Large Scale Travelling Ionospheric Disturbances LSTIDs: Sources, propagation characteristics, and detection techniques

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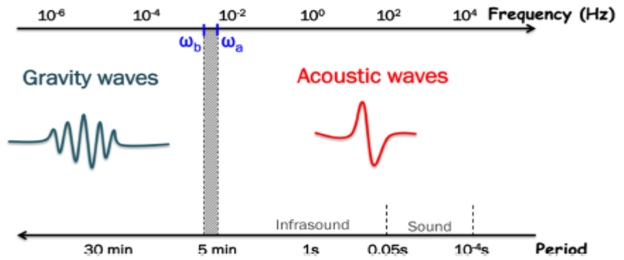
Outline

- **Introduction to TIDs**
  - Large Scale TIDs (LSTID)
  - Medium Scale TIDs (MSTID)
- **Sources of TIDs**
  - External Sources (Coupling from above)
  - Internal Sources (Coupling from below)
- **Propagation characteristics of LSTIDs**
- **Detection techniques of LSTIDs**

Introduction to TIDs

- **Travelling Ionospheric Disturbances (TIDs)**
  - ➢ Plasma density fluctuations propagating as waves through the ionosphere at a wide range of velocities and frequencies
  - ➢ Ionospheric manifestation of internal atmospheric gravity waves (AGW) in the neutral atmosphere
  - ➢ Play an important role in the exchange of momentum and energy between various regions of the upper atmosphere



Waves with $\omega > \omega_a$ are acoustic and propagate through the atmosphere (ω_a acoustic cutoff frequency). Waves with $\omega < \omega_b$ are the gravity waves (ω_b buoyancy or Brunt-Väissälä). Waves with frequencies $\omega_b < \omega < \omega_a$ (shaded rectangle) are evanescent waves and can only propagate horizontally

Hines CO. 1974. The upper atmosphere in motion, Geophysical Monograph, Vol. 18. American Geophysical Union, USA. ISBN: 9780875900186.

Hocke K, Schlegel K. 1996. A review of atmospheric gravity waves and travelling ionospheric disturbances: 1982–1995. Ann Geophys 14: 917–940. https://doi.org/10.1007/s00585-996-0917-6.

Introduction to TIDs

- **Classification of TIDs (according to wavelength, λ)**
  - Large Scale TIDs (LSTID), λ > 1000 km.
    - Horizontal velocity $v \approx$ 400 – 1000 m s^{-1} .
    - Temporal Period $T \approx$ 0.5 – 4 h .
  - Medium Scale TIDs (MSTID), $\lambda \approx$ 100 - 600 km.
    - Horizontal velocity $v \approx$ 100 – 250 m s^{-1} .
    - Temporal Period $T \approx$ 0.25 – 1 h .

Hocke K, & Schlegel K. 1996. A review of atmospheric gravity waves and travelling ionospheric disturbances: 1982–1995. Ann Geophys 14: 917–940. https://doi.org/10.1007/s00585-996-0917-6.

Fedorenko YP et al. 2013. Model of traveling ionospheric disturbances. J. Space Weather Space Clim., 2013, 3, A30. https://doi.org/10.1051/swsc/2013052.

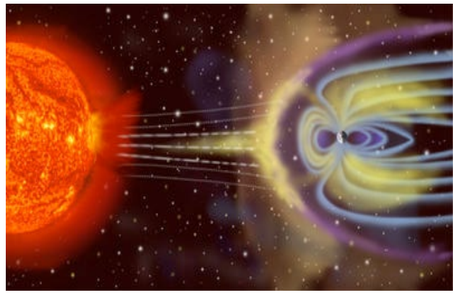
Sources of TIDs

Solar Terminator

Meteorites

Solar Eclipses

Solar Storms



Impact from external sources – Coupling from above

IONOSPHERE

Impact from internal sources – Coupling from below

Earthquakes

Tsunamis

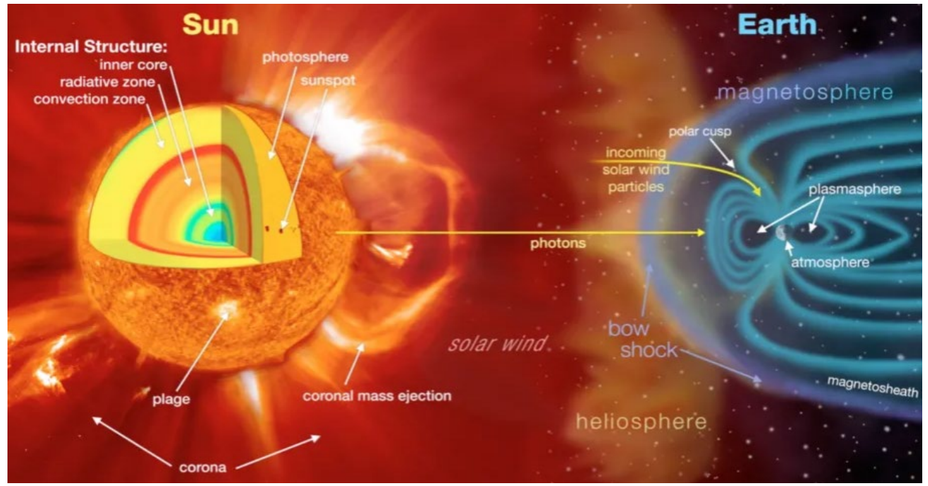
Volcanoes

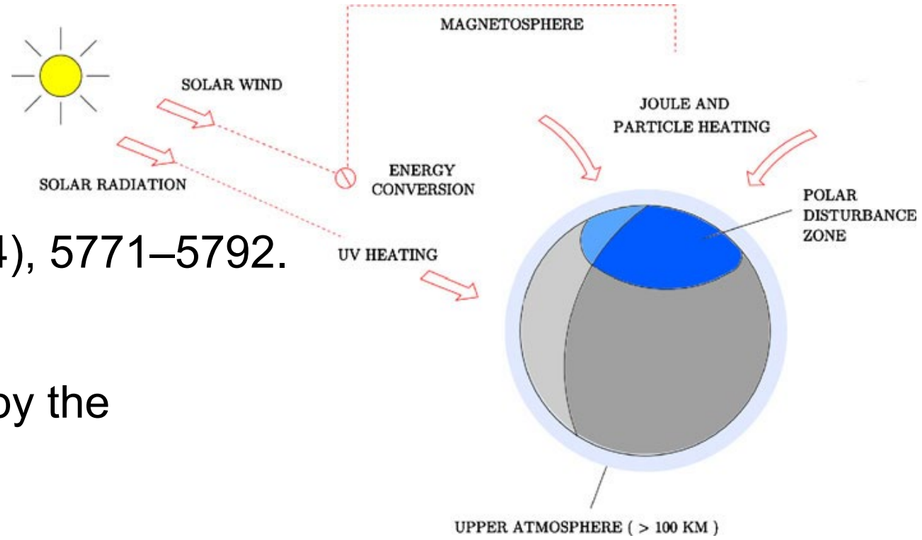
Meteorological

Artificial

Sources of TIDs

- **External (Ionospheric Coupling from above)**
  - ➢ Space Weather events.
    - Transitory events originated in the solar activity: Coronal Mass Ejections (**CME**), Corotating Interaction Regions/High Speed Solar wind Streams (**CIR/HSS**), … carry the particle precipitation in the polar cusp (electrons and protons) and **drive** geomagnetic storms and auroral activity.





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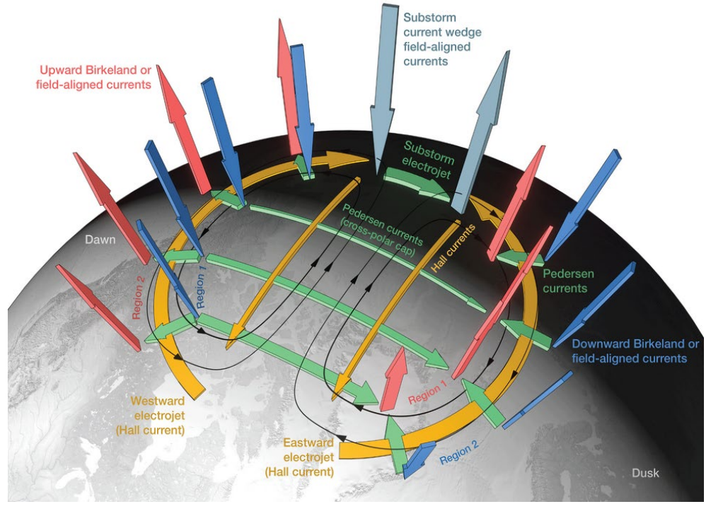
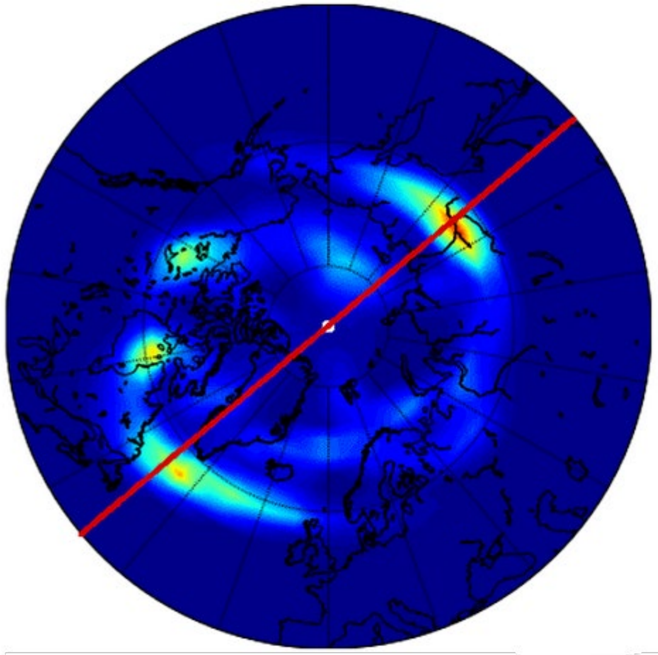
Sources of TIDs

- **External (Ionospheric Coupling from above)**
  - ➢ Space Weather events.
    - High latitude thermosphere is heated via the Joule effect during geomagnetically disturbed periods and energy is transferred towards lower latitudes in the form of waves that interact with the ions in the ionospheric plasma.





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Prölss GW, Očko M. 2000. Propagation of upper atmospheric storm effects towards lower latitudes. Adv Space Res 26: 131–135. https://doi.org/10.1016/S0273-1177(99)01039-X.

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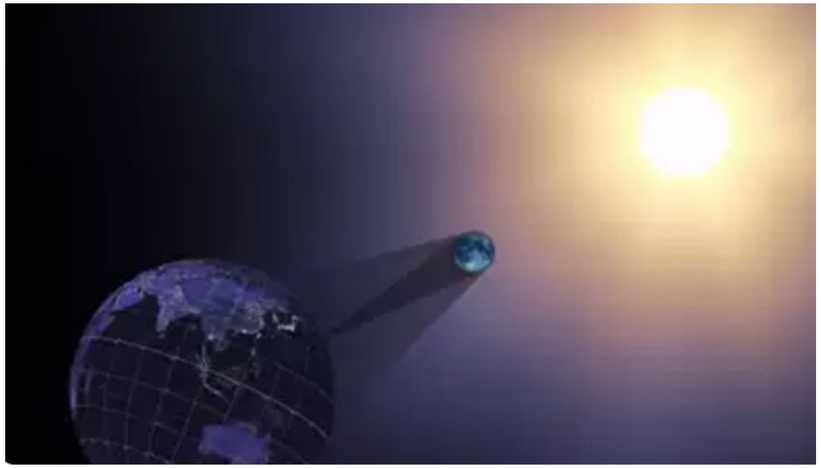
Sources of TIDs

- **External (Ionospheric Coupling from above)**
  - ➢ Solar Eclipses.
    - Earth's atmosphere and ionosphere are affected by rapid increasing/decreasing ionizing radiation, thermospheric cooling/heating, and changes in the neutral winds, diffusion, and composition.



This NASA file handout photo illustration shows a visualization animation still image of the Earth, moon, and sun during the eclipse. (Used for representation only)

The Moon casts a shadow on Earth during a total solar eclipse over Europe in this image taken by a French astronaut on the Mir Space Station. Credit: CNES

Chimonas, G, Hines, CO, 1970. Atmospheric gravity waves induced by a solar eclipse. Journal of Geophysical Research 75, 875. https://doi.org/10.1029/JA075i004p00875.

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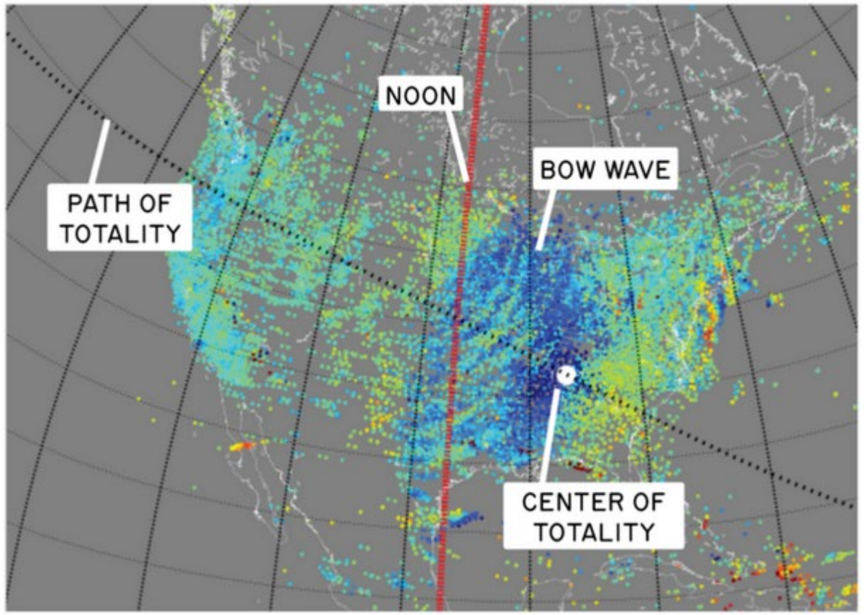
Sources of TIDs

- **External (Ionospheric Coupling from above)**
  - ➢ Solar Eclipses.
    - The cooling source of Moon's umbra propagating at supersonic speed build up a wave front contributing to generation of AGW.



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Zhang S-R, et al. 2017. Ionospheric bow waves and perturbations induced by the 21 August 2017 solar eclipse. Geophysical Research Letters,44, 12,067–12,073. https://doi.org/10.1002/2017GL076054.

Sources of TIDs

- **External (Ionospheric Coupling from above)**
  - ➢ Moving Solar Terminator.
    - Moving step of atmospheric magnitudes (e.g. pressure, temperature) result in a linear mechanisms for wave excitation of Solar terminator.
    - Atmospheric instabilities inside the Solar Terminator region generate nonlinear mechanisms of wave excitation (e.g., gradient-radiation instability arising from the vertically inhomogeneous absorption of solar radiation, turbulence, and the plasma instability in the evening hours caused by the increase of the electron pressure gradient).

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Galushko VG et al., 1998. Incoherent scatter radar observa-tions of AGW/TID events generated by the solar terminator. Ann. Geophys., 16, 821−827. https://doi.org/10.1007/s00585-998-0821-3.

Sources of TIDs

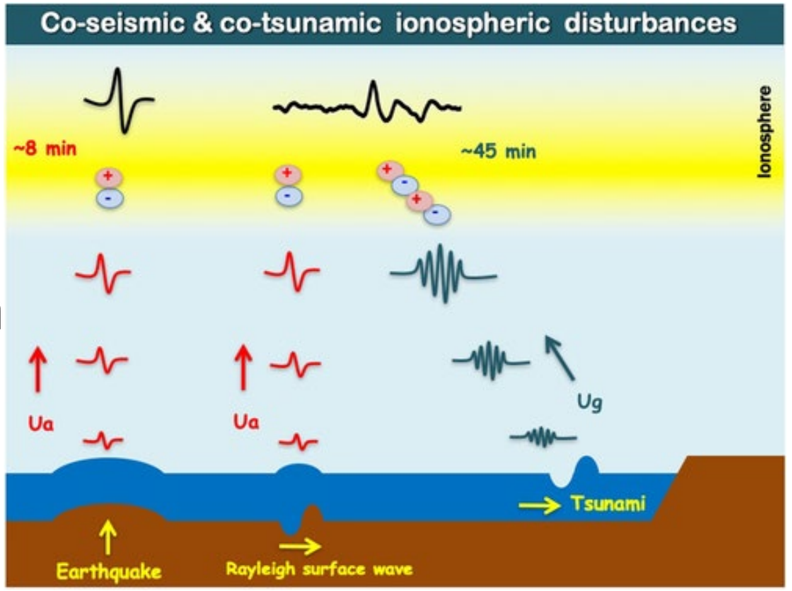
- **External (Ionospheric Coupling from above)**
  - ➢ Bolides - Meteorites.
    - Acoustic wave driven from the associated burst in the atmosphere launched to the ionosphere and Acoustic Gravity wave driven from the associated burst in the atmosphere again launched to the ionosphere.
    - A similar phenomenon to the seismic induced ionospheric disturbances.

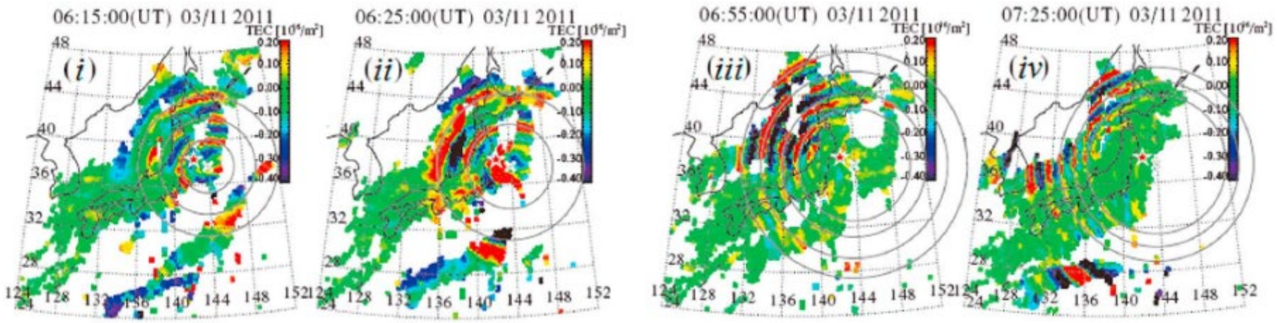
Berngardt, OI et al. 2013. Geophysical phenomena accompanying the Chelyabinsk meteoroid impact, Dokl. Earth Sc. 452, 945–947. https://doi.org/10.1134/S1028334X13090080.

Perevalova, NP et al. 2015. Ionospheric disturbances in the vicinity of the Chelyabinsk meteoroid explosive disruption as inferred from dense GPS observations, Geophys. Res. Lett., 42, 6535–6543, https://doi.org/10.1002/2015GL064792.

Sources of TIDs

- **Internal (Ionospheric Coupling from below)**
  - ➢ Earthquake - Tsunamis.
    - Rayleigh wave driven from the associated disturbance in the epicenter are launched to the ionosphere and Acoustic Gravity Wave driven from the associated disturbance epicenter again launched to the ionosphere.





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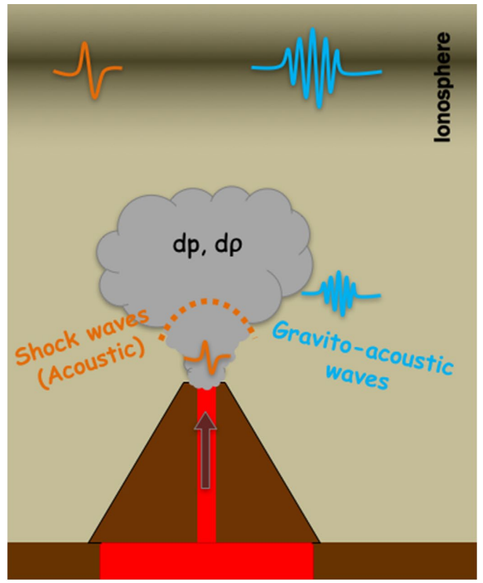
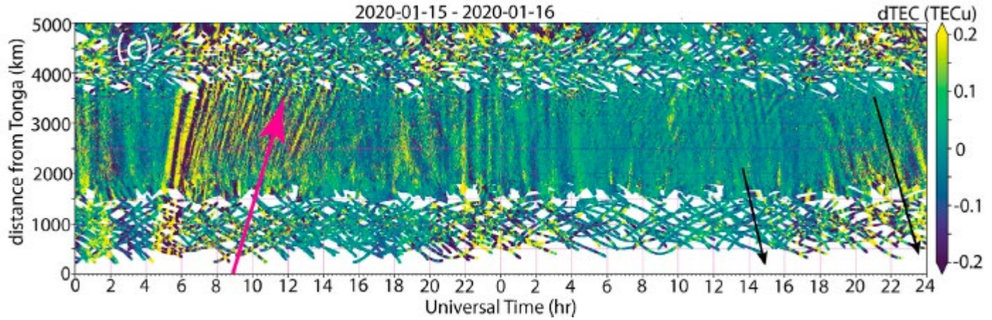
Sources of TIDs

- **Internal (Ionospheric Coupling from below)**
  - ➢ Volcanoes.
    - Shock-acoustic waves generated may reach the ionosphere from ~8–9 min after an eruption.
    - Sudden changes of local pressure (dp) and density (dρ) may drive AGW reaching the ionosphere by ~45 min the eruption.





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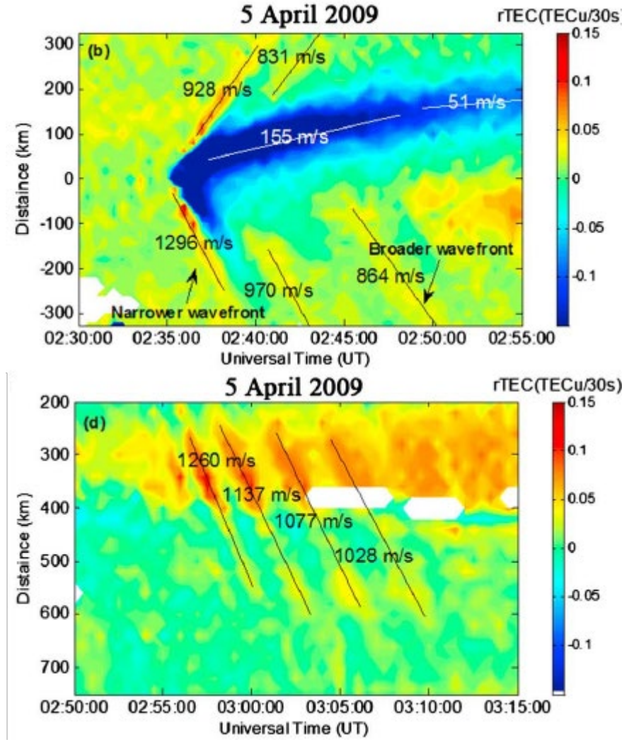
Zhang S-R et al. 2022. 2022 Tonga Volcanic Eruption Induced Global Propagation of Ionospheric Disturbances via Lamb Waves. Front. Astron. Space Sci. 9:871275. https://doi.org/10.3389/fspas.2022.871275.

Sources of TIDs

- **Internal (Ionospheric Coupling from below)**
  - ➢ Rocket launch effects.
    - The observed AGW-related TIDs and ionospheric perturbation waves due to the rocket passage are similar to the solar eclipse effect. A localized heat sink traveling through a gravitationally stratified atmosphere with supersonic may result in shock waves observable in the ionospheric plasma perturbation.



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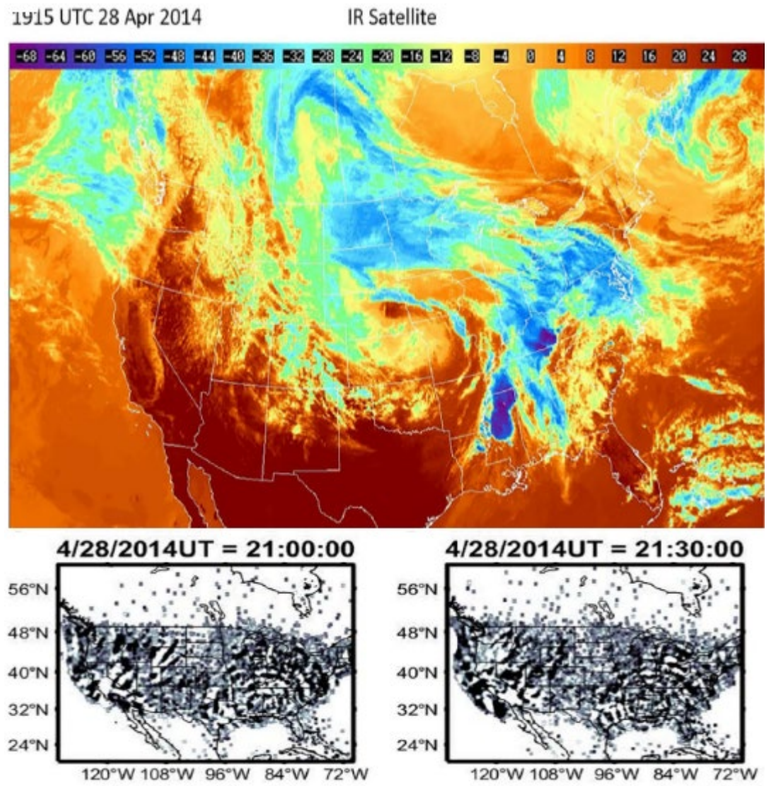
Sources of TIDs

- **Internal (Ionospheric Coupling from below)**
  - ➢ Meteorological effects.
    - Although most primary gravity waves from deep convection break or dissipate in the lower atmosphere, those primary gravity waves with intrinsic phase speeds > 100 m/s can propagate into the thermosphere and ionosphere.



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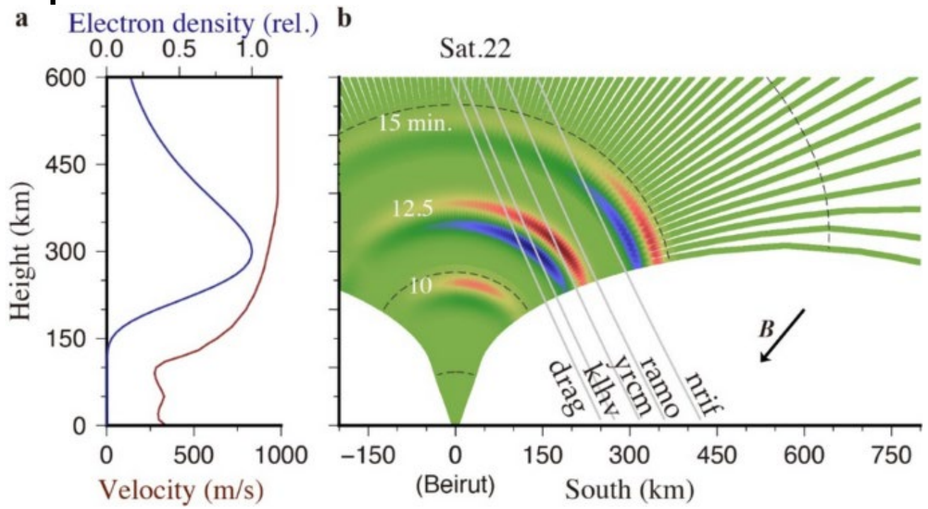
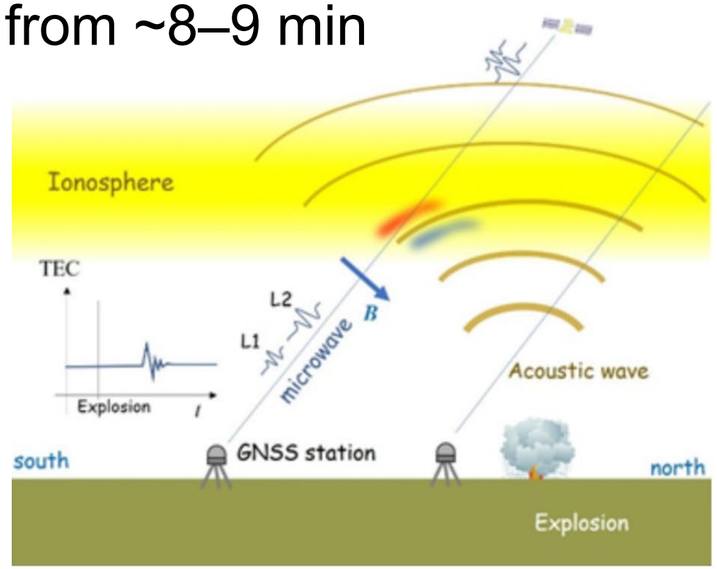
Sources of TIDs

- **Internal (Ionospheric Coupling from below)**
  - ➢ Artificial explosions.
    - Shock-acoustic waves generated may reach the ionosphere from ~8–9 min after a blast or explosion.





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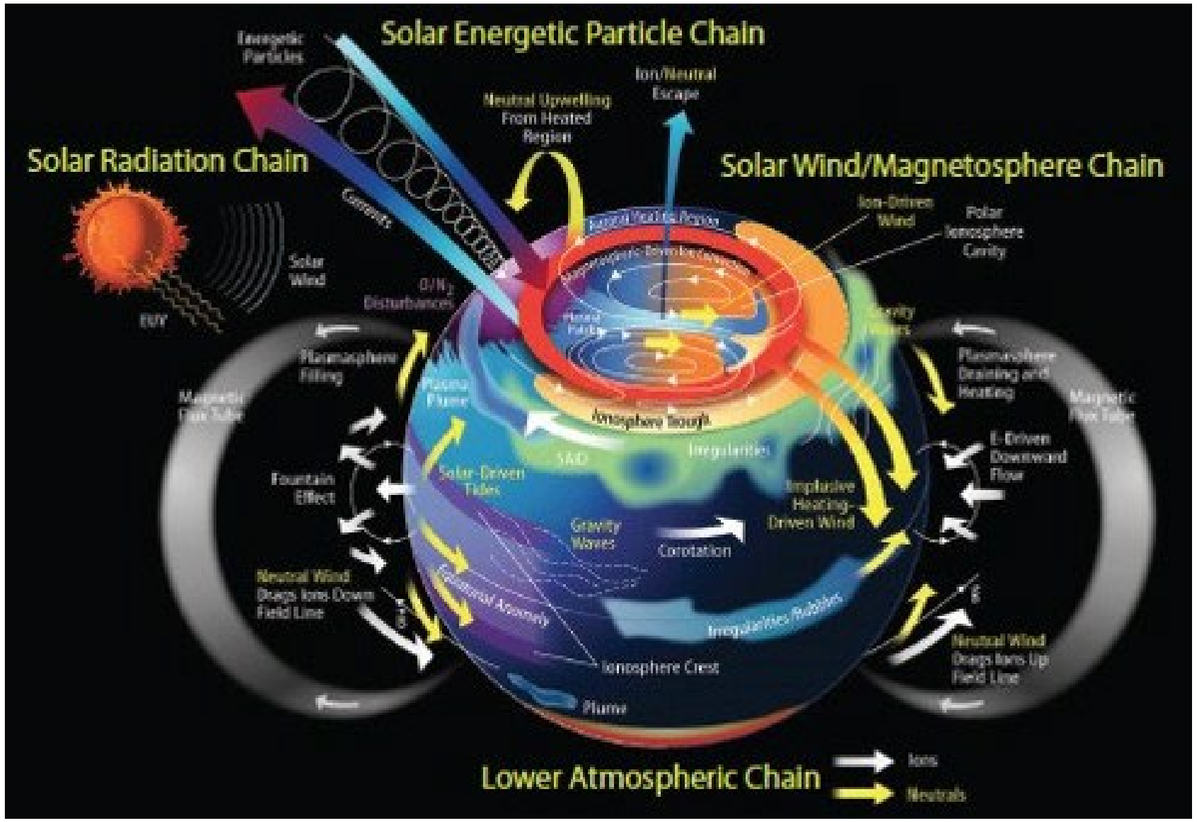
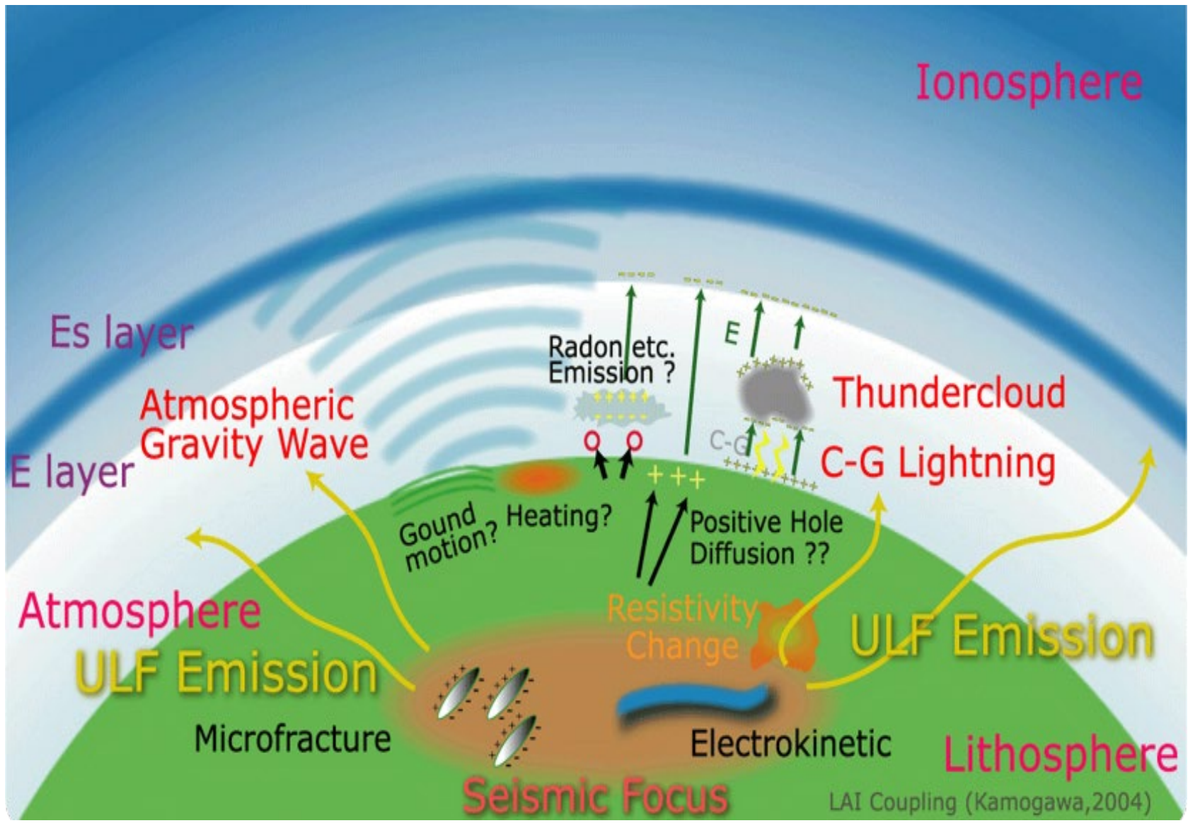
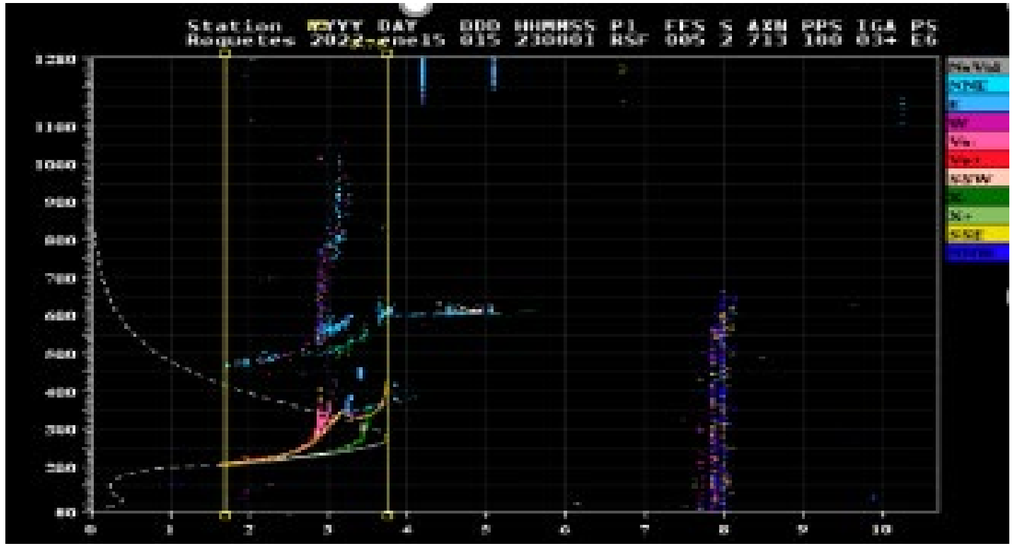
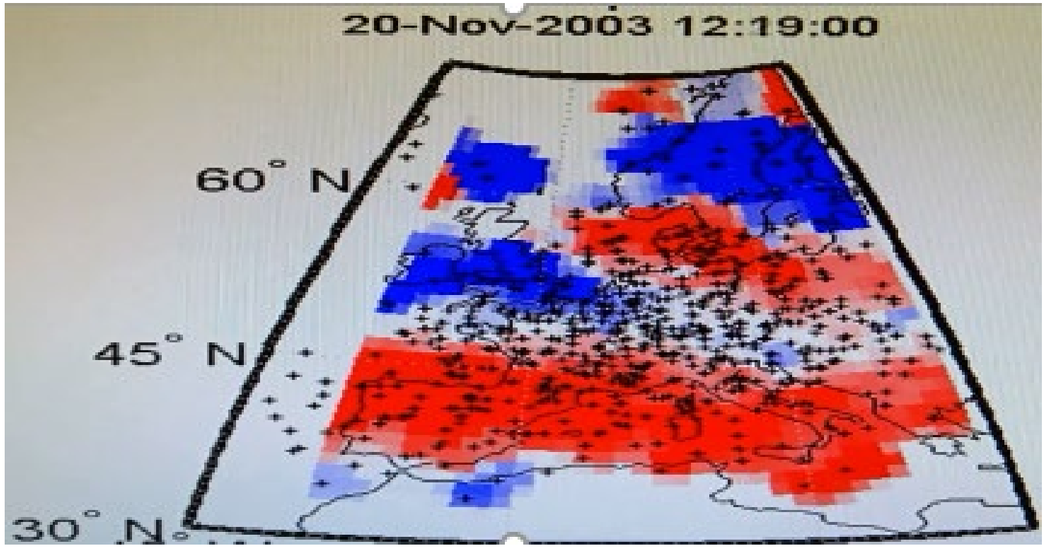
Sources of TIDs





Sources of TIDs





Propagation characteristics of LSTIDs

- **Model perturbation in the background electron density**
  - $\Delta N_e\,(\vec{r},t) = |\Delta N_e| e^{(i\psi)}$
    - $\vec{r}$ - Position, t - time, $|\Delta N_e|$ - Magnitude of the perturbation.
  - $\psi = \omega t - \vec{k}\cdot\vec{r} + \tan^{-1}\left[\frac{\sin(I)}{k_{br}}\left(\frac{1}{Ne}\frac{\partial Ne}{\partial z} + k_{zi}\right)\right]$
    - $\vec{k}$ - Phase vector, ω - angular frequency, I - Inclination of the magnetic field, k_{br} and k_{zi} - real and imaginary parts of $\vec{k}$.
  - Assuming no dissipation
    - $k_{zi} = {}^{1}/_{2H}$, H - Scale Height, $H = \frac{k_B T}{\bar{\mu} m_u g}$, k_B - Boltzmann's constant, T - Temperature, $\bar{\mu}$ - mean molecular mass, m_u - atomic mass unit, g - acceleration due to gravity.

Hooke, WH. 1968. Ionospheric irregularities produced by internal atmospheric gravity waves, J. Atmos. Terr. Phys., 30, 795–823. https://doi.org/10.1016/S0021-9169(68)80033-9.

Propagation characteristics of LSTIDs

- **Model perturbation in the background electron density**
  - ➢ Magnitude electron density perturbation by AGW

$$|\Delta N_e| = N_e U_b(z_0)\, e^{[k_{zi}(z-z_0)]}\, \omega^{-1} \sin(I) \cdot \left[\left(\frac{1}{N_e}\frac{\partial N_e}{\partial z}\right) + \left(\frac{k_{br}}{\sin(I)}\right)^2\right]^{1/2}$$

- N_e - Unperturbed electron density, $U_b(z_0)$ - neutral gas velocity parallel to the magnetic field at reference height z_0, I - Inclination of the magnetic field, k_{br} and k_{zi} - real and imaginary parts of $\vec{k}$.
- Valid for below F layer peak.

Hines, CO. 1968. An effect of molecular dissipation in upper atmospheric gravity waves, J. Atmos. Terr. Phys., 30, 845–849. https://doi.org/10.1016/S0021-9169(68)80036-4.

Propagation characteristics of LSTIDs

- **Model perturbation in the background electron density**

  - Assuming planar phase fronts of the AGW & direction of travel is parallel to one of the horizontal axes:

$$\vec{k} = k(k, 0, m)\ , m^2 = k_{zi}\left(\frac{\omega_B^2}{\omega^2} - 1\right) + \frac{(\omega^2 - \omega_B^2)}{c^2}$$

  - ω_B - buoyancy or Brunt-Väissälä frequency, ω_a - acoustic cutoff frequency, c - speed of sound. AGW $\omega < \omega_a$.

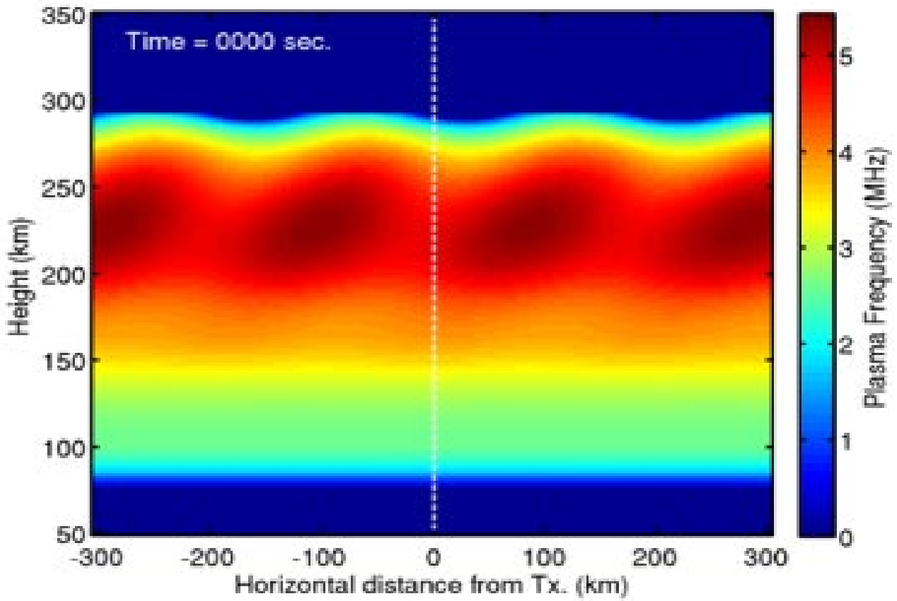
$$\omega_B = \frac{(\gamma - 1)g}{\gamma H},\ \ c = \sqrt{\gamma g H},\ \omega_a = \frac{c}{2H}$$

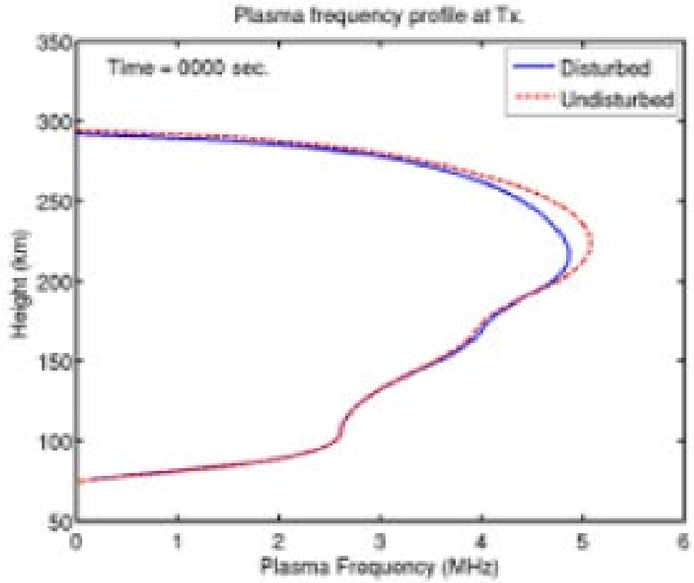
  - γ - ratio of the specific heat of dry air at constant pressure to the specific heat at constant volume, c - speed of sound.

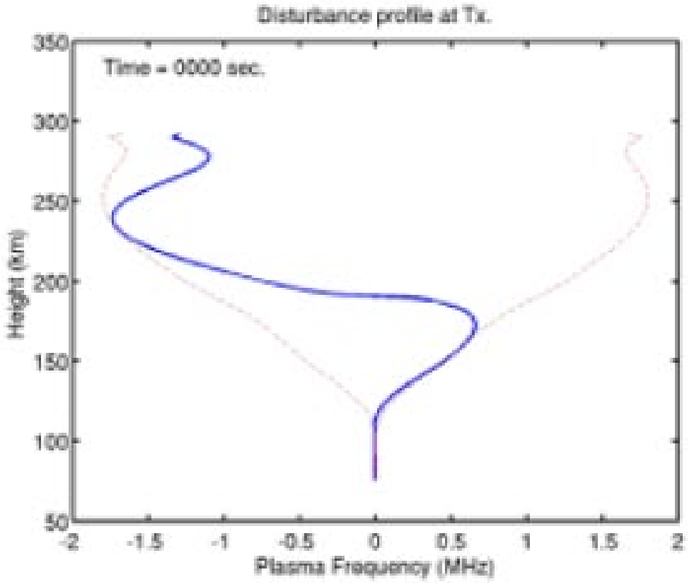
Cervera, MA and TJ Harris. 2014. Modeling ionospheric disturbance features in quasi-vertically incident ionograms using 3-D magnetoionic ray tracing and atmospheric gravity waves, J. Geophys. Res. Space Physics, 119, 431–440,, https://doi.org/10.1002/2013JA019247.

Propagation characteristics of LSTIDs

- **Model perturbation in the background electron density**
  - TID generated by AGW in Australian region, traveling in the direction 225º from N. With λ = 200 km, T = 20 min, and U_b = 15 ms^{-1} , z_0 = 250 km. TID tilted by 55º,







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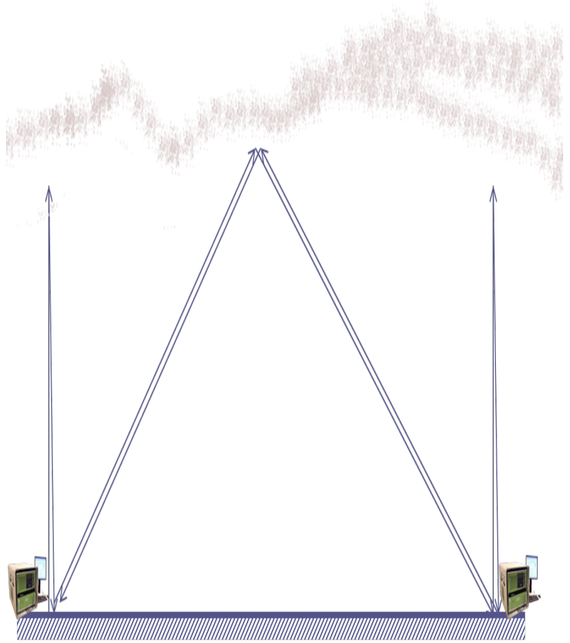
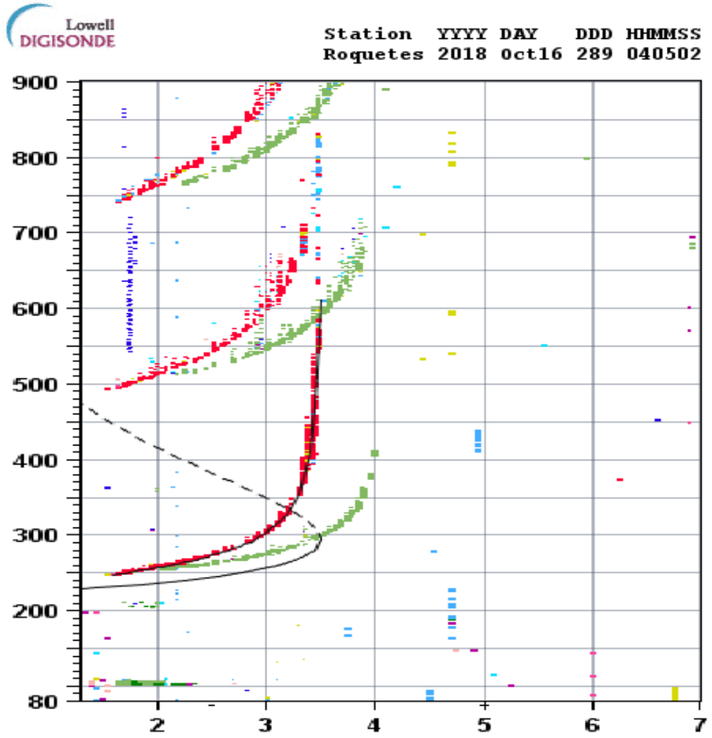
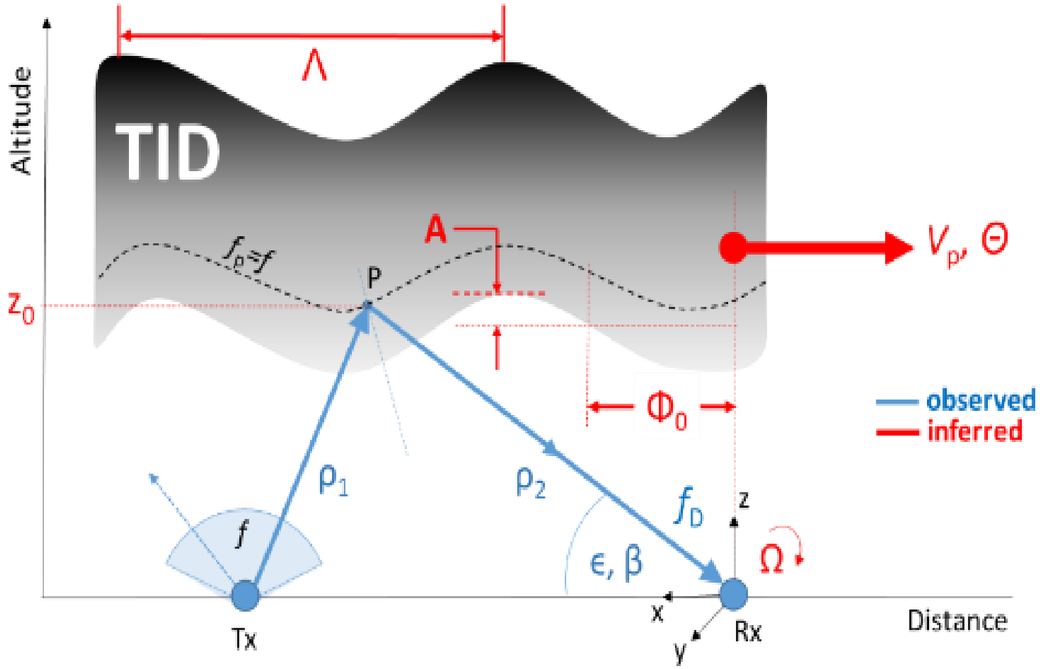
Detection techniques of LSTIDs

- **Ground Based sensors**







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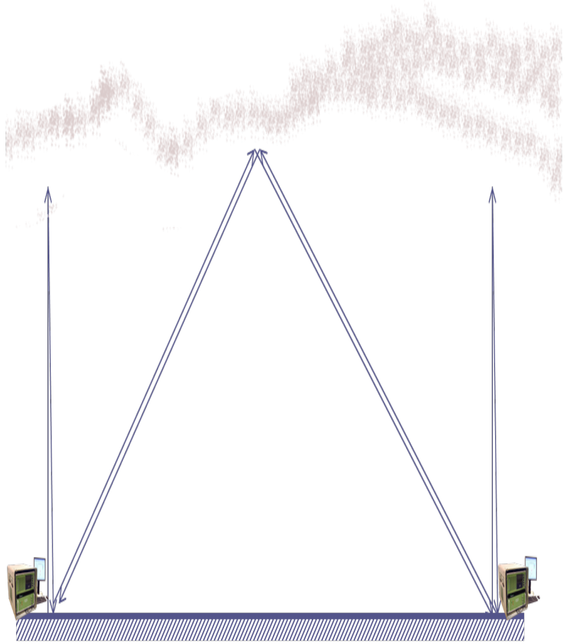
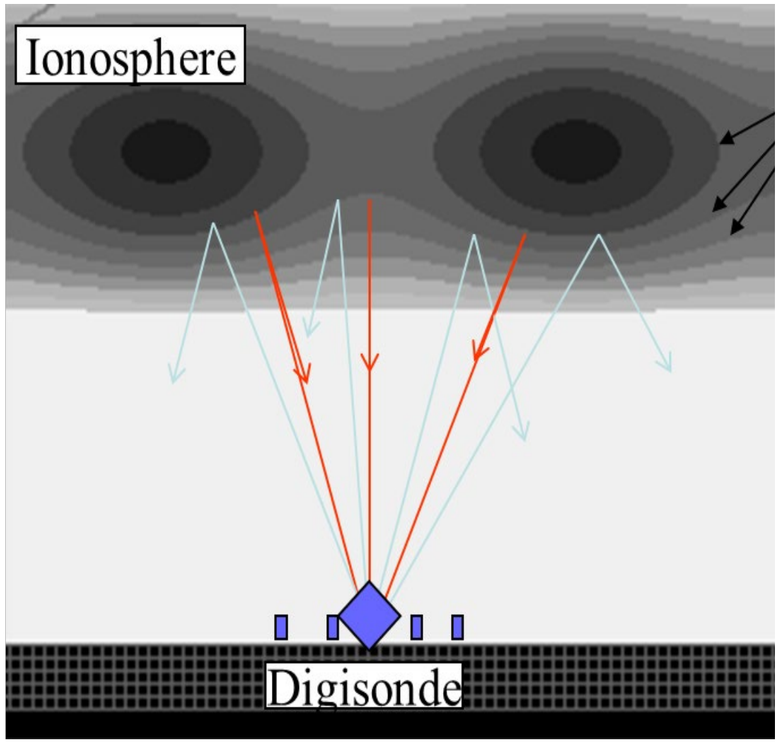
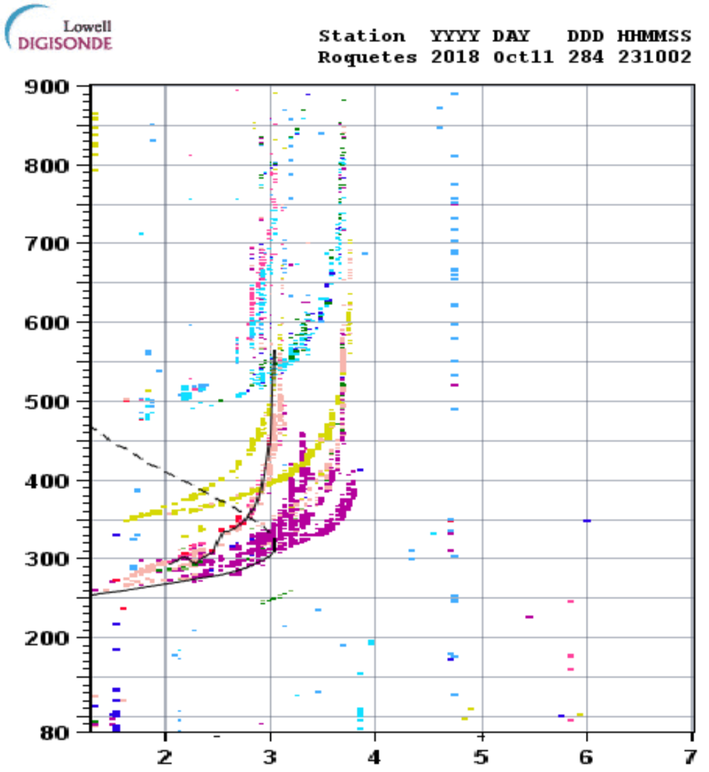
Detection techniques of LSTIDs

- **Ground Based sensors**







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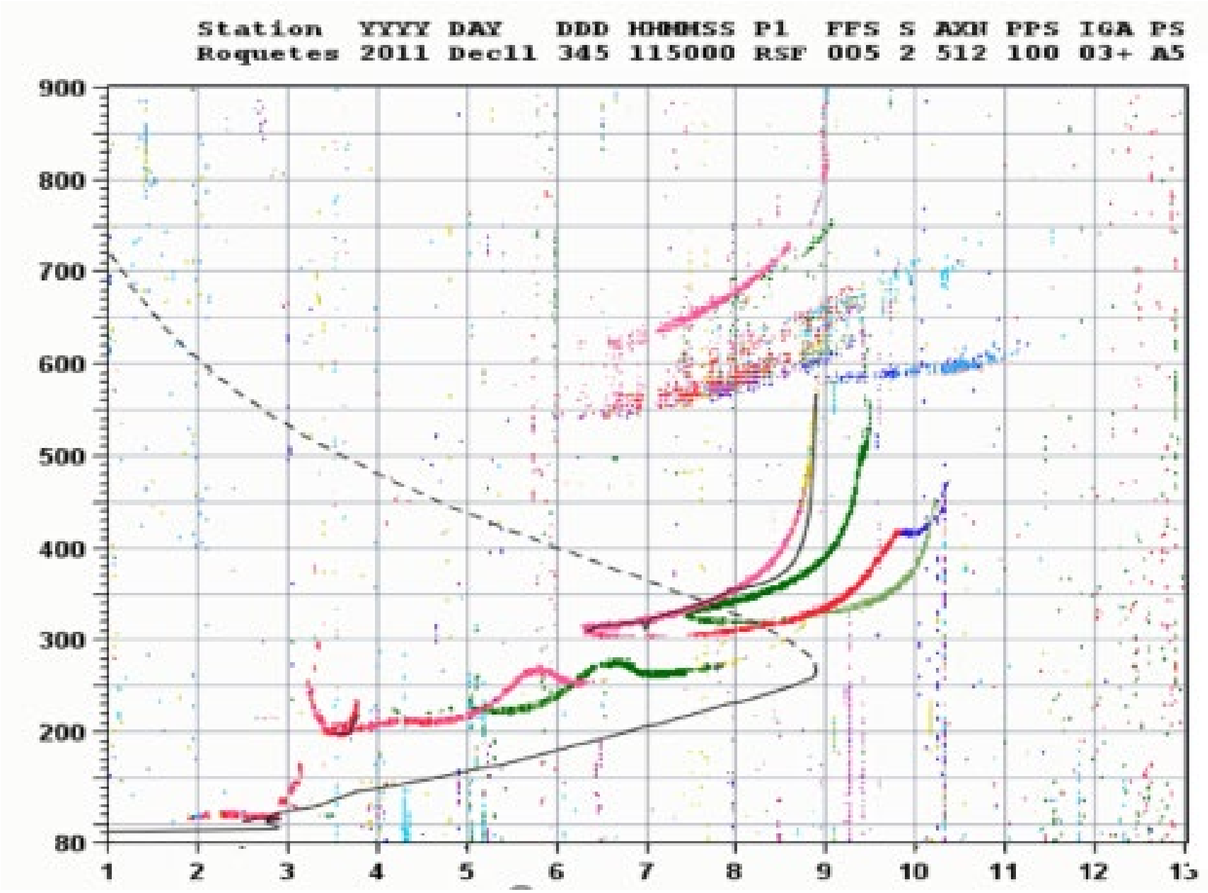

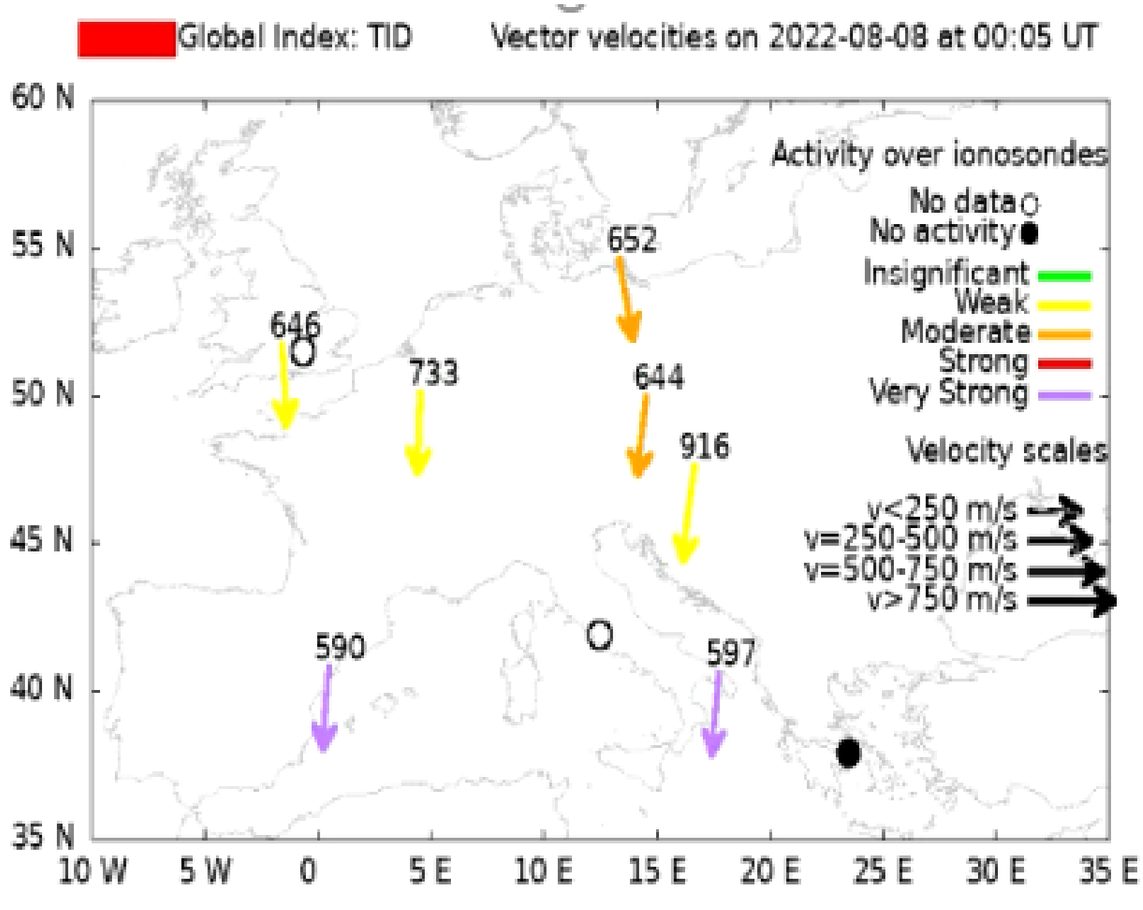

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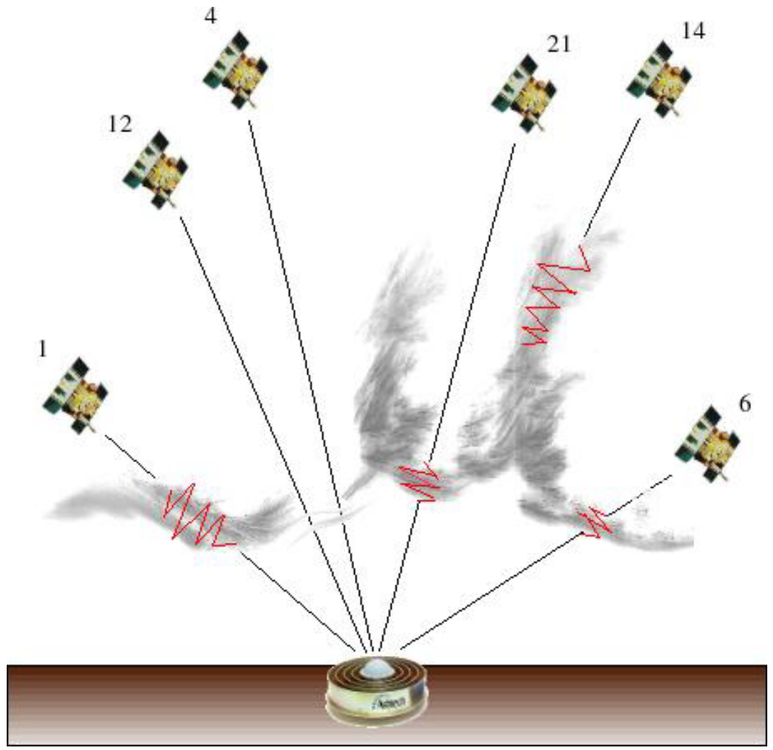
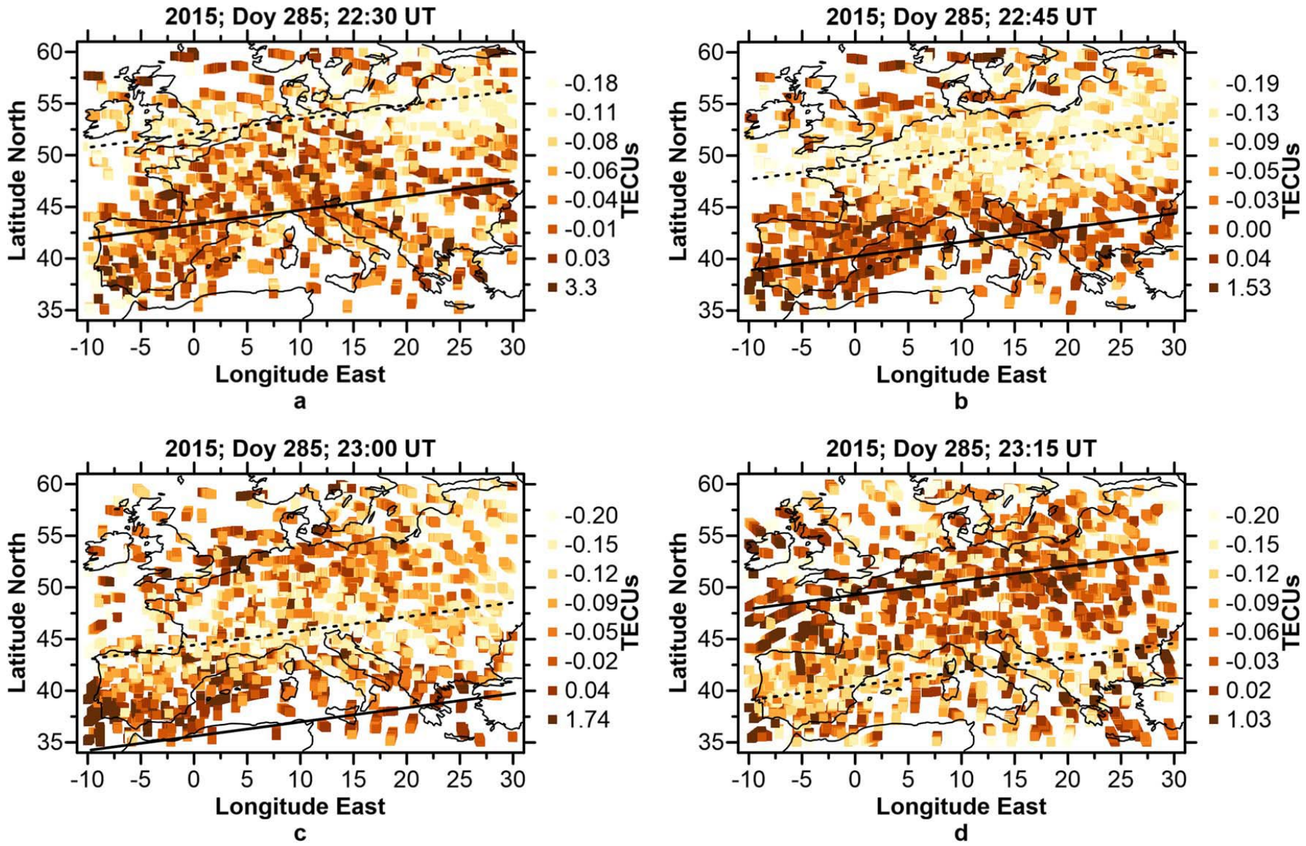
Detection techniques of LSTIDs

- **Satellite Based sensors**





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Detection techniques of LSTIDs

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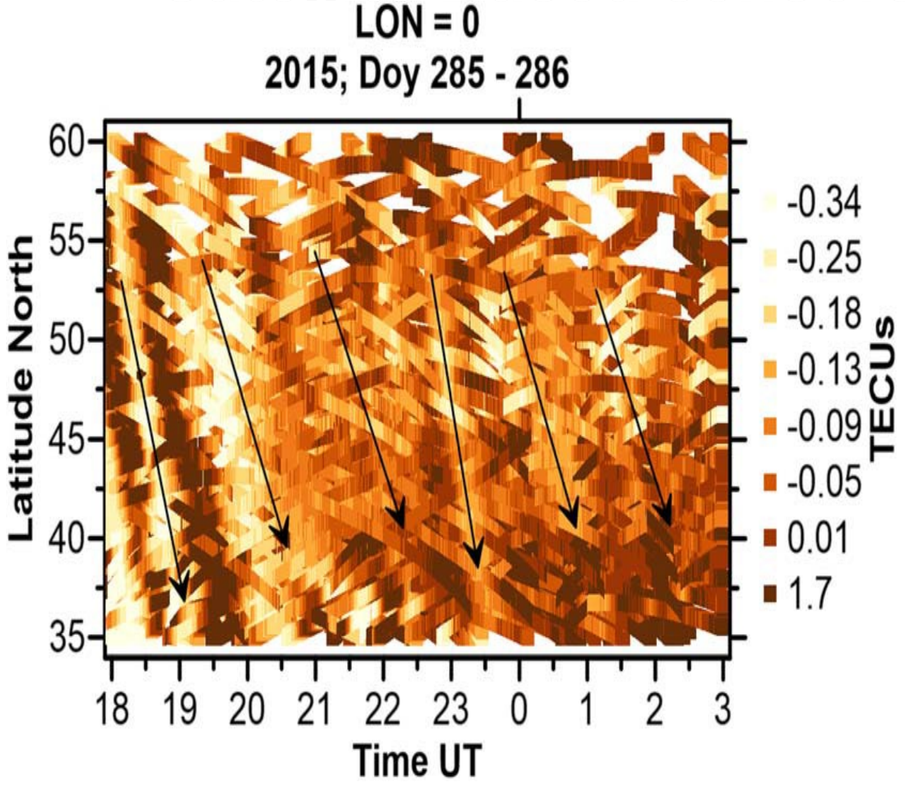

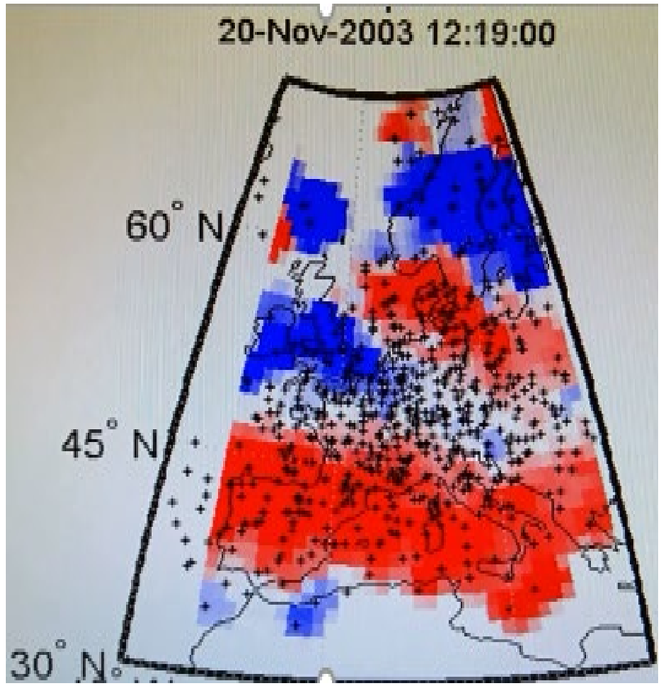

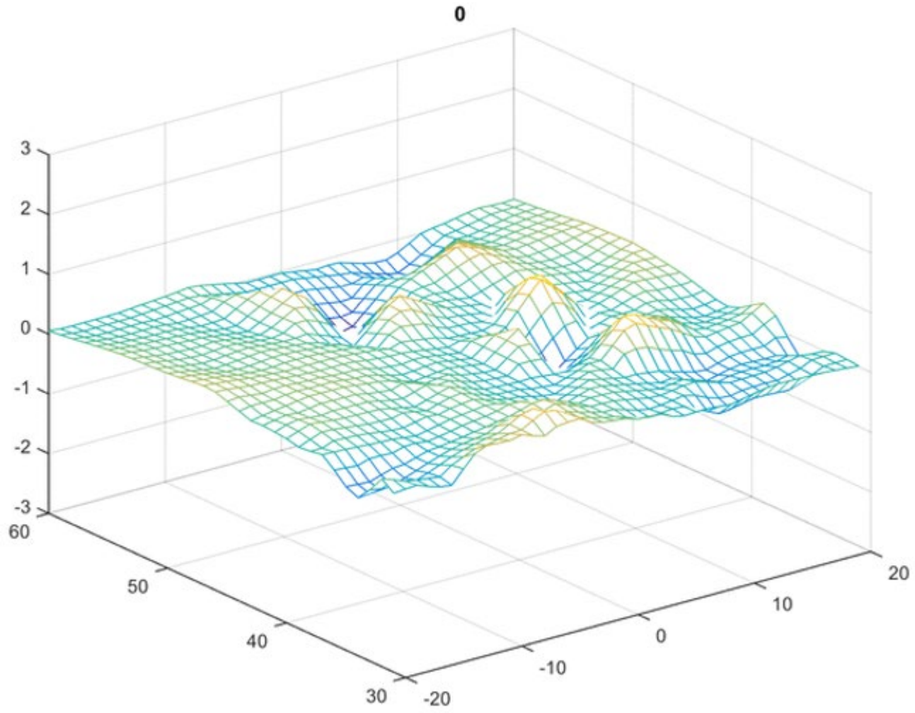

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Thank you for your attention!

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