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Tsunami warning and Ionosphere seismic tomography (TWIST) (Using and Understanding ionospheric driver from below with telluric sources)

Progress report, October, 2015

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1. LONG-TERM GOALS

The last decade demonstrated that seismic waves and tsunamis are coupled to the ionosphere. Observations of Total Electron Content (TEC) and airglow perturbations of unique quality and amplitude were made during the Tohoku, 2011 giant Japan quake. Observations of much lower tsunamis down to a few cm in sea uplift are now routinely done. A comprehensive science of the coupling of ocean to space must therefore integrate oceanic and ground seismic sources, which are important and strong ionospheric drivers from below. These telluric ionospheric signals are important for improving the tsunami warning strategy, especially for tsunamis occurring in areas not covered by ground warning systems or generated by non-seismic sources in the open ocean (i.e. air or sea explosions, landslides, impacts). Ionospheric detection of seismic events and tsunamis are also unique to understand the coupling between the lower atmosphere and ionosphere: in several cases, data of the driver from below (i.e. ground displacement) and of the ionospheric impact (i.e. ionospheric perturbations) can be recorded. We can therefore expect to better constrain, through travel time and waveform inversion, the various parameters (atmospheric viscosity, collision frequencies) controlling the coupling between the lower atmosphere and the ionosphere.

2. OBJECTIVES

The proposed efforts will be focused toward two objectives, two related to inversions and an additional one related to new data acquisition. The first will be to demonstrate that a tsunami oceanic uplift can be retrieved from the ionospheric data, while the second one will be to demonstrate that the coupling physics and coupling parameters can be inverted from the joint data set of surface drivers (e.g., tsunami or seismic signals) and ionospheric perturbations. The third is to setup a new monitoring facility in the Pacific, in order to get new data from tsunami-generated airglows.

3. Project Progress report in October 2015

3.1. WP1.1 Preparing the record of TEC profiles from USN aircrafts *M.Drilleau, Software engineer funded by ONR.*

3.1.1 Flight software developement

A software has been developed at IPGP to estimate the flight route of aircrafts for an optimized data acquisition of the Total Electron Content (TEC) using their onboard GPS receiver. These data will be then inverted to estimate the minimum tsunami height. The majority of the programs included in this software have been originally developed by Pierdavide Coïsson and modified by Mélanie Drilleau. This software estimates the most suitable take-off time(s) for the aircraft to record TEC data, with respect to the earthquake location, the take-off and landing locations, the cruise speed and the autonomy of the aircraft, and the position of the GPS satellites. The software is divided into 5 steps. (1) After the calculation of the tsunami travel times, (2) a flight route is estimated for a given take-off time. (3) Knowing the location of the satellites, the location of the Ionospheric Pierce Points are determined. (4) Then, the simulated TEC values are assigned to these locations. (5) Finally, the quality of the data recorded during the flight route is assessed. This five-step processing is made for different take-off times to choose which time interval is the most appropriate for the recording of TEC data.

Following the re-organization of ONR, the original proposal based on the use of Orion or F18 USN, which were the best suited for the measurement, has been strongly re-oriented. We are currently discussing with scientists of the Naval Postgraduate School (California) to realize measurements using Twin Otter aircrafts. The following example (*Figure 1*) of simulation shows the ability of the aircraft to detect TEC signal. We take the example of the recent earthquake of magnitude 8.3 that occurred last 16 September in Chile (epicenter location: 31.58S, 71.75W).

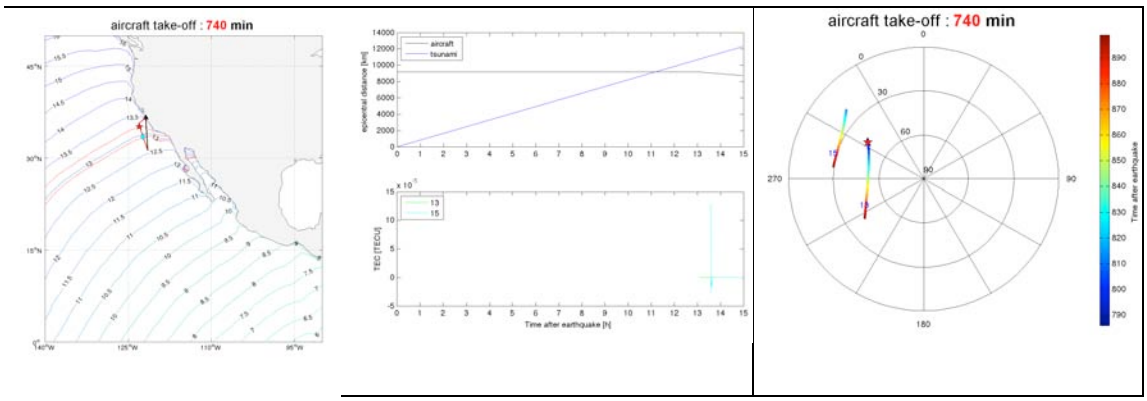

Figure 1: Results of simulation for a Twin Otter leaving an airport in California. Left: Blue lines are the tsunami hodochrones after the earthquake origin time. The black triangle corresponds to the airport location. Red and black dots show the outward and return flight, respectively. The red star shows the crossing of the aircraft with the tsunami wave front. The blue diamond is the crossing with the ionospheric perturbation. Middle: Simulated TEC data for the 2 satellites in visibility. Right: Polar view of the elevation and azimuth angles of the GPS satellites as seen by the aircraft during the time of GPS recording. The color bar indicates the time after the earthquake.

To calculate the ionospheric perturbation model generated by the tsunami, we use a modified version of the NeQuick model (Nava et al., 2008). Considering the Twin Otter speed (252 km/h) and its ferry range (1260 km), the software automatically computes the flight route. 12.3 hours after the earthquake, the aircraft takes-off from the Monterey Regional Airport in California and flies toward the epicenter. The aircraft crosses the tsunami perpendicularly to the wave front and records the TEC values until it reaches the end of the ionospheric perturbation, which occurs approximately 1 hour after the wave front. Finally, it turns back toward the landing base by the straightest route. We hope that our collaboration with the Naval Postgraduate School will make possible a first flight in the following month.

3.2. WP1.2 INVERTING TEC TSUNAMI DATA IN TERM OF SEA LEVEL UPLIFT *V.Rakoto, ONR Funded PhD (IPGP)*

Large earthquakes (i.e $M \geq 6$) and tsunamis associated are responsible for ionospheric perturbations. These perturbations can be observed in the total electron content (TEC) measured from multi- frequency Global Navigation Satellite systems (GNSS) data (e.g GPS). First, explain our modeling of Tsunami waveform and the TEC perturbation using a Normal modes summation. Then we compare with the GPS data. We finally present the inversion of synthetics TEC data in order to estimate the height of Tsunami using a least square analysis. This year, we focused on the Haida Gwaii Earthquake and Tsunami happened the 2012 october 28th.

3.2.1 COMPUTATION OF THE NORMAL MODES

We first compute Earth Normal modes with Minos Program by Woodhouse & Dahlen, 1978. It assumes a spherical non rotating Earth. Viscosity in atmosphere is not taken into account in this step but later. We use the 1D PREM model with a constant bathymetry (4.7km for the Haida Gwaii Earthquake and Tsunami case). We take a rigid boundary condition in the bottom and a free boundary condition in the top. The dispersion diagram of the modes is shown on *Figure 2*. The green branches are solid modes, atmospheric acoustic and gravity modes in dark blue, Lamb modes in light blue and Tsunami modes in red. Then, we add the attenuation due to the viscosity by using the variational theory by Lognonné et al., (1998).

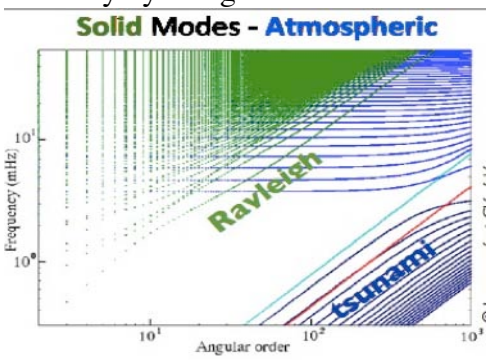

Figure 2 : Dispersion diagram computed by Minos.

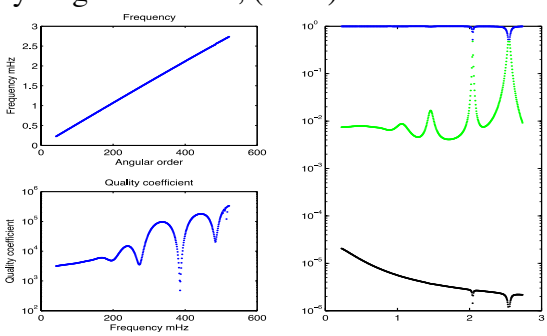

Figure 3 : On the left top, dispersion of the Tsunami branch. In the left bottom, Quality coefficient . In the right, repartition of energy between the atmosphere (green), ocean (blue) and solid Earth (black).

The fraction of energy between the solid part, ocean and atmosphere is shown in *Figure 3*. We have two main resonances at 2.0 mHz and 2.55 mHz, due to the fact that at these frequencies, the tsunami branch crosses the first two gravity modes overtones. This demonstrates that window for the energy transfer from ocean to atmosphere exists and can be modeled. If we looked at gravity modes, we would have seen the opposite phenomenon (i.e transfer of energy from the atmosphere to the ocean). For the Normal modes summation, we will filter between 0.1 mHz and 2.75 mHz.

3.2.2 Summation of the Normal modes and comparison with the data

The comparison between synthetics and Dart data for the Haida Gwaii tsunami is shown in Figure 4. For the DART data, the tide effect has been removed using a polynomial fit. This data set has been choosen as reference for inversion validation.
The computation of the TEC is done in several steps. First, we compute the normal modes. Second, we compute the ion displacement normal modes using IGRF (International geomagnetic reference field) (Mandea et al., 2001). Third we compute the perturbed electron densityby using IRI (International reference ionosphere) model by Bilitza & Reinisch, 2008. Finaly, we integrate the perturbed electron density along each satellite station line of sight in order to compute the dTEC (TEC is the total electron content). The comparison between the data and modeling are shown in figure 5. The vertical model assumes the line of sight between the station and the satellite is vertical. It is of course an approximation. The slant model takes into account the displacement of the satellite with the time.

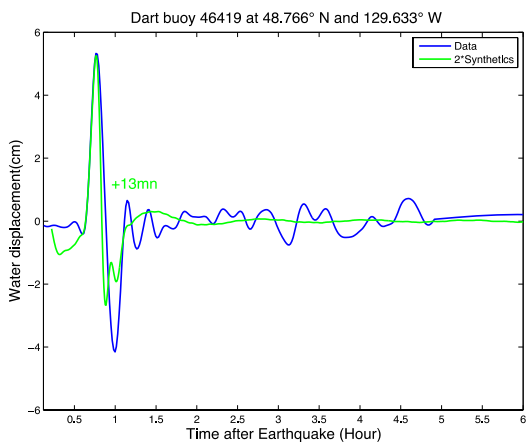

Figure 4 : The synthetics tsunami waveform is ploted in green and the data in blue.

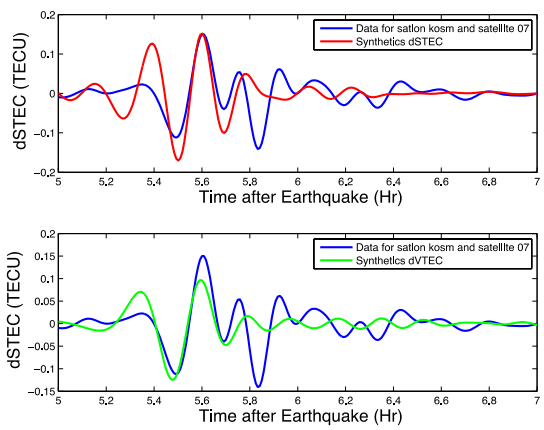

Figure 5 : in the top, comparison between the data (blue curve) for kosm station and slant TEC model (red curve). In the bottom, comparison between the data (blue curve) for kosm station and slant TEC model (green curve).

3.2.3 INVERSION OF THE SYNTHETICS DATA TEC

The inversion of the TEC is made in order to retrieve the ocean tsunami signal. The chosen approach is based on the recontruction of the TEC by the 6 TEC signals generated by the 6 components of the moment tensor. This is made in a linear way, from the dVTEC data with a least square method analysis. The method and the results are shown in figure 5. The results show very good fit, demonstrating the perspective of this techniques for inversion of data, either from Ground based GPS or from airborne GPS.

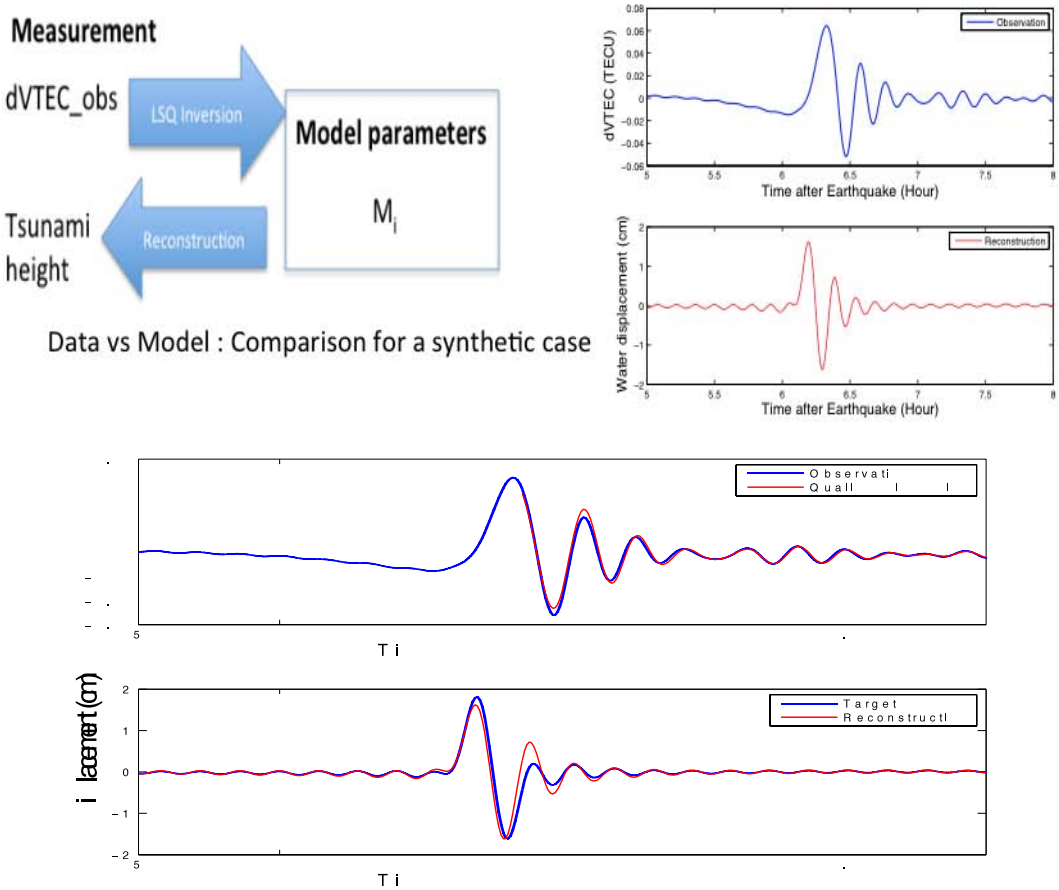

Figure 6 : Results of inversion from dVTEC synthetics data. Results fits with 90% of variance réduction confirming the perspectives.

3.3. DENSE TEC DATA MODELLING AND RETRO-PROPAGATION FOR HIGH-RESOLUTION MAPPING OF THE SEA LEVEL CO-SEISMIC UP

Lucie Roland, former ONR funded Postdoc, now at University of Nice, C.Larmat (LANL), P.Lognonné (IPGP)

3.3.1 COSEISMIC ACOUSTIC WAVES WAVEFORM MODELING USING 3D SPECTRAL ELEMENT METHOD

3D moment tensors are used to represent seismic sources in our SEM modelin allowing our exploration of the seismo-acoustic response to diverse types of

sources. Figure 7 shows synthetic waveforms generated by a reverse fault earthquake that display both the rapid Rayleigh-induced phase (˜3.5km/s) and the slower direct acoustic phase (~1 km/s) routinely observed in the TEC data. Leakage of the modes trapped in the low atmosphere waveguide is also visible especially on figure 2 that represents the wave amplitude as function of time and altitude for a receiver located 340 km from the source. We are currently workin on fitting observed TEC amplitude, especially an implementation of dissipatio effects taking into account the latest understanding of the different processes at the origin of atmosphere dissipation.

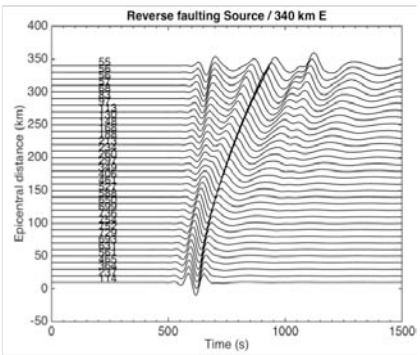

Figure 7: Waveforms modeled at 250 km height plotted versus the distance to the source. We show the vertical component of the neutral atmosphere particle velocity in the case of a purely vertical reverse faulting mechanism (strike North/South). Waveforms are normalized and convolved with a Gaussian function (acting as a low frequency passband) of 28.6s.

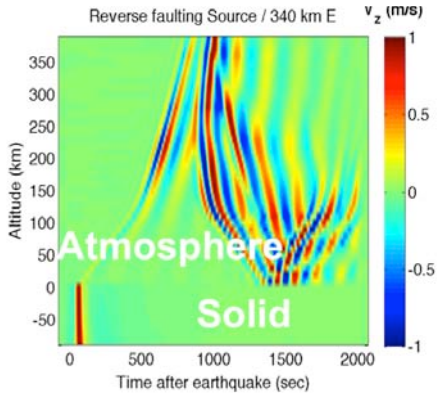

Figure 8: Waveforms modeled for the same earthquake but at a distance to the source of 340km and plotted versus the altitude.

3.4. WP2 INVERTING NEUTRAL/IONOSPHERIC COUPLING PARAMETERS FROM JOINT SEISMIC/TSUNAMI/IONOSPHERIC DATA

K.Khelfi, IPGP funded PhD, 6 months PhD extension ONR funded.

In the light of the results obtained last year with specfem2D, the modeling has now been upgraded for 3D simulation and allow to compute the variation of TEC in each direction of the grid and to model the non-linear effects of the acoustic wave generated by the tsunami onset. The main goal was to succeed in modeling ionospheric hole, observed after major earthquakes, and which remains one of the main difficult signals to explain.

This has been done with success, with the complete 3D modeling described below. Top of Figure 9 shows snapshot images for the wavefield of the ions velocity in the Z direction, few minutes after the onset of the Tohoku earthquake. This simulation is made on a 720 km by 720km grid horizontal and for 500 km height. Time resolution is about 20 s, with a CMT point source.

Integration is then done along the GPS integration path corresponding to a GPS satellite, and allows to retrieve the non linear variation of the TEC after the earthquake of Tohoku shown in the bottom of Figure 11.

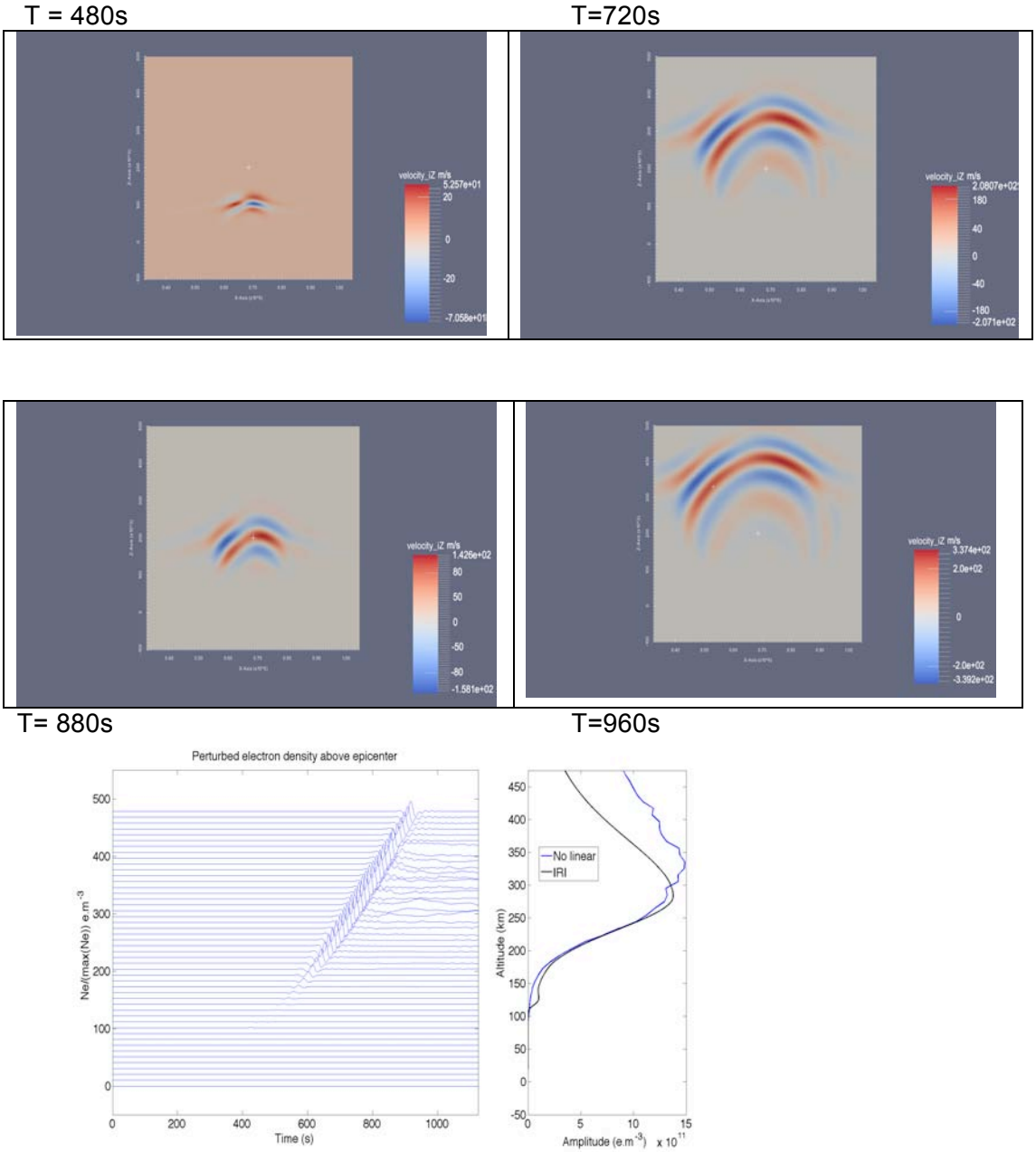

Fig 10 – left : propagation of the electron density perturbation, computed with nonlinear integral of the continuity equation of the electrons density- Right we present the electron density obtained from IRI in black and the perturbed electron density in blue

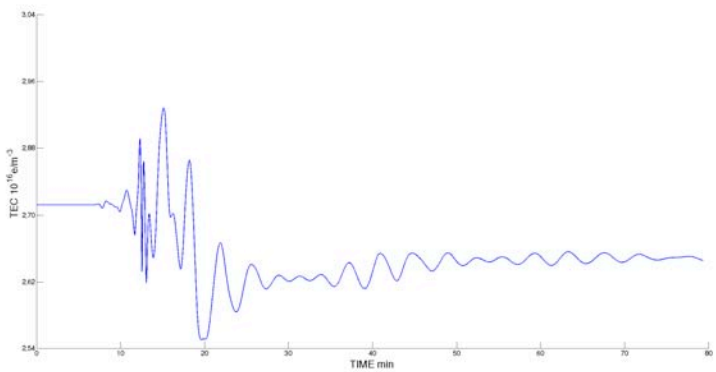

Figure 11 -The perturbed TEC repsented for Station of the PNR 26 in the vicinity of the epicentre of Tohoku 80 min after the earthquake

4. PUBLICATIONS SINCE LAST REPORT

4.1. PUBLICATIONS

Bletery, Q., A. Sladen, B. Delouis, M. Vallée, J.-M. Nocquet, L. Rolland and J. Jiang (2014). A detailed source model for the Mw9.0 Tohoku-Oki earthquake reconciling geodesy, seismology and tsunami records. Jounal of Geophysica Research - Solid Earth. 119, 7636–7653, DOI: 10.1002/2014JB011261.

Coisson, P.D., P.Lognonné, D.Waiwer, L.Rolland, First tsunami gravity wave detection in ionospheric radio occultation data, *Earth and Space Science*, 125d 133, **2**, doi : 10.1002/2014EA000054, 2015

Occhipinti, G., Chap. 9, The Seismology of Planet Mongo: the 2015 Ionospheri Seismology Review, October 2015, American Geophysical Union, Subduction Dynamics: From Mantle Flow to Mega Disasters, ed. G. Morra, D. Yuen, S. Lee, S. King, ISBN: 978-1-118-88885-8, *in press.*

4.2. CONFERENCE ABSTRACTS

Rolland, L., C. S. Larmat, D. Mikesell, A. Sladen, K. Khelfi, E. Astafyeva, and P. H. Lognonne (2014), Toward seismic source imaging using seismo-ionospheric data, AGU Fall Meet. Abstr., C3873., poster

Rolland, L. and Larmat, C. (2014) Seismic and Ionospheric signatures for monitoring the initiation of a tsunami, SSA 2015, Pasadena, poster

Arrowsmith, S. ; Bowman, D. ; Rolland, L. ; Lees, J. ; Mimoun, D. et al. (2014)
On the use of microbarometers on balloon platforms to probe the internal structure of Venus, SSA 2015, Pasadena, poster

P.Lognonné, Ionospheric Seismology : from Earth Maturity to Venus Dreams, SSA 2015, invited talk.

Larmat, C. ; Rolland, L. and Remillieux, M. (2015) Seismic and Ionospheri Signatures for the Study of Underwater Earthquakes: from seismic rupture to Tsunami Generation, 2015 IGPPS days, poster

Rakoto, V., Lognonné, P. Rolland, L, Inversion of tsunami height usin ionospheric observations. The case of the 2012 Haida Gwaii tsunami, American Geophysical Union, Fall Meeting 2014, abstract #NH31C-3878

Fisher, D. J.; Grawe, M.; Makela, J. J.; Coisson, P.; Rolland, L.; Rakoto, V.; Lognonne, P. H., Investigation of Tsunami-Ionospheric Coupling Efficiency, American Geophysical Union, Fall Meeting 2014, abstract #NH31C-3875,

Astafyeva, E.; Rolland, L.; Sladen, A.; Lognonne, P. H., Toward seismic source imaging using seismo-ionospheric data, American Geophysical Union, Fall Meeting 2014, abstract #NH31C-3873,

Occhipinti, G.; Rolland, L.; Coisson, P.; Watada, S.; Makela, J. J.; Hebert, H.; Lognonne, P. H., From Sumatra 2004 to Tuhoku-Oki 2011: what we learn about Tsunami detection by ionospheric sounding, American Geophysical Union, Fall Meeting 2014, abstract #S21A-4399