Tsunami detection in the ionosphere

[by Juliette Artru (Caltech, Pasadena, USA), Philippe Lognonné, Giovanni Occhipinti, François Crespon, Raphael Garcia (IPGP, Paris, France), Eric Jeansou, Noveltis (Toulouse, France) and Makoto Murakami (GSI, Tsukuba, Japan]

Introduction

Tsunamis are surface gravity waves that propagate for great distances in the oceans, usually triggered by earthquakes or landslides. In the open ocean, their long wavelengths (typically 200 km), long periods (20 minutes) and small amplitudes (a few to 50 cm for the gigantic event of 26 December 2004) make their detection very challenging, even with the deployment of GPS buoy systems (Gonzalez *et al.* 1998). Recently, satellite altimetry has proved to be capable of measuring the sea surface variation in the case of large tsunamis (Okal *et al.* 1999) as was shown for the recent Sumatra 26 December tsunami (e.g., Gower 2005). Here we present some recent results regarding the detection of tsunami waves through perturbations induced in the ionosphere.

Over the last decade, progress in the detection and modelling of ionospheric perturbations induced by seismic waves have shown that very small vertical displacements of the Earth's surface can induce significant signals in the ionosphere (e.g., Lognonné *et al.* 1998 2005*a*). Indeed, through dynamic coupling, a small fraction of the energy is transferred to the atmosphere in the form of acoustic-gravity waves. By conservation of kinetic energy, the amplitude of these waves increases exponentially while propagating upward, leading to amplification factors as large as 10^4. 'Ionospheric-seismic' surface waves are routinely detected on ionospheric Doppler sounding networks after large earthquakes, as is shown in Figure 1 (Artru *et al*. 2004).

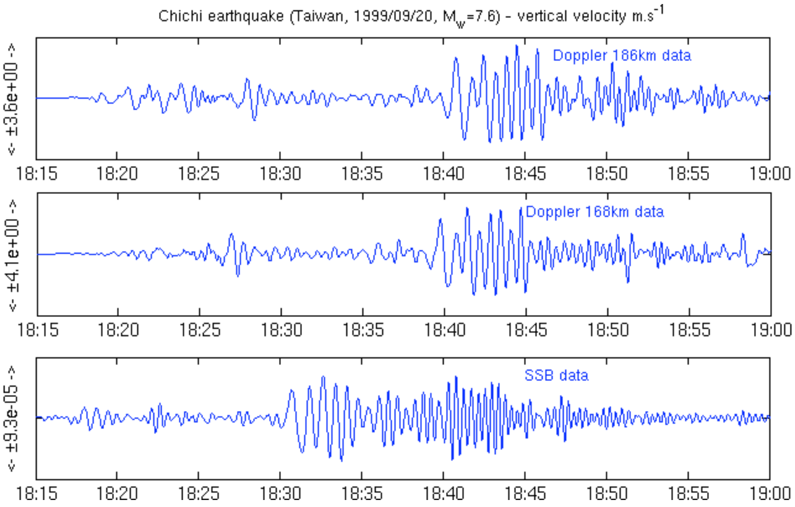

Figure 1. Seismic surface waves after the M_w = 7.6 Chi-Chi earthquake (Taiwan, 20 September 1999) as measured on a ground seismometer (bottom panel) at the Geoscope station SSB (Saint-Sauveur, France) and on the CEA ionospheric Doppler sounding network (Francourville, France), corresponding to the vertical motion of ionospheric layers at altitudes of 168 and 186 km. All traces show the vertical velocity perturbation in the 1-50 mHz frequency band. An amplification of 4 x 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.

In addition, GPS ionospheric monitoring allows the detection of those perturbations (Calais *et al.* 1995) with less sensitivity as the measure is then of the total electron content (TEC) perturbations along the satellite-receiver line-of-sight, and is therefore sensitive to the variations in electron density induced by the acoustic gravity wave on the ionospheric plasma. However, the geometry of GPS ionospheric measurements present some unique advantages: first the dense continuous GPS network, e.g., as in California or Japan, gives a high density of measurements and access to imaging the 2D (Ducic *et al.* 2003) or 3D structure of the perturbation (Garcia *et al.* 2005). Moreover, it allows for offshore detection of the signal: as the maximum sensitivity is obtained in the F region along the satellite-receiver rays, GPS receivers on coastal areas will provide offshore coverage, up to several hundred km away from the coast. We therefore applied GPS ionospheric monitoring to the search for tsunami-related signals.

Tsunami–gravity wave coupling

Based on the same mechanism, it is expected that atmospheric gravity waves can be generated in the wake of a tsunami (Peltier *et a*l. 1976). A simple test case of a plane tsunami wave propagating in a 1D ocean-atmosphere model is shown on Figure 2. Tsunami waves are non-dispersive, and the velocity depends only on gravity g and water depth d, as $v = \sqrt{gd}$. From the gravity wave dispersion equation, we can estimate the group velocity of the induced gravity wave. Horizontally, it appears to be very close to typical tsunami wave speed, while the vertical component is much slower than sound speed (about 50 m/s).

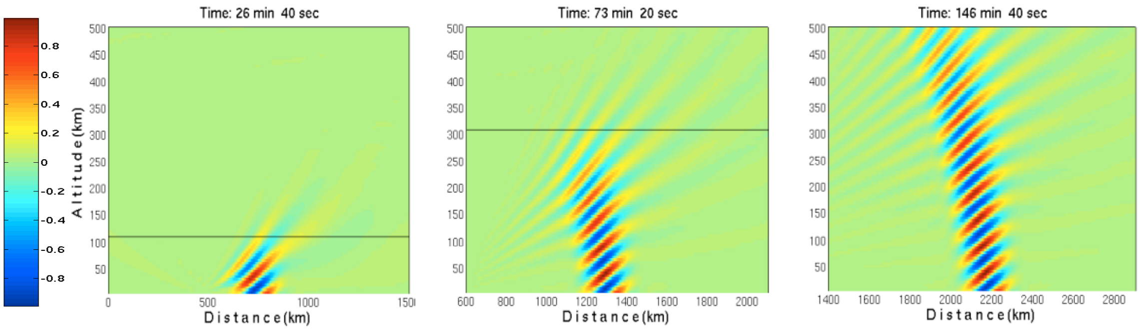

Figure 2. Numerical simulation of the gravity wave induced by a tsunami propagating at 200 m/s with atypical period of 15 minutes. The amplitude give the vertical normalized velocity ($v\sqrt{\rho}$) in kg$^{1/2}$/s/m$^{1/2}$. The atmospheric model used an isothermal model, corresponding to the mean temperature of the ionosphere (about 550°C), and the tsunami wave simulated is propagating from left to right. At 400 km, the velocity is amplified by a factor 10^5 (this simulation neglects any attenuation mechanism) due to the density decrease.

Depending on the period, it would therefore take from one to a few hours for the gravity wave to reach the ionosphere (*cf.* ~10 minutes for seismic-acoustic waves), and the ionospheric perturbation lies just behind the tsunami front, with a delay increasing with altitude. Of particular interest is the fact that because of their much shorter wavelength and period, ocean swell–atmosphere coupling would not produce any upward propagating waves in the atmosphere. Therefore, the atmosphere will act as a filter, enhancing the long wavelength tsunami perturbation over other sources.

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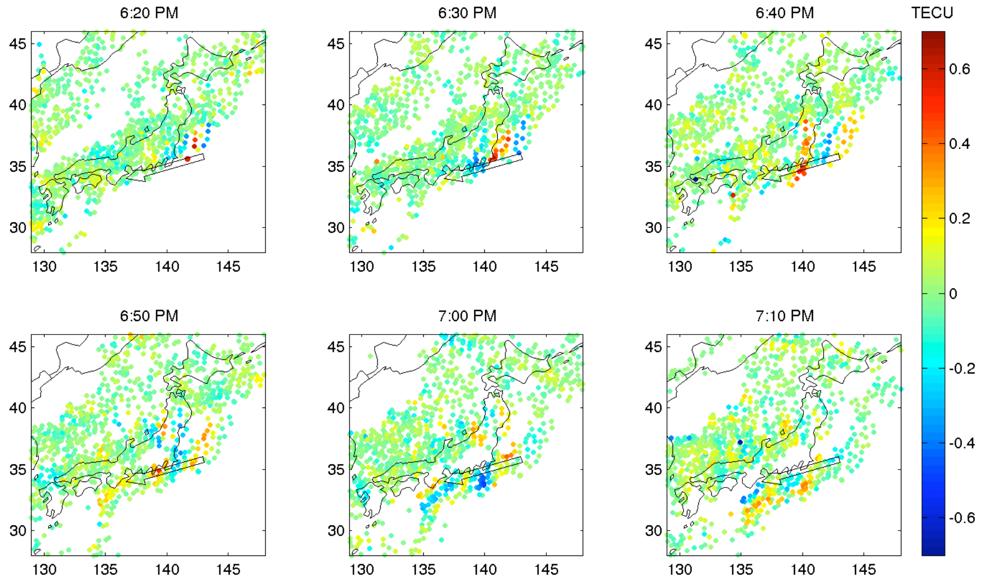

Figure 3: Observed signal for the June 23, 2001 tsunami (initiated offshore Peru): TEC variations plotted at the ionospheric piercing points. A wave-like disturbance is propagating towards the coast of Honshu. This perturbation presents the expected characteristics of a tsunami induced gravity waves, and arrives approximately at the same time as the tsunami wave itself.

Observations of the 23 June 2001 earthquake and tsunami (Artru *et al*. 2005)

In order to study the possible existence of such ionospheric signature of tsunamis, we processed data from the continuous GPS network in Japan (GEONET) at the predicted arrival time of a tsunami generated by the Peru earthquake of 23 June 2001 (M=8.4 at 2033 UTC). The data processing applied facilitated the detection of various TIDs (Travelling Ionospheric Disturbances) propagating in the area, mostly during daytime. At the time of the tsunami arrival, however, the background activity was low. We observed a signal that has indeed the expected characteristics of a coupled tsunami-gravity waves in terms of arrival time, wave front orientation, horizontal velocity and

The tsunami arrival was observed on Japanese tide gauge between 20 and 22 hours after the earthquake, with wave amplitudes of between 10 and 40 cm (open ocean amplitude was estimated to be about 1 to 2 cm) and dominant periods of 20 to 30 minutes. The ionospheric perturbation would have arrived at approximately the same time, between 1730 and 1900 GMT (0230-0400 local time) on 24 June 2001. Figure 3 shows the signal observed at approximately 1830. Each dot represents the Total Electron Content (TEC) calculated from one satellite-receiver ray, corrected for ray zenithal angle and high-pass filtered to remove diurnal variation. The location of the points corresponds to the intersection of the rays with the F2 peak in the ionosphere, named as the ‘piercing point’. The arrival time, orientation, wavelength, velocity of the wave packet observed correspond to an expected tsunami-induced perturbation. We additionally performed the same data processing on several days before or after the event to ensure that this signal was not an artifact of our data processing, or related to the diurnal cycle of the ionosphere. Indeed, no such signal was observed and, generally speaking, TID activity was found to be fairly low at this local time. diurnal cycle of the ionosphere.

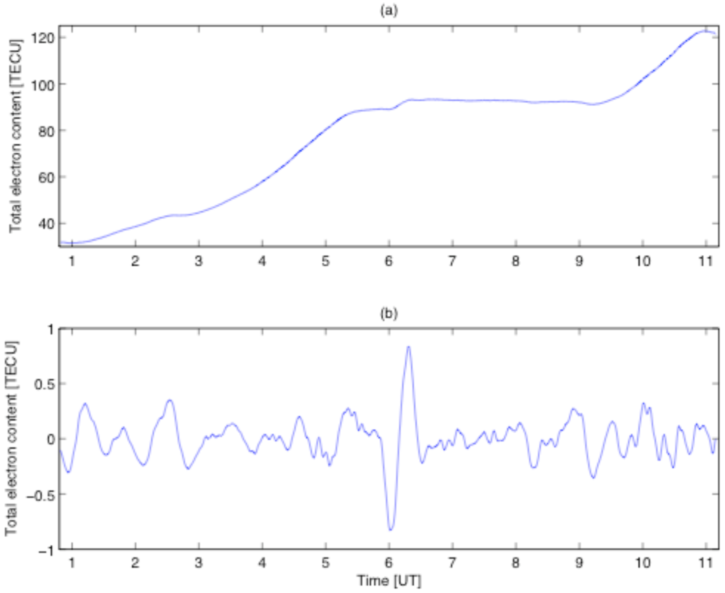

Figure 4a. Ionospheric perturbation observed at the DGAR/IGS station from GPS satellite 28. The sub-ionospheric point is approximately located at 1.65ºN and 72.78ºE for an altitude of 350 km, at an epicentral distance of 2460 km of the tsunami. The top trace is the Slant Total Electronic content, while the bottom trace is filtered between 0.3 mHz and 3.3 mHz.

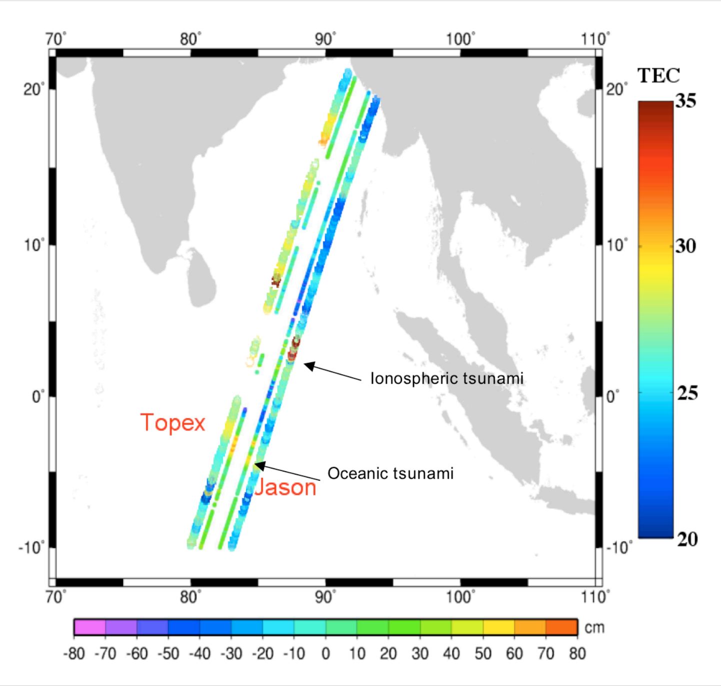

Figure 4b. *TOPEX/Poseidon* and *Jason* TEC observations of the tsunami ionospheric perturbation. The *TOPEX/Poseidon* (left) and *Jason* (right) tracks are parallel. The thin track corresponds to the altimeter, the large one to the TEC. The *Jason* ionospheric perturbation shows a waveform with two peaks, correlating well with altimetry data.

Observations of the 26 December 2004 Sumatra tsunami

The gigantic and dramatic Sumatra tsunami of 26 December 2004 (M=9 at 0058 UTC) confirmed the possibilities of observing tsunami-generated ionospheric signals. Initial observations performed with TEC measurement onboard *TOPEX/Poseidon* and *Jason*, gave very large TEC signals well correlated to the vertical oceanic displacement (Lognonné *et al.* 2005*b*). Other groups also reported the ionospheric signals on GPS data (Vigny *et al.* 2005, Liu *et al.* 2005). In all cases, the ionospheric perturbations were observed about one hour after the tsunami arrival at the ocean surface. This one-hour delay is coherent with the vertical propagation of 15-minute period gravity waves. These two set of observations can now be examined in depth in relation to existing theories, especially if a more precise analysis, taking into account the interaction processes between the neutral tsunami atmospheric wave and the electron density perturbation as well as a full modelling of the altimetry or GPS signals, is performed (Occhipinti *et al*. 2005). This will enable the ionospheric response to be calibrated against the tsunami amplitude and to lead to a better understanding of the limitation in the ionospheric signal detection.

Conclusions

Advances in the monitoring of small-scale perturbations of the ionosphere have allowed tsunami-induced gravity waves to be detected with both ground systems based on GPS and ionospheric sounding performed by *TOPEX* and *Jason*. These observations will complement the space-based, direct observations of tsunamis with altimetry missions (e.g., Okal *et al.* 1999, Gower 2005).

These observations still need a quantitative understanding of the coupling mechanism, especially in order to be able to model fully the ionospheric response to gravity waves. This will become possible by a complete modelling of the coupling processes as well as by simulations of the different radio-sounding techniques (Occhipinti *et al.* 2005) as well as by 3D reconstructions of the signals (Garcia *et al.* 2005). However, the perspectives of these first observations are very exciting, as tsunami waves are extremely difficult to observe in the open ocean. The associated gravity waves in the ionosphere might prove to be a valuable signature for remote sensing systems. Their monitoring by joint ground/ space techniques, such as continuous GPS tomography of the ionosphere (e.g., Lognonné *et al.* 2005*a*) or even by a future dedicated space system, might improve our understanding of tsunami propagation in the open ocean and, possibly, the efficacy of any future tsunami warning systems.

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