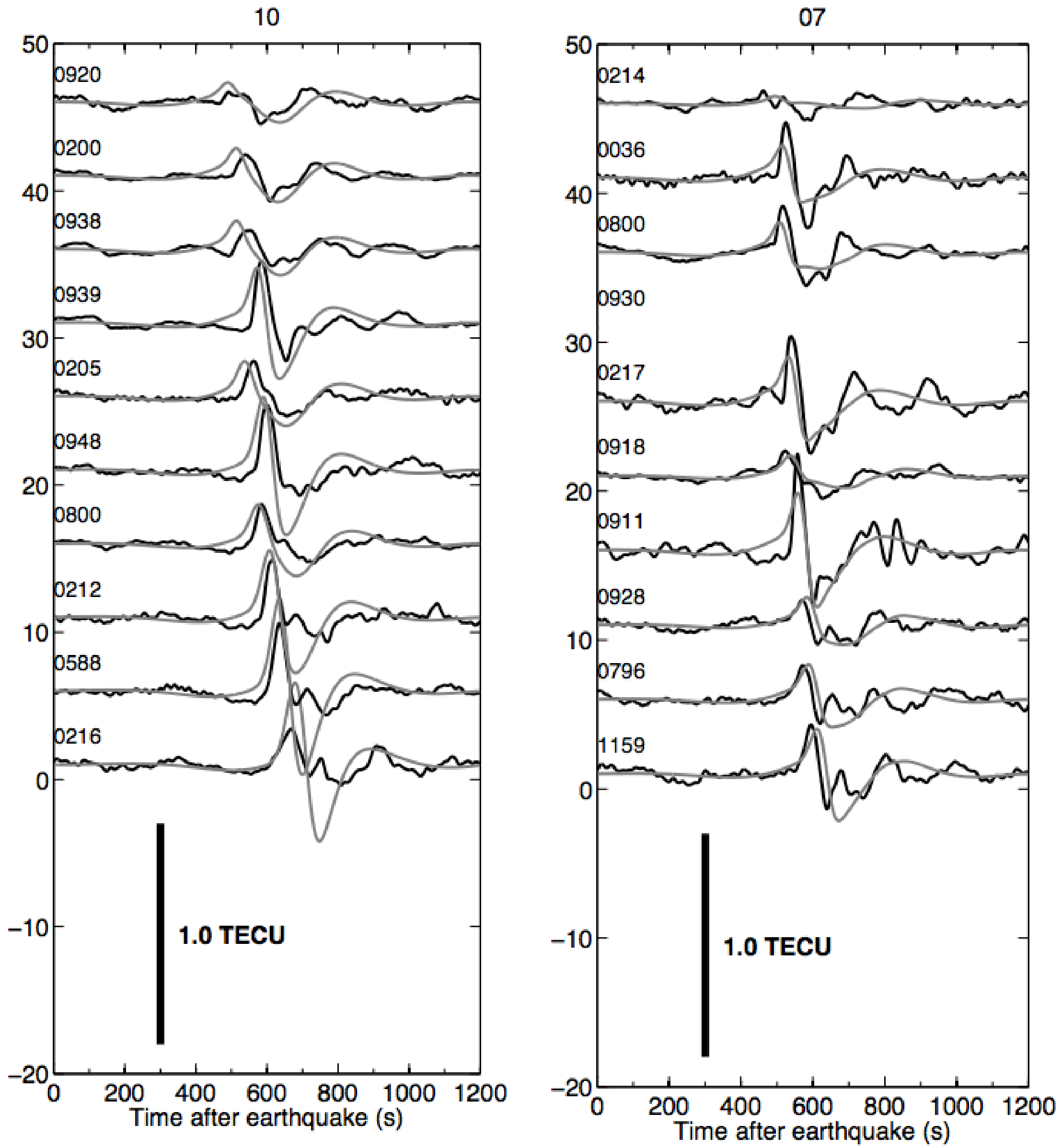
Rolland et al., 2013

Southward directivity, polarity negative North and positive South
Pattern primarily due to the geomagnetic field driving effect

Modeling the near-field coseismic response

The case of the 2011 Mw 7.3 Sanriku-Oki earthquake (Japan)

OBS.
MODEL



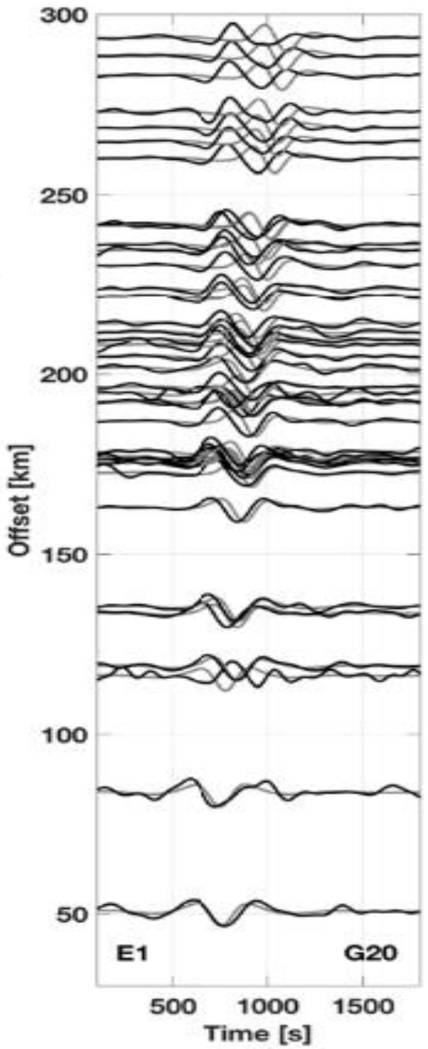
Earthquakes with Mw < 7.5:
Fairly good agreement for relative amplitudes and arrival times

Modelling the co-seismic GNSS-TEC signature

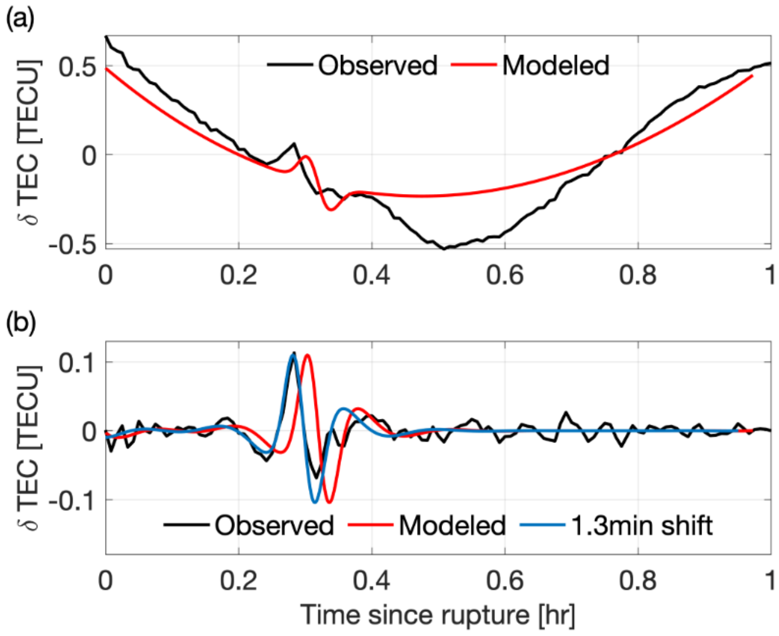
Systematic delay for earthquakes M>7.5

2016 Mw 7.8 New Zealand earthquake

OBS.
MODEL

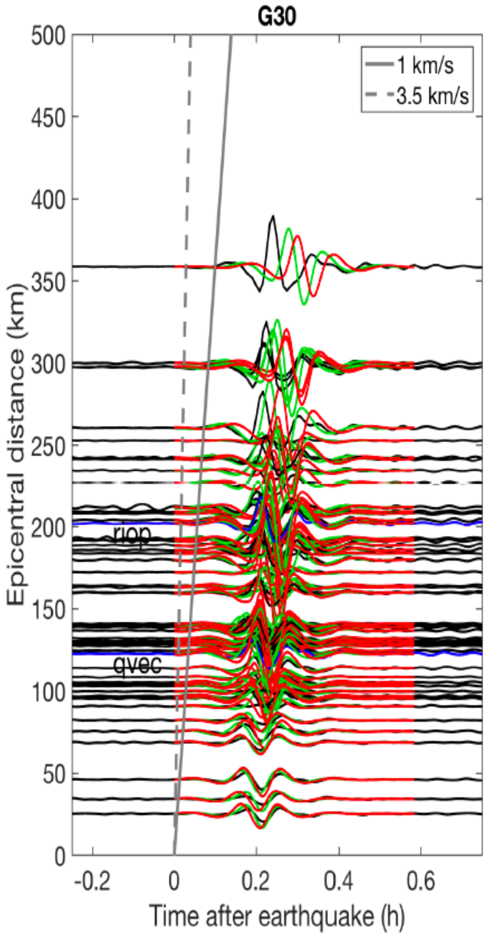


2018 Mw 7.8 Palu earthquake



2016 Mw 7.8 Pedernales earthquake

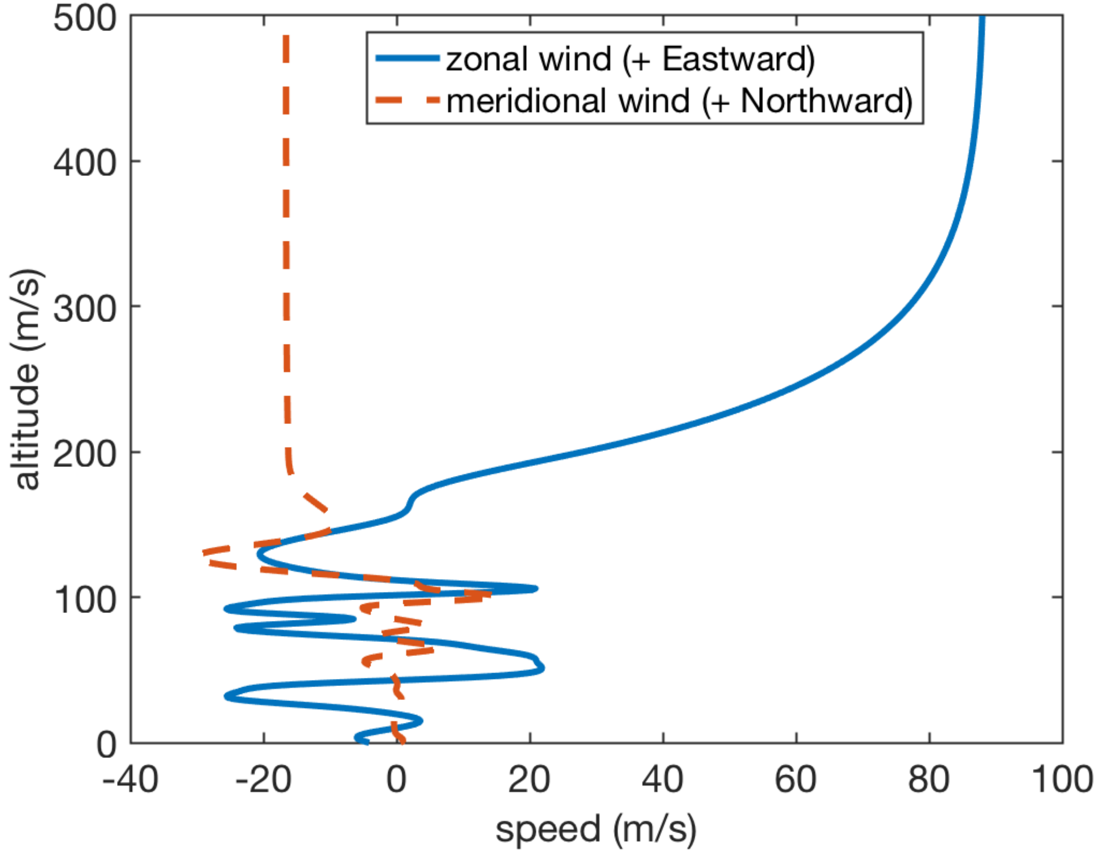
OBS.
MODEL



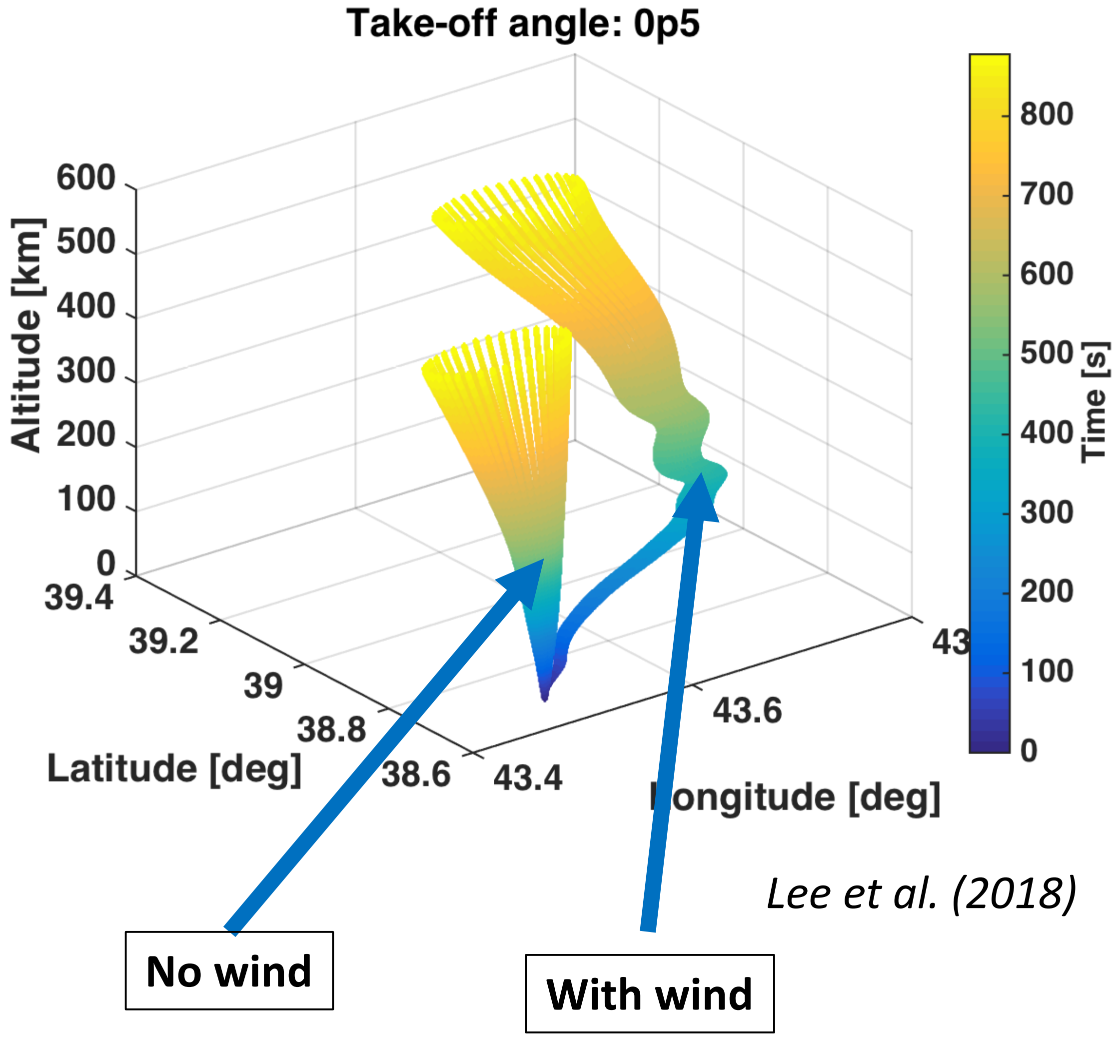
~10% mismodelling on time delay

Horizontal Winds cannot explain the time delay mismodeling

Winds can explain <1% of the time delay in the wind direction



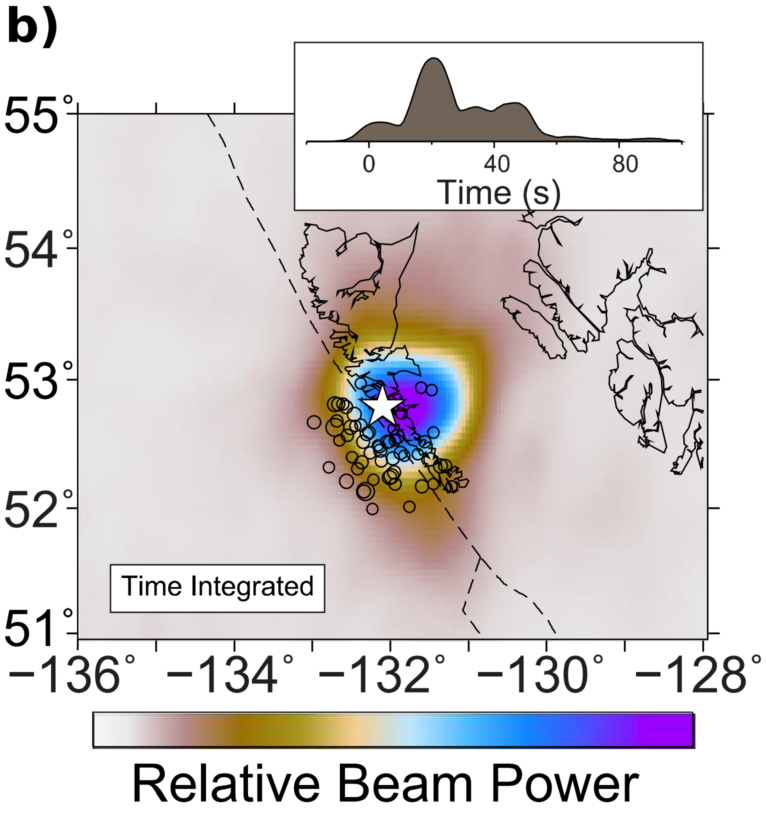
2016 KAIKOURA EARTHQUAKE (NEW-ZEALAND)



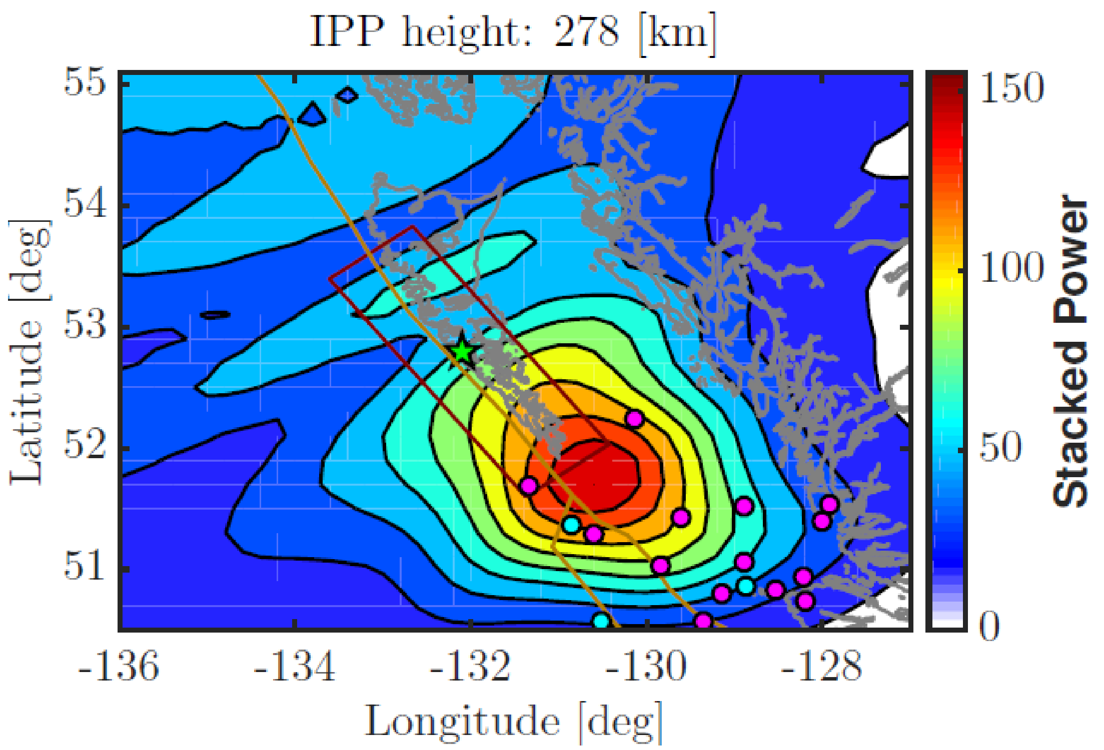
Lee et al. (2018)

Mismodelling on time delay affects backprojection

Haida Gwaii earthquake, 2012, Mw 7.8



Seismic w/ 50+ stations in Europe (Lay et al. 2013)

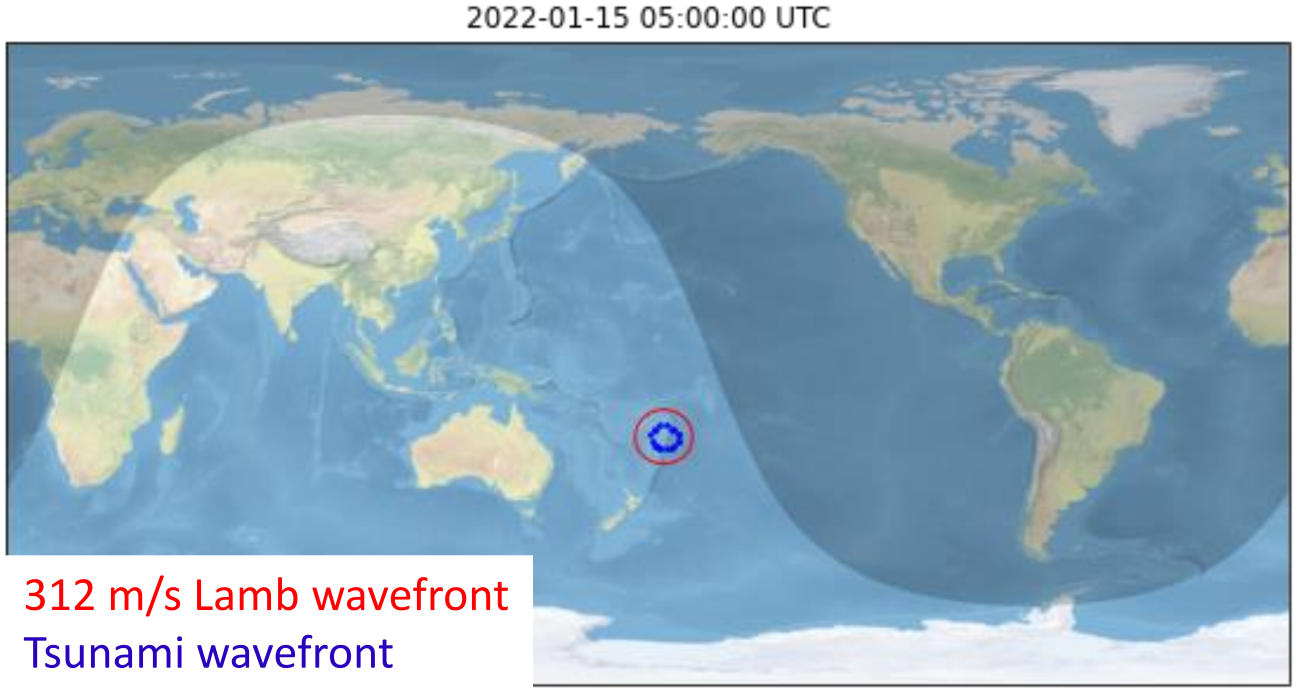


TEC w/ 2 satellites and 18 stations

Courtesy: D. Mikesell

The 2022 Hunga Tonga-Hunga Ha'apai volcano eruption

https://fealse.com/2022/01/15/tonga-volcano-eruption-one-of-the-biggest-ever-captured-from-space/



The 2022 Hunga Tonga-Hunga Ha'apai volcano eruption

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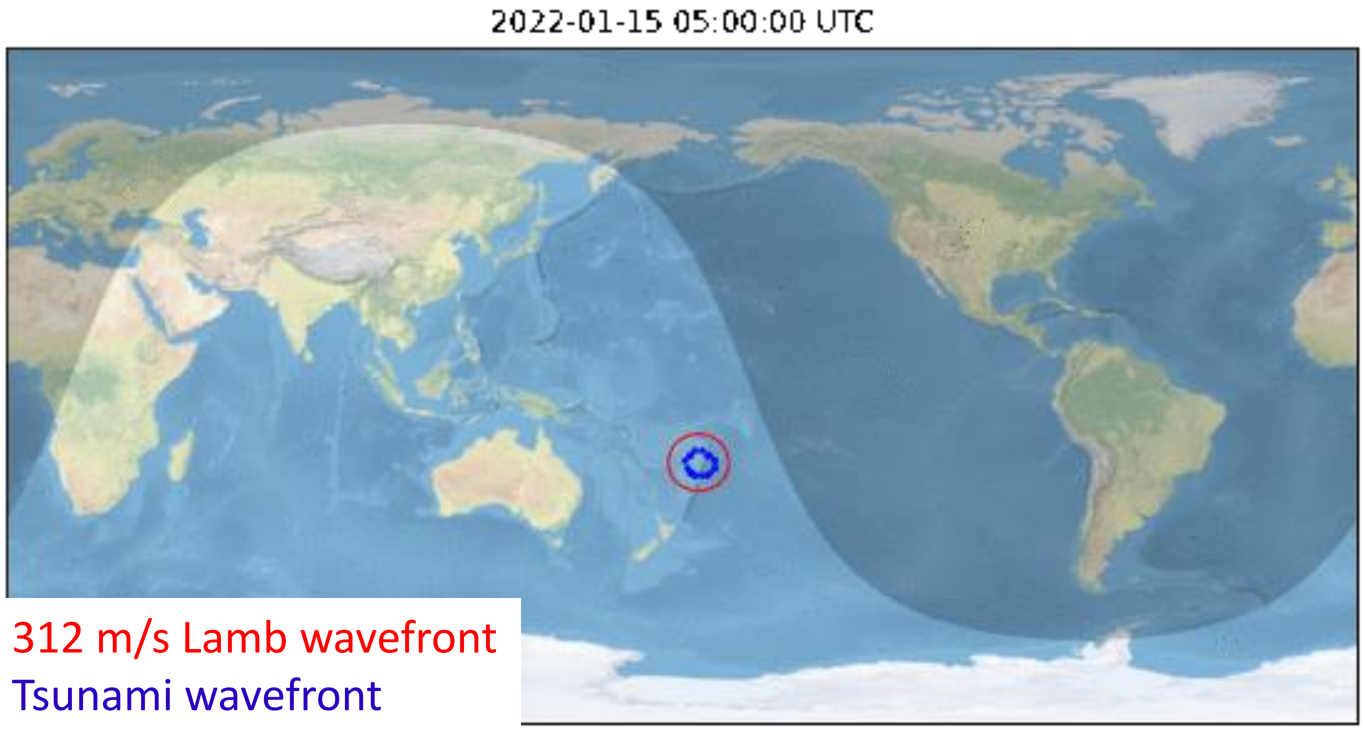
https://fealse.com/2022/01/15/tonga-volcano-eruption-one-of-the-biggest-ever-captured-from-space/



The 2022 Hunga Tonga-Hunga Ha'apai volcano eruption

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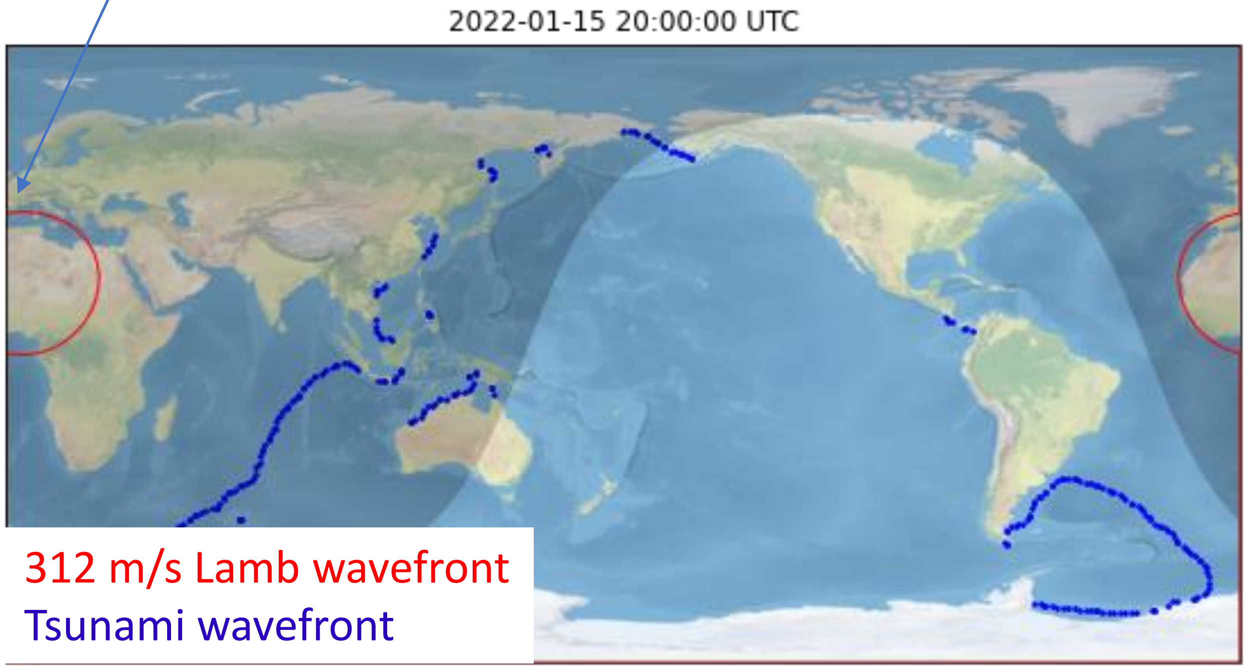
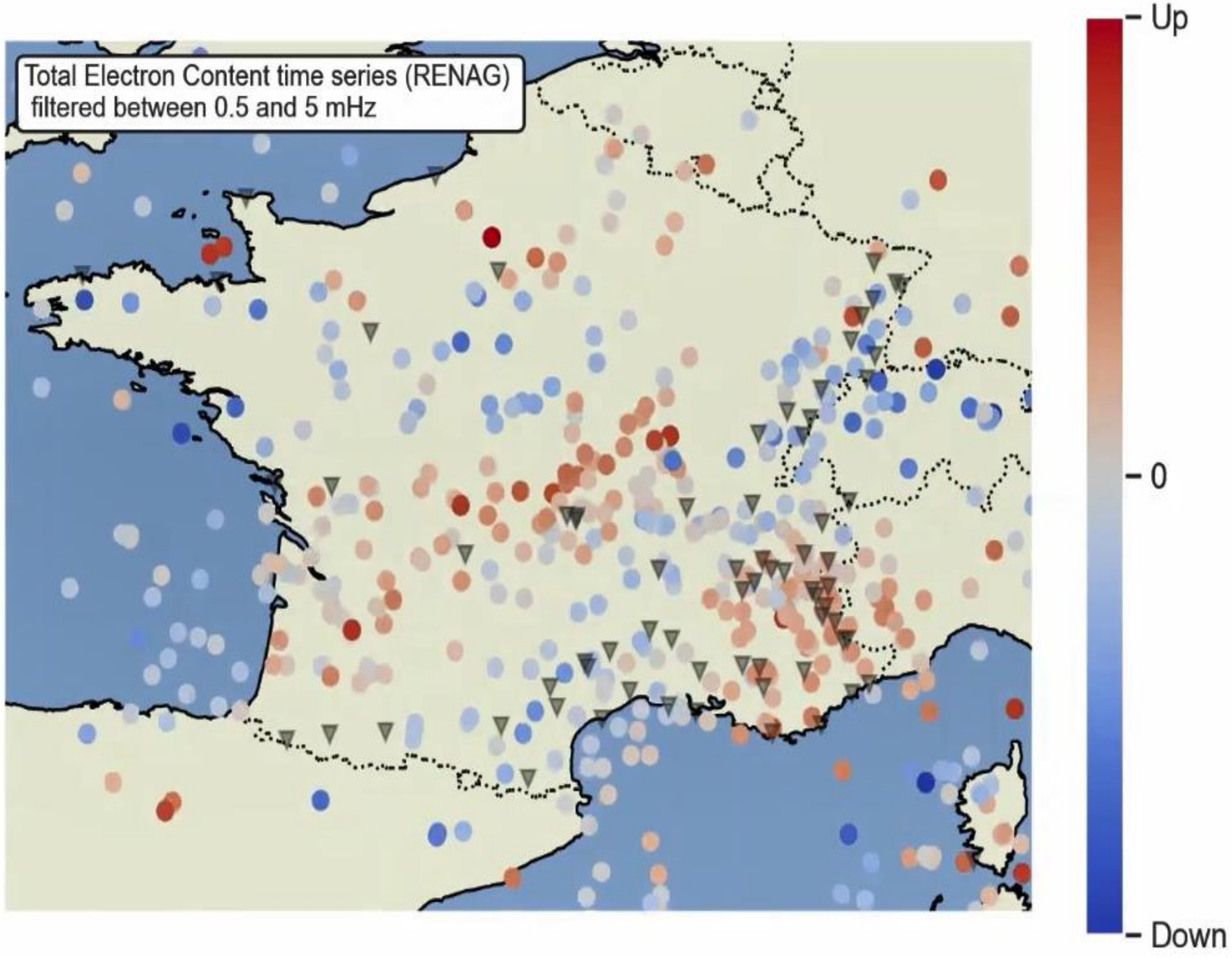
https://fealse.com/2022/01/15/tonga-volcano-eruption-one-of-the-biggest-ever-captured-from-space/

Arrives in France at ~20 UTC



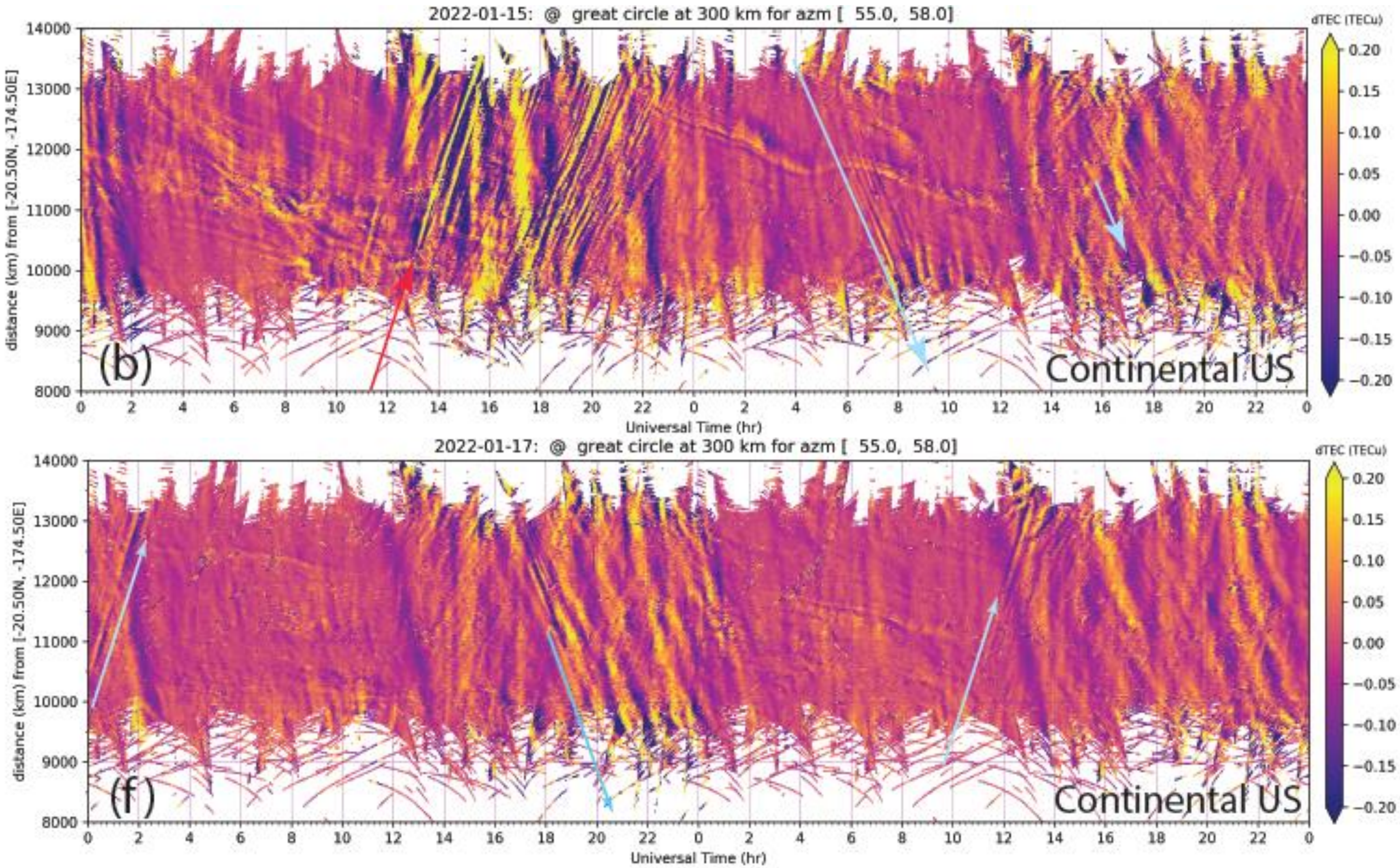
GNSS-TEC observations of the Hunga-Tonga eruption from France

IONOSPHERIC (RENAG GNSS network)



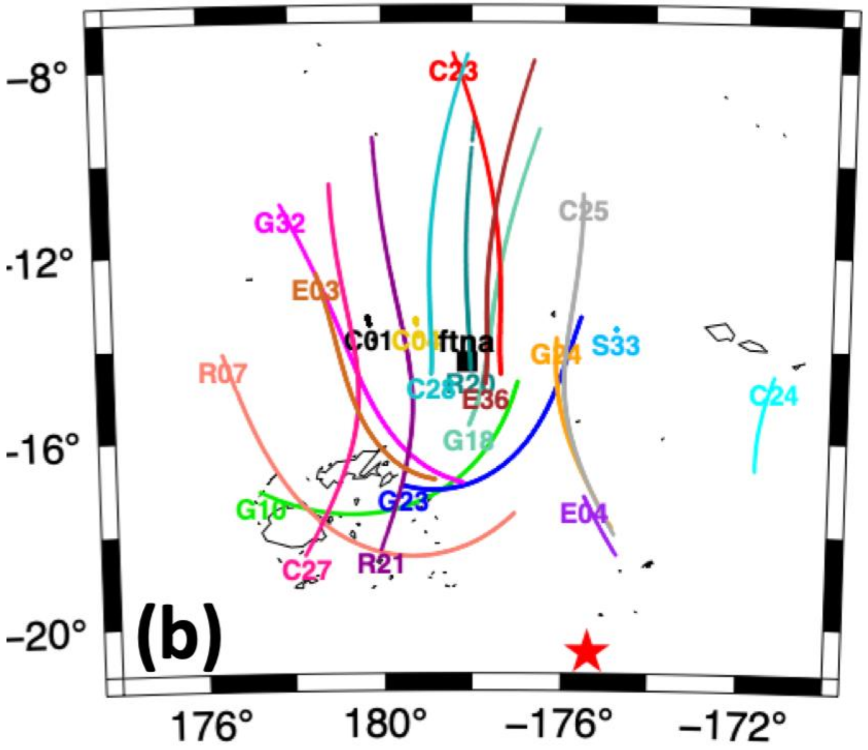
Lamb wave ionospheric imprint globally observed, with multiple passage during at least 6 days long

Global propagation of the Lamb wave: 4 days



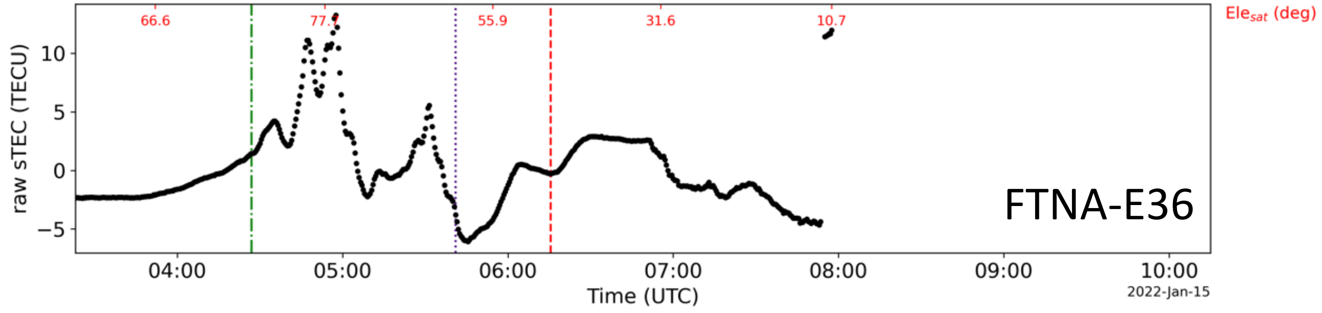
Zhang et al. (2022)

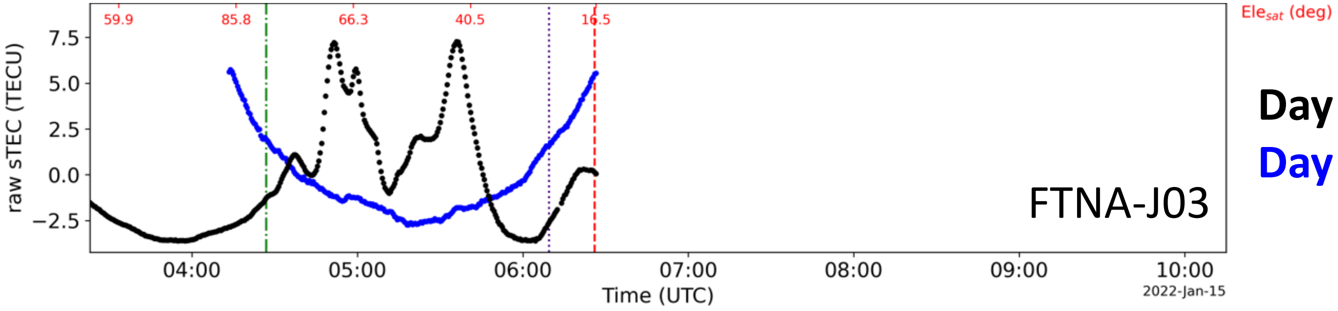
Near-field ionospheric TEC disturbances (FTNA, Wallis & Futuna)



Astafyeva et al. (submitted)

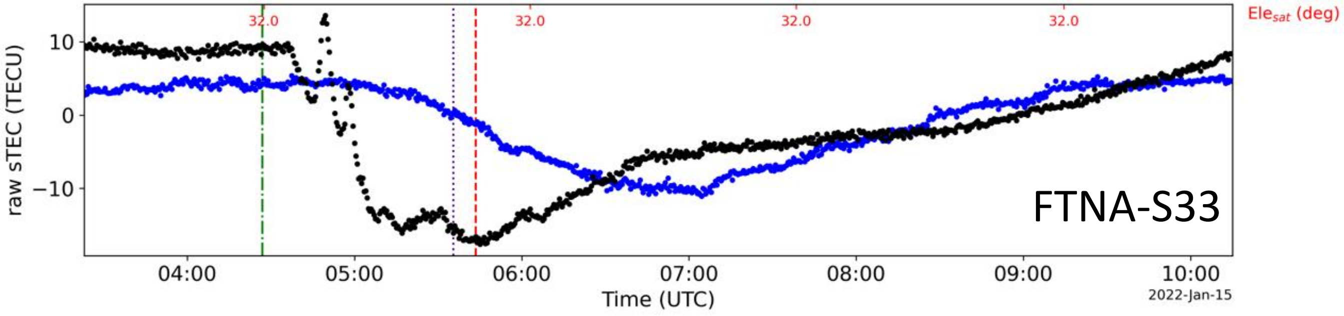
Main explosion time



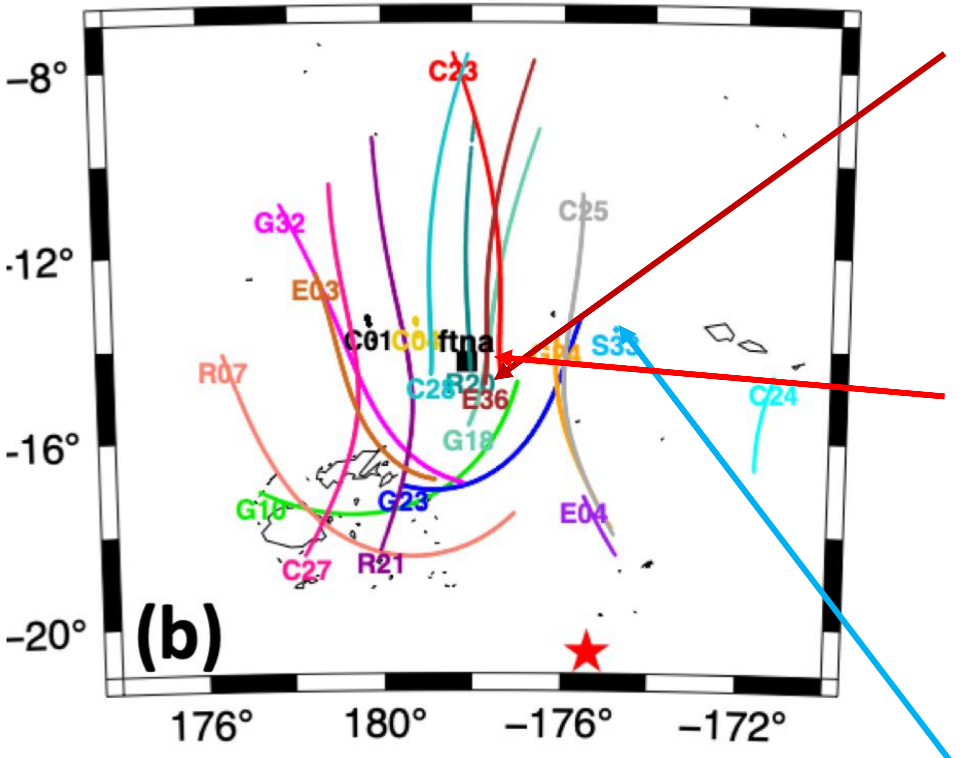


Day

Day before



Near-field ionospheric TEC disturbances (FTNA, Wallis & Futuna)



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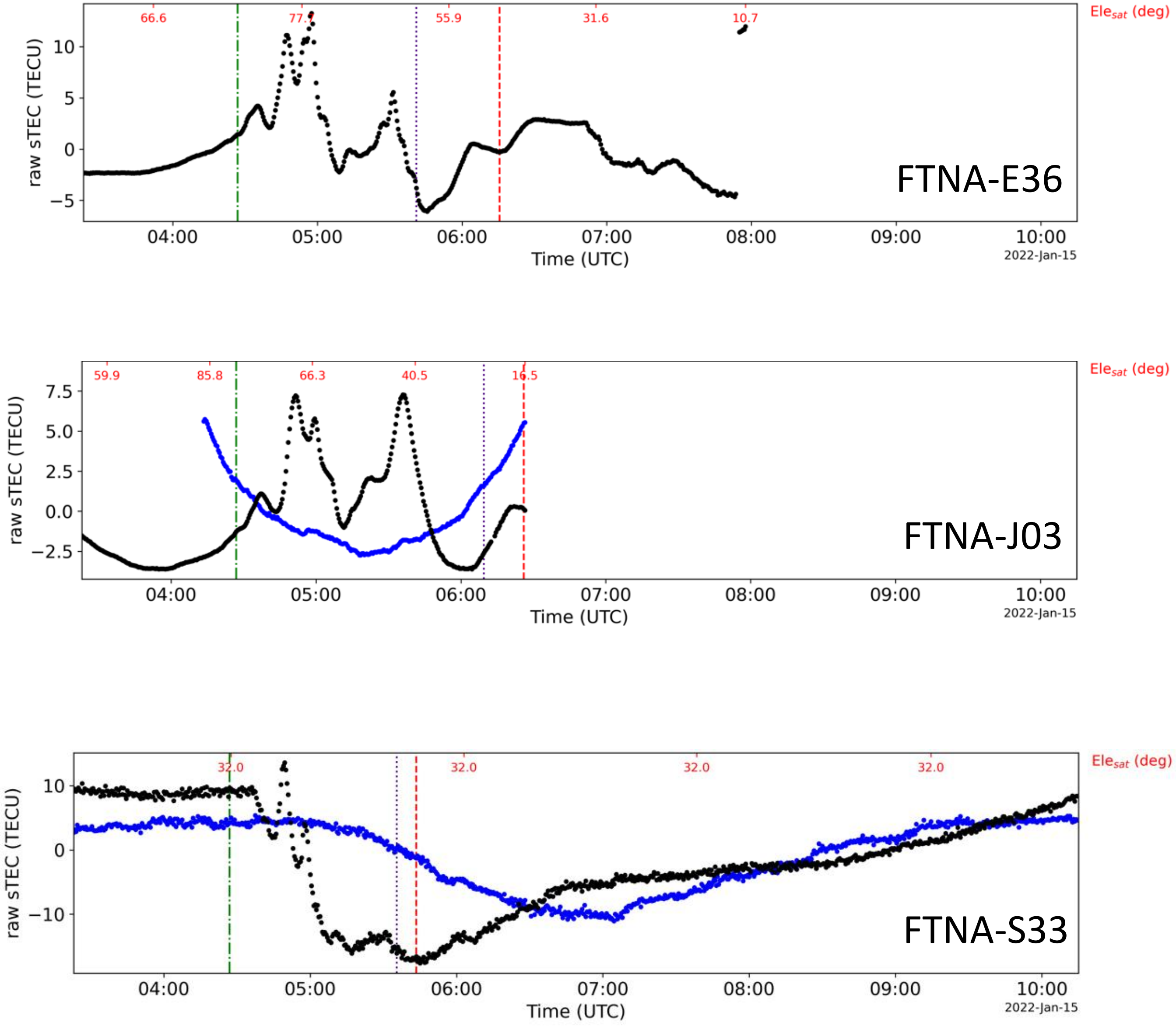
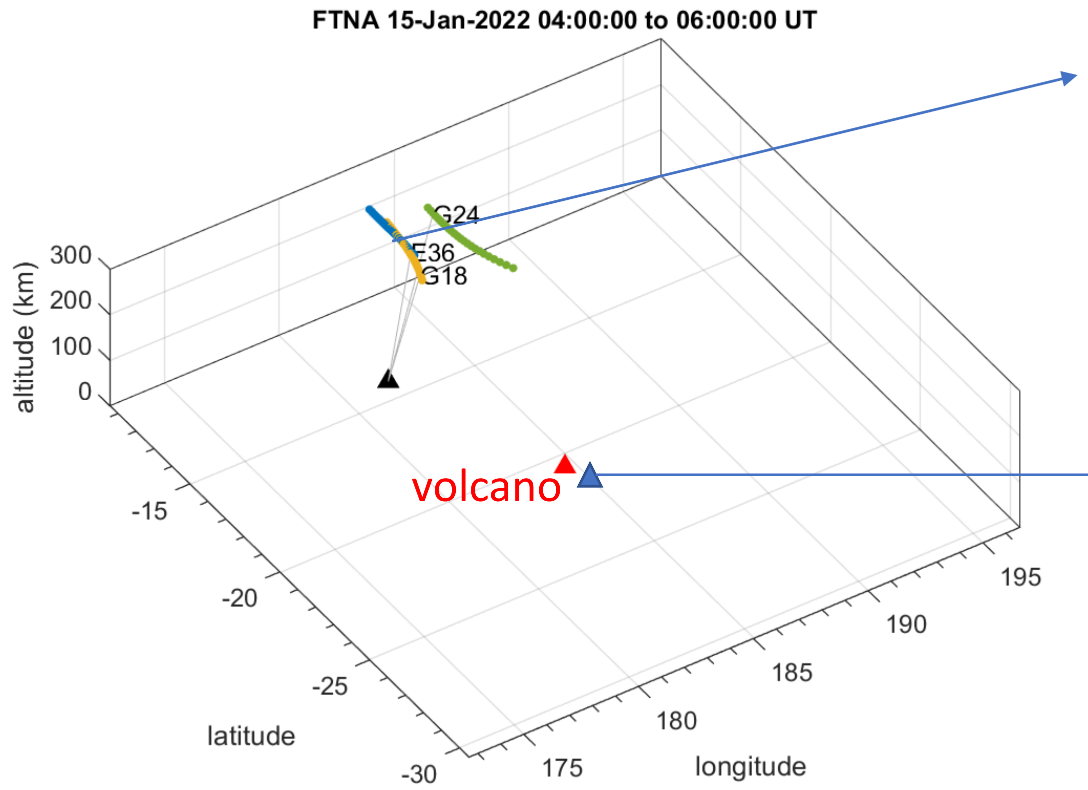
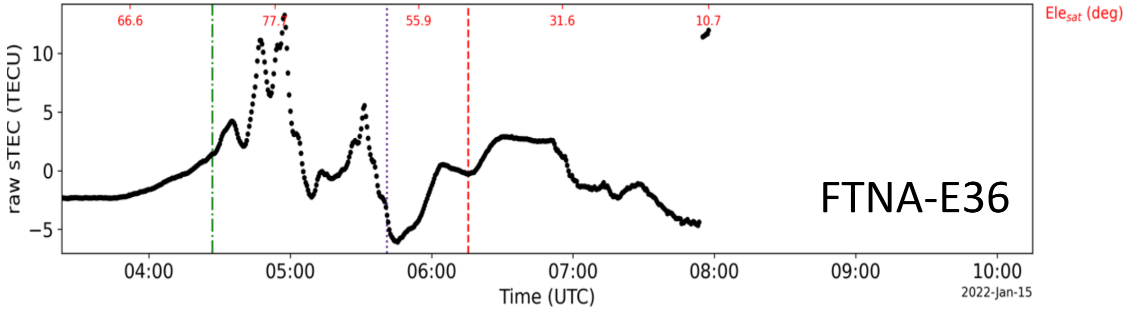


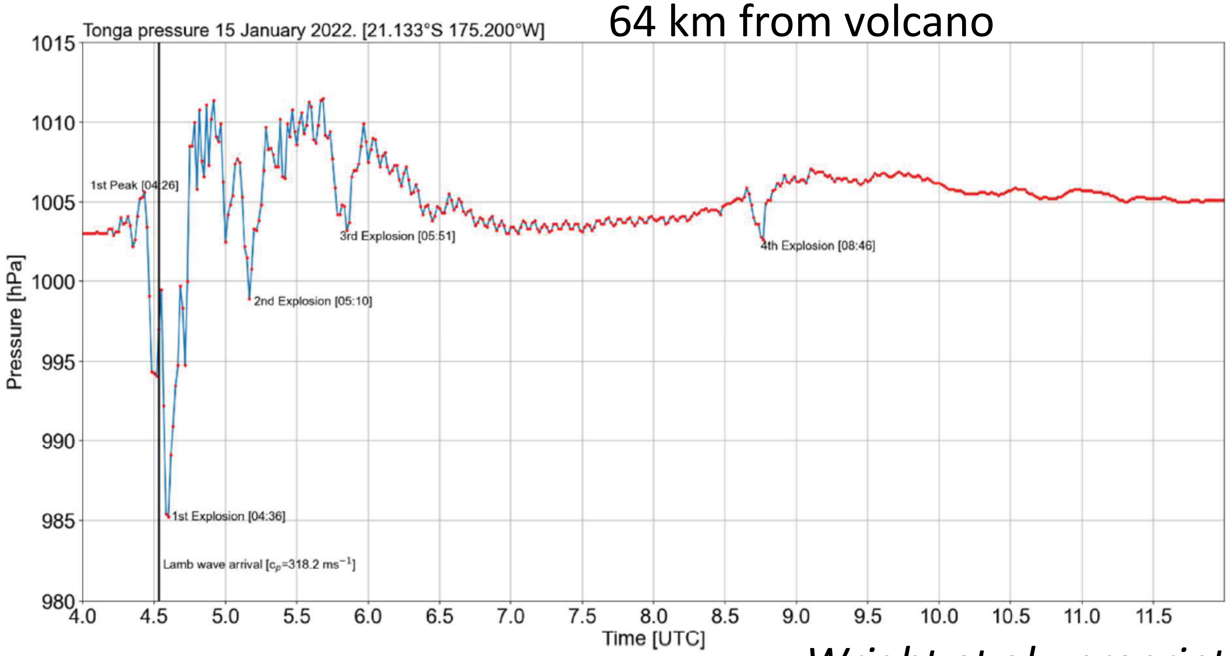
Multiple explosions signatures: ionosphere at height and pressure at ground



Main explosion time

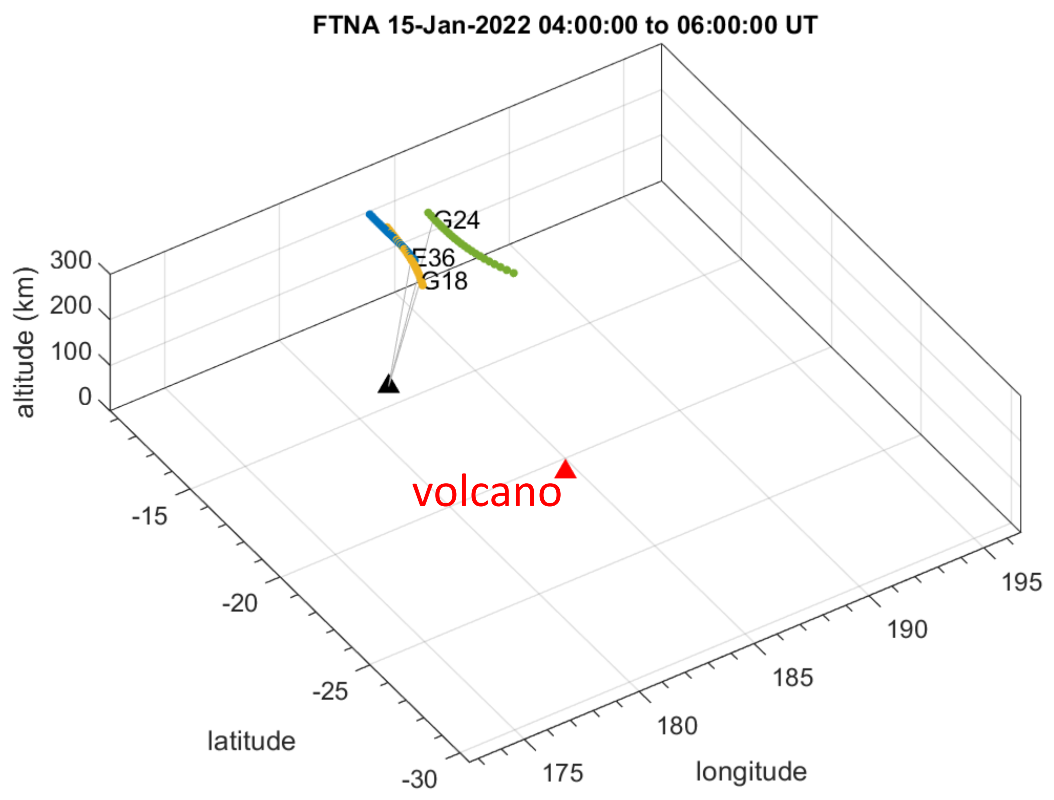


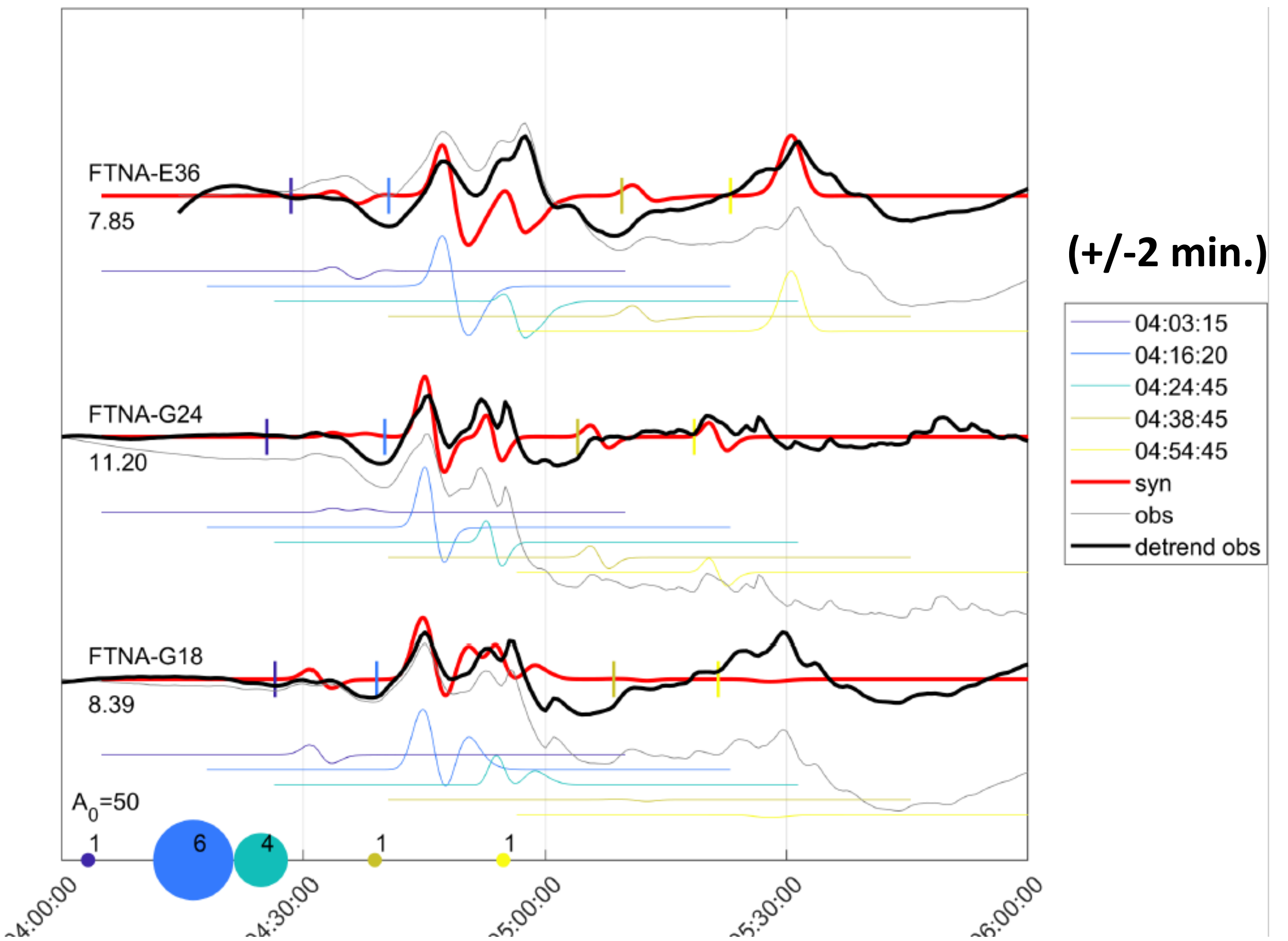
64 km from volcano



Wright et al., preprint

Near-field TEC disturbances (FTNA, Wallis & Futuna) – Simulations results





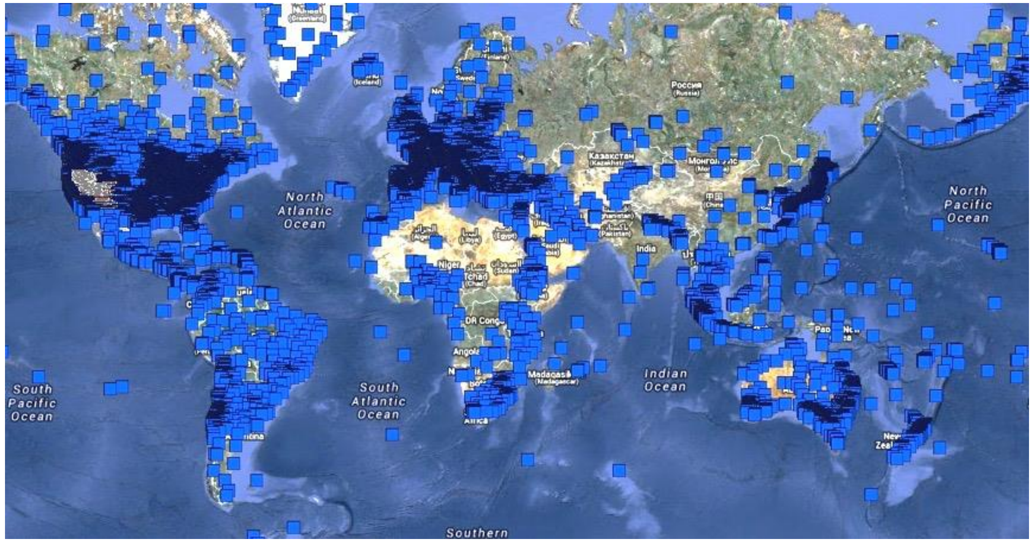
Astafyeva et al., submitted

Large pulse from an acoustic wave triggered at 04:16:20 UTC, seismological estimation is 04:15:45 UTC (USGS)
A trigger event at 04:03:15 UTC, confirmed by recent publications

Conclusive remarks: GNSS as thermospheric infrasound sensor

- GNSS-TEC monitoring:
  - for **rapid characterization** of earthquakes, volcano eruptions and tsunami sources
  - excellent **worldwide coverage**, sounds over oceans, thousands of measurement points (one GNSS station up to 30 concurrent measurements), completed by low-cost GNSS receivers
  - **more or less favorable locations** (geomagnetic field effect and ionosphere background noise)

- Ionosphere signature of direct acoustic wave
  - Simulations based on linear acoustic ray tracing and ionospheric coupling
  - **Non-linearities** for the most energetic sources (Mw>7.5 for earthquake) -> mismodelling
  - Significant filtering of the atmosphere on frequencies/wavelengths (energy dissipation)



Global permanent GNSS network

mail: lrolland@geoazur.unice.fr