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Introduction: Recent developments in ionosphere remote sensing, in particular techniques using the Global Positioning System (GPS), Doppler HF sounder or even over-the-horizon radar provide unprecedented capabilities for monitoring the reaction of the ionosphere to seismic waves. Three types of signals can be addressed by a routine survey and monitoring of the ionosphere. The first ones are produced by an acoustic coupling between the solid Earth and the ionosphere near the source and lead to post-seismic acoustic signals. The second are related to the generation of acoustic waves associated to surface waves and even body waves, and can be detected remotely far from the source. For quakes with moment magnitude larger than about 7, the detection is worldwide. Finally, the third are related to coupling of oceanic gravity waves (i.e. tsunami) with atmospheric and ionospheric gravity waves.

We present briefly in this paper the state of the art in the detection of these signals by several groups in France and address the perspectives.

Theoretical and historical background: After an earthquake, seismic waves or tsunami generate surface motion of the Earth's surface. By continuity of the vertical displacement, the atmosphere is forced to move with a vertical velocity equal to the surface vertical velocity, and the induced perturbation propagates upward as an atmospheric wave. The propagation is done primarily by acoustic processes, for signals with frequencies higher than the Brünt-Vaïssalla frequency, and by gravity processes, for frequencies above.

These atmospheric vibrations produce adiabatic pressure and temperature variations in the neutral atmosphere. At higher altitude, the velocity of the neutral atmosphere can be transferred to ions, through collision processes, and forces the later to oscillate. Due to the neutrality of the ionosphere, these ions perturbations then generate electron density perturbations. Both the electrons and ions in the processes are sensitive to the Lorentz forces related to the magnetic and electric fields.

In the 1960s, the first published observations were performed with ionospheric sounders for M_s=8 quakes [1-4]. The development of Doppler sounders in the last thirteen years has lead to a reduction of the detection threshold, as we will see later.

The Global Positioning System (GPS), with the development of the associated ground networks, has opened new possibilities in the detection and imaging of these signals. As a by-product of geodetic measurements, phase and code measurements from GPS stations can indeed be used to calculate the electron density of the ionosphere between the receiver and the satellite. The primary data provide the integrated value of the electron density, or Total Electronic Content (TEC) [5]. After the first detection following the 1994 Northridge earthquake [6], seismic signals have been detected for many other quakes and have been interpreted as the result of a shock wave generated by the supersonic Rayleigh wave [7].

A detailed theory has then been developed [8] to take into account the coupling between the solid Earth, the ocean and the atmosphere. In the later, the boundary conditions of the elasto-dynamic operator at the solid Earth - atmosphere interface is integrated in the normal modes theory. A radiative boundary condition simulates the escape of acoustic and gravity atmospheric waves in the upper ionosphere, where no refraction of waves is observed. This theory allows the computation of normal modes, and those can be used to compute not only seismograms for spherical models, but also barograms and neutral velocities. The dissipation related to viscosity was later incorporated [9]. This technique provides the neutral density perturbation and velocities of the upper atmosphere. The later acts as neutral wind and generates ionospheric perturbations[10].

Toward remote sensing seismology? During more than 4 decades, the detected signals described above were however more or less considered as some "funny" or "exotic" observation in seismology, unable to provide new valuable informations, either on the source or on the internal structure of the Earth. However, we are now facing, with the development of new technologies in ionospheric sounding, or with the dense GPS networks progressive changes, which put a new light on these researches and start to point out possible seismological interests and applications.

Following the pioneering works done with analog Doppler sounder, new generations of sounders have been developed such as the Doppler sounder operated by CEA/DASE in France and working continuously since August 1999[11]. The French instrument is detecting most of the earthquakes with M_s greater than 6.5 [12]. Doppler data are very similar to seismograms in the sense that they measure directly the vertical motion of a given ionospheric layer. The performances of Doppler sounder are moreover such that both the surface waves and body waves are detected in the ionosphere, including SV waves (see Fig 1). However they remain limited to a small number of point measurements and cannot resolve the 3D structure of the perturbation. New studies are therefore done in order to use Over-The-Horizon radars, which might provide maps of the ionospheric vertical displacements [13]. Preliminary results show that the signal to noise ratio of these instruments is probably comparable to those obtained by Doppler sounders and that these instruments could therefore be a way to provide dense measurements of the seismic wavefront, with sampling as low as 1 measurement per 25 km^2 over surface of several 10^6 km^2.

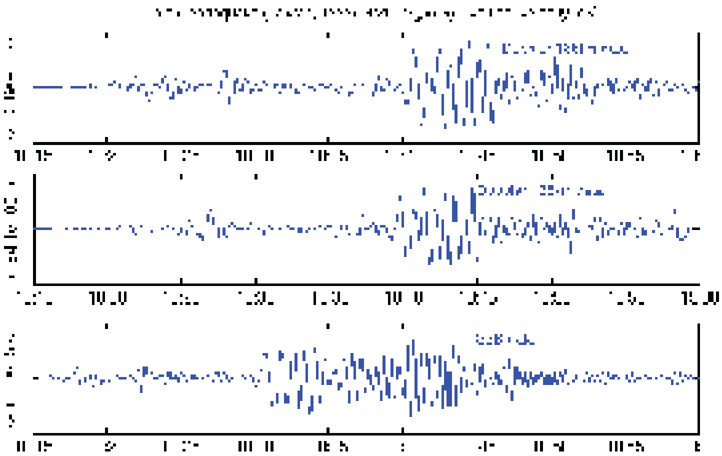

Figure 1: Seismic surface waves after the Mw = 7.6 Chi-Chi earthquake (Taiwan, September 20, 1999) as measured on a ground seismometer (bottom panel) at the Geoscope station SSB (Saint-Sauveur, France) and on the CEA ionospheric Doppler sounding network (Francourville, France), corresponding to the vertical motion of ionospheric layers at altitudes 168 and 186 km. All traces show the vertical velocity perturbation in the 1-50 mHz frequency band. An amplification of 4.10^4 is observed between the ground and the ionosphere. The ~ 8 minutes delay between the ground and the ionosphere corresponds to the propagation time of the acoustic wave. Due to this delay, body waves are expected to arrive in the ionosphere at 18h17, 18h23 for PP and S waves respectively, while surface waves arrive at about 18h40. SV waves, due to SV-P conversion, are detected.

A next step was performed following the 2002 Denali earthquake [14,15]. The dense California GPS networks was used to map the ionospheric perturbations and to compute the group velocity with a high spatial resolution above the Northwestern US coast, with a precision compatible with the identification of the signature associated to lateral variation in the Earth's lithosphere. The 3D structure of the seismic ionospheric signal was then characterized [16] and with such approach, the comparison of signals from identical altitude can be performed. Figure 2a shows a vertical cut of the signal detected above Hokkaido, after the Hokkaido Tokacho-Oki earthquake of September 25, 2003 while Figure 2b shows signals with increasing epicentral distances, all corresponding to a 300 km altitude. These results were obtained thank a collaboration with Japan GSI. In the near field, these signals are associated to the near-field seismic waves and especially to infrasonic waves generated near the source and propagating in the atmospheric wave-guide. It has been shown that the ionospheric total electronic content perturbations are sensitive to the focal mechanism and can therefore be used for inverting the source dynamic and geometry [17]. Note that 2D ionospheric maps over Europe are now available for either seismic or other applications, in the framework of an academic-SME collaboration with the Toulouse based SME Noveltis [18]. See also [19] for a review on GPS seismic observations.

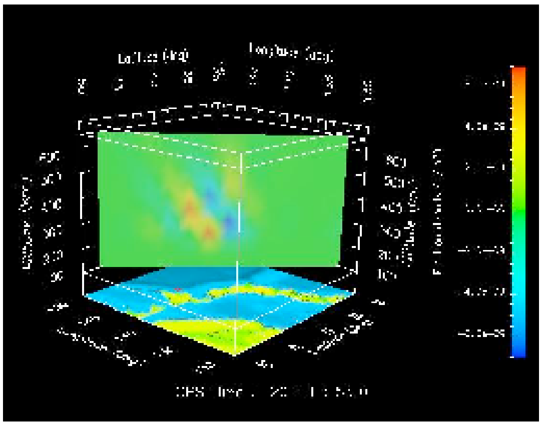

Figure 2a: Vertical cut of the 3D Rayleigh waves impact in the ionosphere for the Tokacho-Oki event. The Total Electronic Content amplitudes observed are typically 0.1 TECU peak-to-peak but 3D local variations reach a few 10^9 e/m^3. No wavefront is observed with a north or northwest propagation direction, due to a poor coverage of the GPS satellite in these directions.

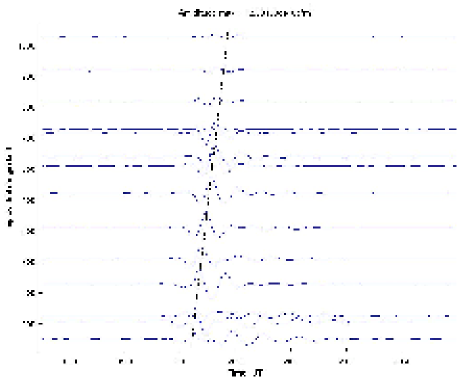

Figure 2b: TEC ionospheric signals at about 300 km of altitude after 3D tomography reconstruction. Note in the far field the signal associated to the Rayleigh waves (dashed line) and in the near field those associated to the acoustic pulse.

Ionospheric tsunamis warning: As for surface waves, early theoretical works in the 1970s predicted that atmospheric gravity waves are generated in the wake of a tsunami [20]. About 30 minutes are needed for the gravity wave to develop its first maximum perturbation in the ionosphere (versus ~10 minutes for seismic-acoustic waves). But after this delay the ionospheric perturbation follows the tsunami front and, as for the seismic waves, the atmospheric oscillations are amplified with altitude. It should be noted moreover that, due to their much shorter wavelength and period, the surface noise of ocean swell does not produce significant upward propagating waves in the atmosphere: the atmosphere acts as a filter, enhancing the long wavelength tsunami perturbation over other sources. Figure 3 shows the result of simulation, where the tsunami first generates an atmospheric gravity wave which is then generating, through collisions between neutral atmosphere and ions, perturbations in the electronic density.

The first observation had however to wait almost 30 years. It was performed after the Peru, June, 2001 tsunami [21]. The tsunami arrival was observed on Japanese tide gauges between 20 and 22 hours after the earthquake, with wave amplitudes between 10 and 40 cm (open ocean amplitude were estimated to be of 1-2 cm) and dominant periods of 20 to 30 minutes. Shortly after, a large ionospheric perturbation was detected through a specific processing of data from the continuous GPS network in Japan (GEONET). The arrival time, orientation, wavelength, velocity of the wave packet observed are consistent with what is expected for a tsunami-induced perturbation.

The gigantic and dramatic Sumatra tsunami of December, 2004 confirmed the possibilities of observing tsunami ionospheric signals, and signals were detected on the Total Electronic Content (TEC) measurement on-board the TOPEX/Poseidon and JASON satellites, and on the GPS stations in Indonesia and in the India Ocean [19]. The modeling of the ionospheric signal was performed, and both the waveform and the amplitude observed by Jason and Topex has been reproduced [22]. These results confirm the interest of a real-time monitoring of the ionosphere, which could be carried out either with active microwave radar or by optical systems detecting the airglow associated with the ion recombination in the ionosphere.

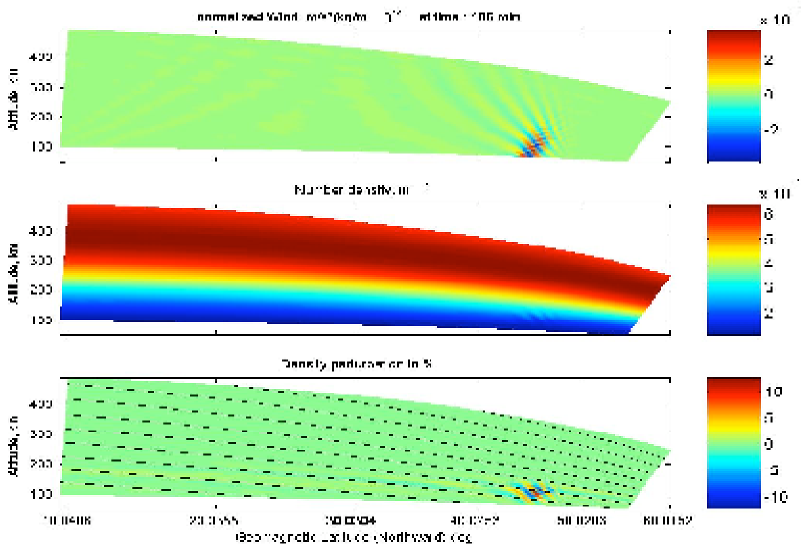

Figure 3: Coupling between the neutral atmosphere gravity wave induced by a tsunami and the ionosphere. The tsunami amplitude has a 0.5 meter amplitude and about 13min period, corresponding to the amplitude of the Sumatra, 2004 tsunami. From top to below are the normalised neutral wind, and the absolute and relative electron density. This shows that large perturbations, reaching 10%, are generated by such tsunamis.

Exporting remote sensing seismology on Venus? Although on Earth this technique would never provide the same quality of seismic data as a seismic network, it can be the unique way to obtain seismic data on planets too hostile for the deployment of long lived seismic stations. Venus is the best example [23,24]. In addition, the coupling strength is proportional to the acoustic impedance of the atmosphere, equal to ρ_c where ρ is the density and c the acoustic speed. As the atmospheric density at the surface of Venus is about 60 kg/m^3 and the acoustic velocity is slightly higher (410 m/s) than on Earth, this leads to an acoustic impedance about 60 times greater than on Earth, where the atmospheric density is 1.2 kg/m^3. Moreover, at 50 km of altitude, where the Venus pressure is comparable to Earth ground pressure, the decrease by almost 2 order of magnitude of the density leads already to an amplification of 10 of the waves. Consequently, Venus quakes will generate atmospheric infrasonic waves with amplitudes much larger than on the Earth surface [Figure 4]. This profitable effect give an unique opportunity for a future Venus quakes detection by a satellite sounding the Venus ionosphere.

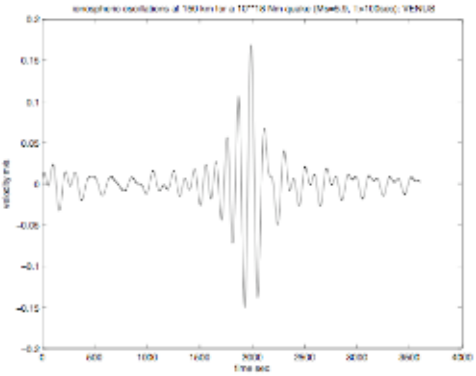

Figure 4: Long period vertical atmospheric oscillations, for a 10^{18} Nm quake (M_w=5.9) and for period larger than 100 sec on Venus. Due to the difference in the acoustic coupling at the ground, ionospheric signals at 150 km of altitude are about 100 stronger on Venus for the same magnitude and altitude than on Earth.

Conclusion: Advance in the monitoring of small-scale perturbations of the ionosphere have allowed the detection of atmospheric Rayleigh waves as well as tsunami-induced gravity waves with both ground systems based on GPS, and ionospheric sounding performed by TOPEX and JASON and Doppler sounders. Doppler soudners are also sensitive to body waves. These new data open exciting prospects in seismology such as the remote sensing of the Rayleigh seismic wave fronts, especially over the ocean, where the deployment of dense seismic networks is the most challenging. These technics might also provide in a future a high resolution picture of the wave front of body waves. These prospects are also very exciting for tsunamis because they are extremely difficult to observe in the open ocean, but their associated gravity waves have a clear impact on the ionosphere and can be detected by remote sensing systems. The monitoring of the ionosphere by joint ground/space techniques, such as continuous GPS networks, over-the-horizon radar or even by a future dedicated space system, might improve our understanding of tsunami propagation in the open ocean and possibly the efficiency of the future tsunami warning systems. Other applications of this technics are also found in planetology, especially with interesting prospects in the remonte sensing of quakes on Venus.

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