Seismic source characterization by ionospheric sounding from ground positioning system data

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Abstract

Imaging the terrestrial ionosphere is becoming possible since the installation of dense GPS networks, with a temporal and spatial resolution allowing the detection of ionospheric seismic waves. Since the 1960s, ionospheric seismic waves are detectable almost punctually after large shallow earthquakes, with current **minimum magnitude of 6.5**. Most recently, the use of dense networks gave the way to a global visualization of the horizontal propagation of co-seismic ionospheric disturbances. Such a use of a Global Positioning System array, and the sounding capability of the method above the ocean, prove the potential of this method as a complement to more traditional techniques used in seismology.

From now on, after imaging seismic waves in the ionosphere, the challenge is the characterization of the seismic source, whose rupture involves coupling mechanisms between the moving solid earth and its surrounding atmosphere. The study presented here is based on the Total Electronic Content variations mapped close to the source and shortly after the Tokachi-Oki earthquake (M=8.3) that occurred on September, 25, 2003, in Japan. The first fundamental source parameters derived from 1 Hz sampled data will be reminded here. The rupture process is then pre-modelled in reference to the co-seismic displacements estimated by other techniques. Therefore, a modelling of the horizontal propagation of acoustic waves generated by three aligned separated sources is developed. The preliminary results of the subsequent GPS data inversion tests will be presented. Finally, for physical modelling of the vertical propagation, we used ray tracing in the atmosphere, in order to study the effects of the near-field pulse spreading in acoustic domain as well as the redistribution of the charged particles under **geomagnetic dependency**. This could explain the south-western directivity of most of the seismic perturbations observed in the TEC above Japan (cf. **[Heki&Ping,2005]**) and first observed in California by **[Calais et al., 1998].**

Earth – Neutral Atmosphere – Ionosphere Coupling

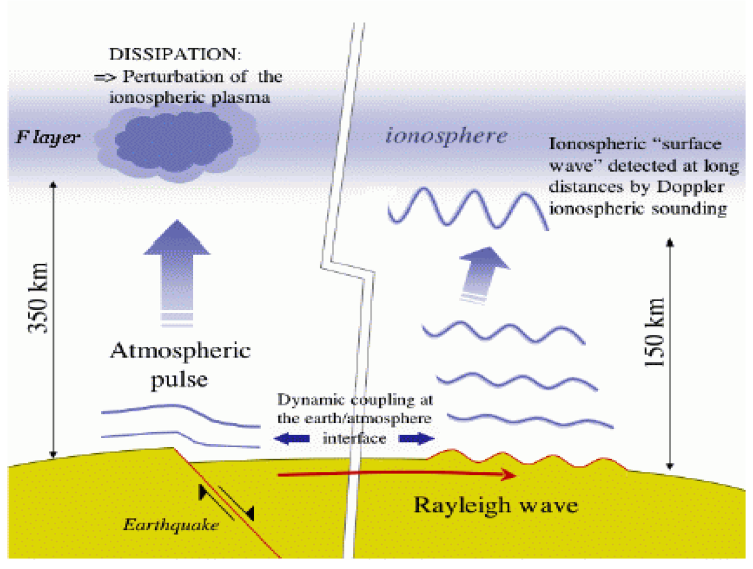


Fig.1 : Coupling mechanisms between earth, its atmosphere and ionosphere involved after an earthquake.

Vertical ground displacements generate atmospheric pressure waves. Those are considerably amplified upward to the ionosphere under the effect of the decreasing density.

The ionospheric waves at **near field** (< 500 km) originate directly from the earthquake rupture process and at teleseismic distance the perturbations are the consequence of Rayleigh surface waves.

GPS ionospheric seismic wave imaging : characteristic patterns

Tokachi-Oki Earthquake, 2005-09-25

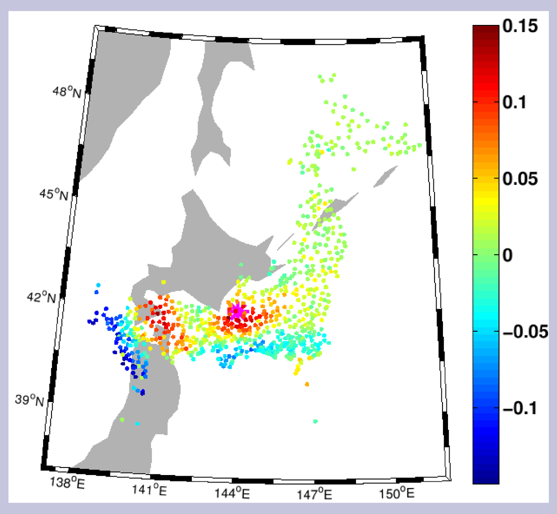


Fig. 2 : Snapshot of Slant TEC at ionospheric piercing points for satellite PRN13, 15 minutes after the rupture.

The earthquake (Mw 8.3) occured at 19:50 UT and induced strong vertical ground dis-placements.
The epicenter was located at 144,1°W and 42,2°N
(red asterisk, see on fig.2).

Honshu Earthquake, 2007-07-16

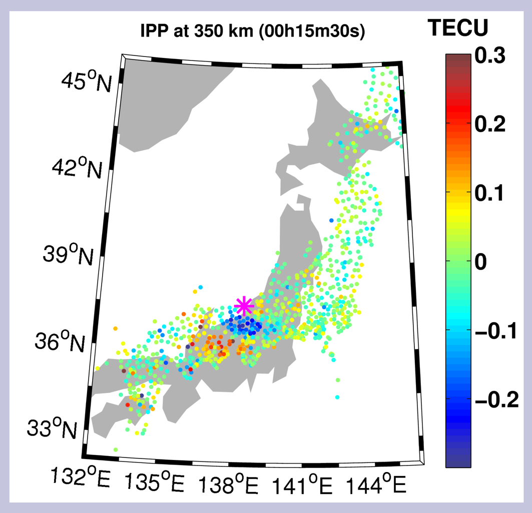


Fig. 3 : Snaphot of Slant TEC at ionospheric piercing points for satellite PRN26 15m 30s after the rupture

The earthquake (Mw 6.5) occured at 10:13 (local time). The low geomagnetic activity (Kp=1) offered favourable conditions to a TEC detection.
The epicenter was located at 37.6°N and 138.5°E
(red asterisk, see on fig.3).

How can we interpret the observed South-Eastern directivity ?

Near field modelling

Phase inversions observed at TEC images (see fig.5) are interpreted here as interferences between separated sources, as shown by fig.4.
[Yagi, Y., 2004] corroborates this assumption : he described 3 separated coseismic displacements focii aligned along the fault. So we modelled each of them as an acoustic source

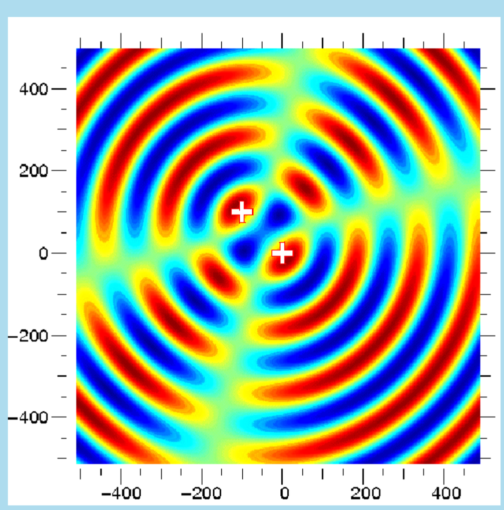


Fig. 4 : Synthetic of two coherent acoustic sources radiation diagrams

The inversion procedure is posed as a least-square problem. Wavelengths exceeding 300 km are found as shown fig.5, so other parameters have to be taken into account. Ingredients for the integration of the pertubed electronic density along the line of sight are based on the determination of the neutral density variations by ray tracing, linked to the electronic density variation (as described on fig.7).

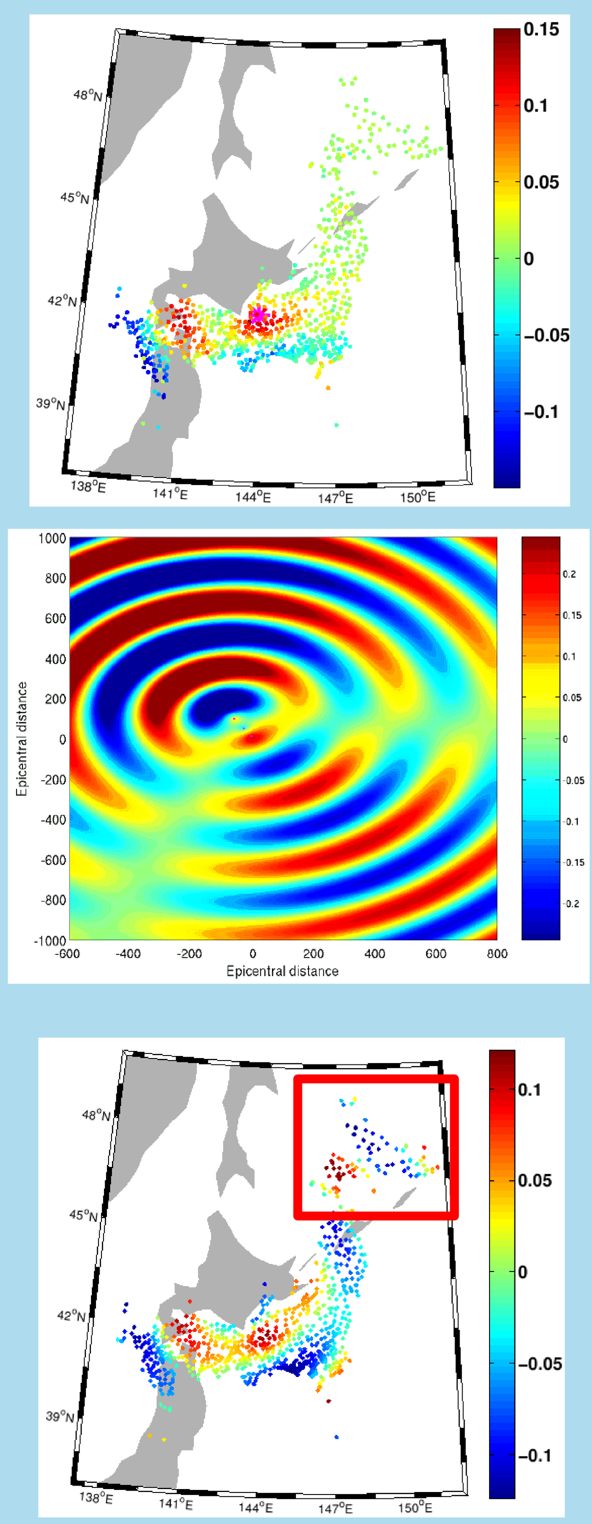


*Fig. 5 : **Preliminary result of the GPS data inversion tests.***
Top : TEC data at ionospheric piercing points (IPPs).
Center : TEC values at IPPs calculated from inversion procedure.
Bottom : synthetic of the inversion result.

Origin of the perturbation

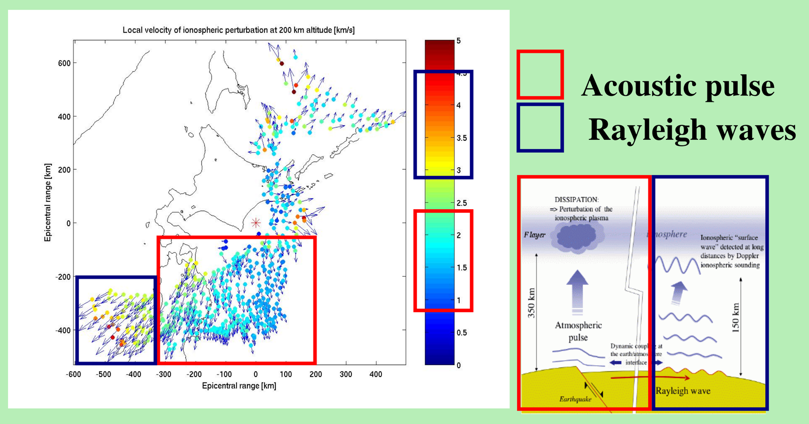
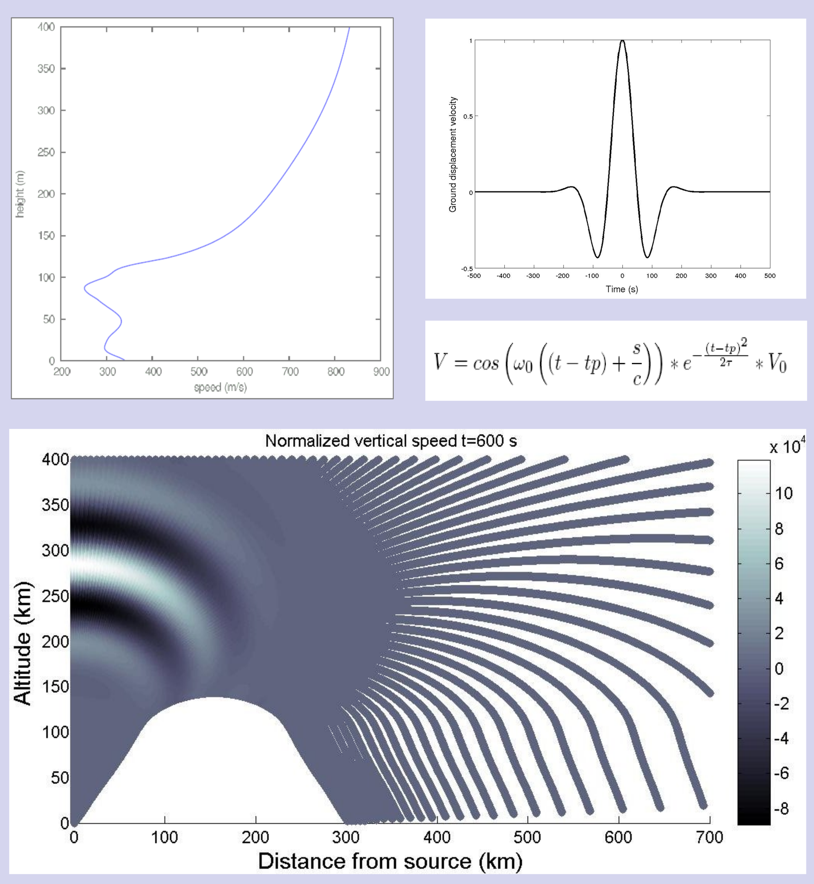


Fig.6** Local group velocities calculated from 1Hz data, **F. Crespon (PhD Thesis, 2007)

Ray tracing



$$V = \cos\left(\omega_0\left((t-t_0)+\frac{\pi}{2}\right)\right) * e^{-\frac{(t-t_0)^2}{2\sigma^2}} + V_0$$

***Fig.7** Due to the speed of sound variations (top left) trajectories of rays are deflected (bottom, represented for increasing launch angles. The velocity is modelled by a pulse function (top right).*

Directivity factors

Geomagnetic field

Charged particules are reorganized under neutral wind effect. This is modelled by a 3D ionospheric coupling program by **[E.A Kherani et al.]**.

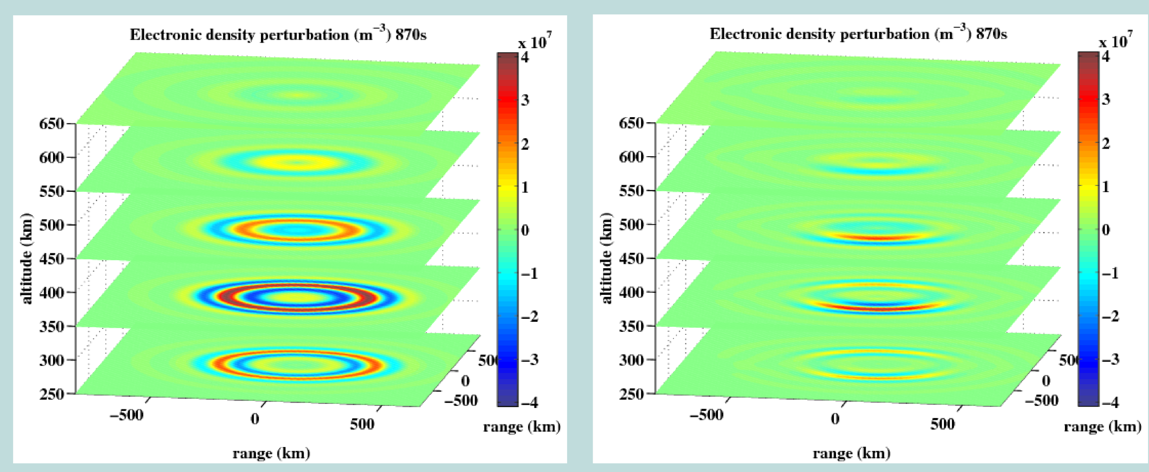


***Fig. 8** :simulated 3D electronic perturbation under the effect of an acoustic plume withput and with magnetic field*

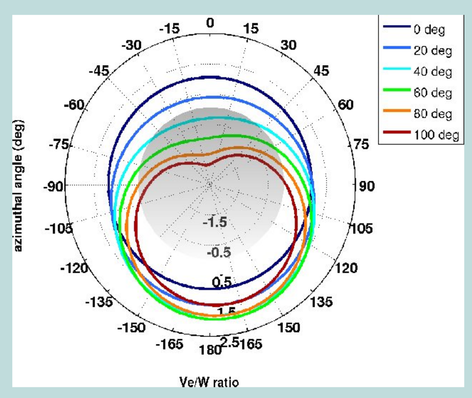
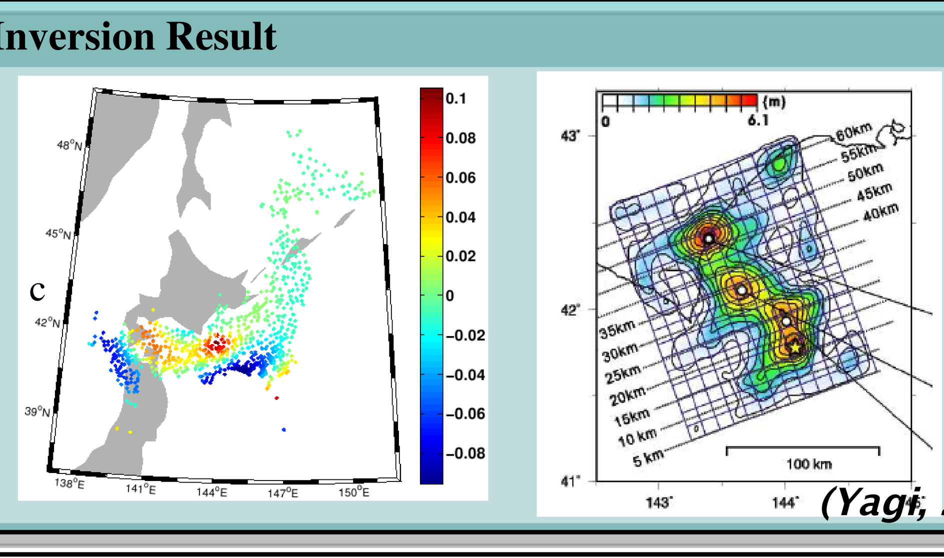


***Fig.9** : Attenuation function in polar representation of the perturbation for different inclination angle of the acoustic ray.*

Inversion Result



B3=45%
B2=20%
B1=35%
(Yagi, 2004)

Conclusions and perspectives:

Basic inversion here supplies a first fit of experimental data. Current developments are considering a more realistic modelling of source and atmospheric propagation of the synthetized acoustic waves. aiming to constrain more completely the parameters of the rupture process by a final inversion.

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