Earthquakes & Tsunamis flirting with the Ionosphere: the Sumatra gossip !!

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References:
[*Occhipinti et al.*, 2006] *GRL*, *33*, L20104, 2006
[*Occhipinti et al.*, 2008] *GJI*, *173*, 3, 753-1135, 2008.

The December 26, 2004 Sumatra Earthquake and the related Indian Ocean Tsunami generated the largest remote sensing data-set observing natural hazards. The observations showed both, ground motion and ocean sea surface displacement, as well as the related strong ionospheric anomalies. Total electron content (TEC) perturbations have been observed on a global scale, using ground-based GPS receivers [DasGupta et al., 2006, Liu et al., 2006b] and dual-frequency altimeters (e.g., Jason-1 and Topex/Poseidon [Artru et al., 2005]); plasma velocity perturbation has been observed by Doppler soundings [Liu et al., 2006b, Occhipinti et al., 2009]. The observed perturbations may be characterized as two different waves: the first one is an atmospheric wave in the acoustic domain induced by propagation of Rayleigh waves on the Earth surface; the second one is a slower atmospheric wave in the gravity domain strongly coupled with the generated tsunami. Both waves are reproduced by our accurate modeling taking into account the earthquake/tsunami-neutral atmosphere coupling at the base of the atmosphere, as well as the neutral-plasma coupling in the overlying ionosphere [Occhipinti et al., 2006, 2006, 2009]. Here we present a review of the ionospheric observations related to the Sumatra event in the light of modeling to deeply investigate the coupling mechanism between Solid- Earth/Ocean/Atmosphere/Ionosphere. The matching between data and modeling opens new perspectives in the solid earth research as well as in the tsunami detection providing a new insight into the role of the remote sensing in the monitoring of natural hazard.

The ocean-atmosphere coupling

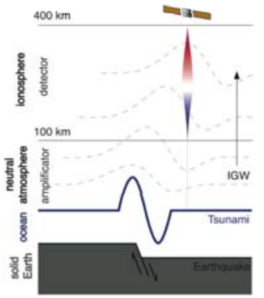
Based on the coupling between Tsunami gravity waves (TGW) and internal gravity waves (IGW), we computes the 3D propagation of IGW in a realistic neutral atmosphere with horizontal stratification. In essence the spectral analysis of the 2D ocean time-depending displacement field allows to propagate vertically the tsunami-generated IGW conserving the geometric features that the wave had in the ocean surface.

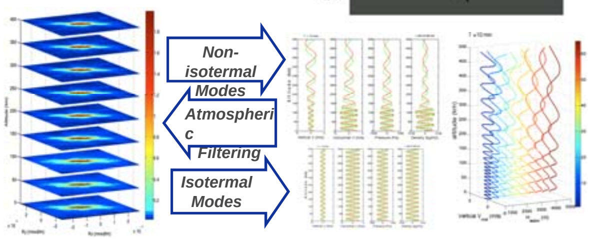
$$\frac{\partial u_x}{\partial t}+u_x\frac{\partial u_x}{\partial x}+u_y\frac{\partial u_x}{\partial y}+u_z\frac{\partial u_x}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial x}$$
$$\frac{\partial u_y}{\partial t}+u_x\frac{\partial u_y}{\partial x}+u_y\frac{\partial u_y}{\partial y}+u_z\frac{\partial u_y}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial y}$$
$$\frac{\partial u_z}{\partial t}+u_x\frac{\partial u_z}{\partial x}+u_y\frac{\partial u_z}{\partial y}+u_z\frac{\partial u_z}{\partial z}=-\frac{1}{\rho}\frac{\partial p}{\partial z}-g$$
$$\boxed{\nabla\cdot\vec{u}=0} \quad \frac{\partial u_x}{\partial x}+\frac{\partial u_y}{\partial y}+\frac{\partial u_z}{\partial z}=0$$
$$\frac{\partial \rho}{\partial t}+u_x\frac{\partial \rho}{\partial x}+u_y\frac{\partial \rho}{\partial y}+u_z\frac{\partial \rho}{\partial z}=0$$

$$\boxed{\frac{dV}{dz}=A\cdot V} \qquad V=\begin{pmatrix}\tilde{u}_z^*\\ \tilde{P}^*\end{pmatrix}$$

$$\tilde{u}_z^*=\tilde{u}_z\sqrt{\rho_0} \qquad \tilde{P}^*=\frac{\tilde{P}}{\sqrt{\rho_0}}$$

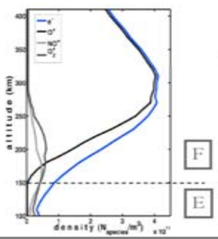
$$\tilde{P}^*=\frac{i}{(k_x^2+k_y^2)}\left(k_x\frac{\partial u_{x0}}{\partial z}+k_y\frac{\partial u_{y0}}{\partial z}+\Omega k_z-\tfrac{1}{2}\Omega\frac{d\ln\rho_0}{dz}\right)\tilde{u}_z^*$$





The neutral-plasma coupling

In the second step we computed the response of ionospheric plasma to the neutral motion. IGW is known to produce irregularities in the ionospheric plasma and to model it, we solved the ionospheric simulation model by *[Kherami et al., 2004]* ***under the action of gravity waves generated by tsunami activity and in the case of a stable ionospheric background.***



$$\frac{\partial n_i}{\partial t}+\nabla\cdot(n_i\vec{v}_i)=\pm\beta n_i-\alpha n_i^2$$
$$n_i\frac{d\vec{v}_i}{dt}=-\nabla p_i+\rho_i\vec{g}+n_iq_i(\vec{E}+\vec{v}_i\times\vec{B})-n_i\mu_{in}(\vec{v}_i-\vec{v}_n)$$

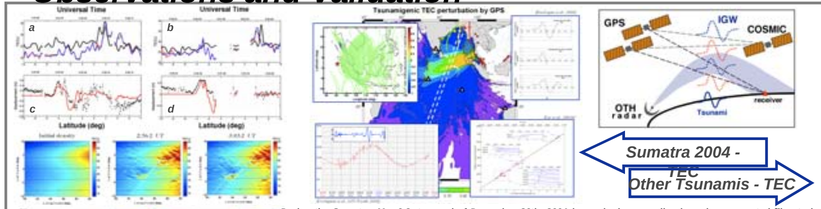
$$n_e=\Sigma_i n_i$$

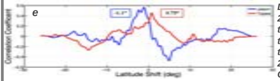
B dependent

B independent

$$O_2^+ + e^- \xrightarrow{\alpha} O+O$$
$$NO^+ + e^- \xrightarrow{\alpha} N+O$$
$$O^+ + O_2 \xrightarrow{\beta} O_2^+ + O$$
$$O^+ + NO \xrightarrow{\beta} NO^+ + O$$

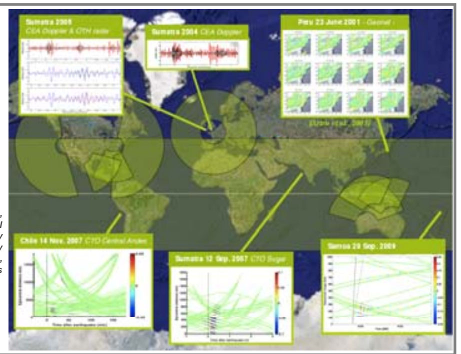
Observations and Validation



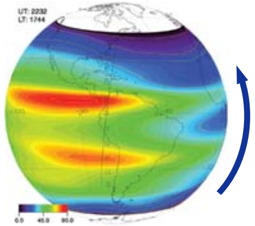


During the Sumatra, Mw=9.3, tsunami of December 26th, 2004 ionospheric anomalies have been reported [liu et al., 2006, Occhipinti et al., 2006, DasGupta et al., 2006]. Strong TEC perturbations has been observed by GPS with arrival times coherent with the tsunami's propagation [Liu et al.,]. Key observations of the Sumatra tsunami were performed by the Topex/Poseidon and Jason-1 sea altimetry satellites, the measured sea level displacements is well explain by tsunami propagation models with realistic bathymetry, as well as the observed TEC perturbation [Occhipinti et al., 2006]. Similar perturbation was observed during the tsunamigenic earthquake in Peru 2001, Sumatra 2007 as well as Chile 2007.

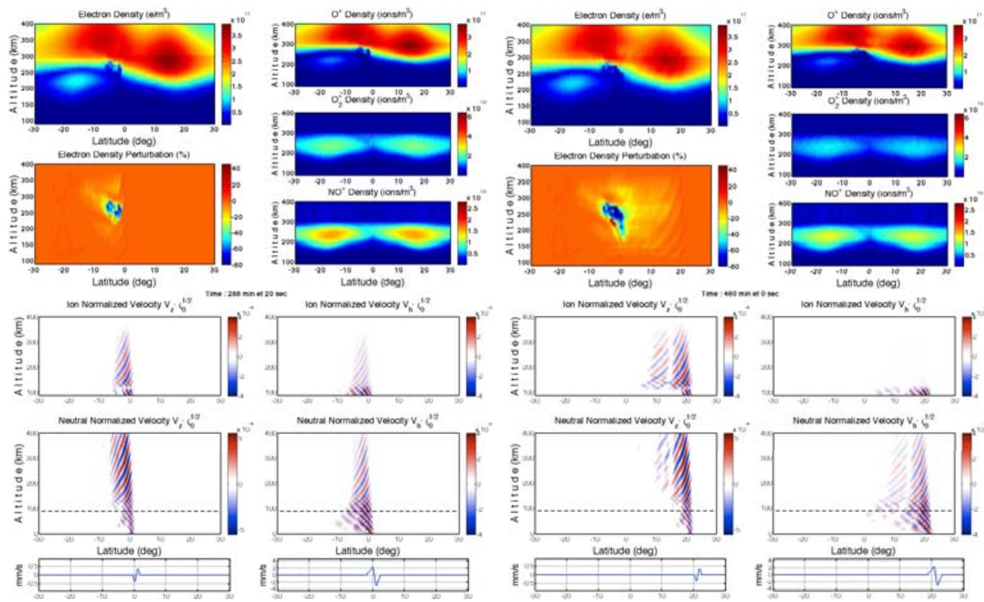
Altimetric and TEC signatures of the Sumatra tsunami. The modelled and observed TEC are shown for Jason-1 (a) and for Topex/Poseidon (b): data (black), synthetic TEC without production-recombination-diffusion effects (blue), with production-recombination (red), and production-recombination-diffusion (green). The Topex/Poseidon synthetic TEC has been shifted up by 2 TEC units. In c and d the altimetric measurements of the ocean surface (black) are plotted for the Jason-1 and Topex/Poseidon satellites, respectively. The synthetic ocean displacements, used as the source of IGWs in the neutral atmosphere, are shown in red. For each plot from a to d, the latitude and corresponding Universal Time are shown. Cross correlation between TEC synthetics and data are shown in e for Jason (blue) and Topex/Poseidon (red).

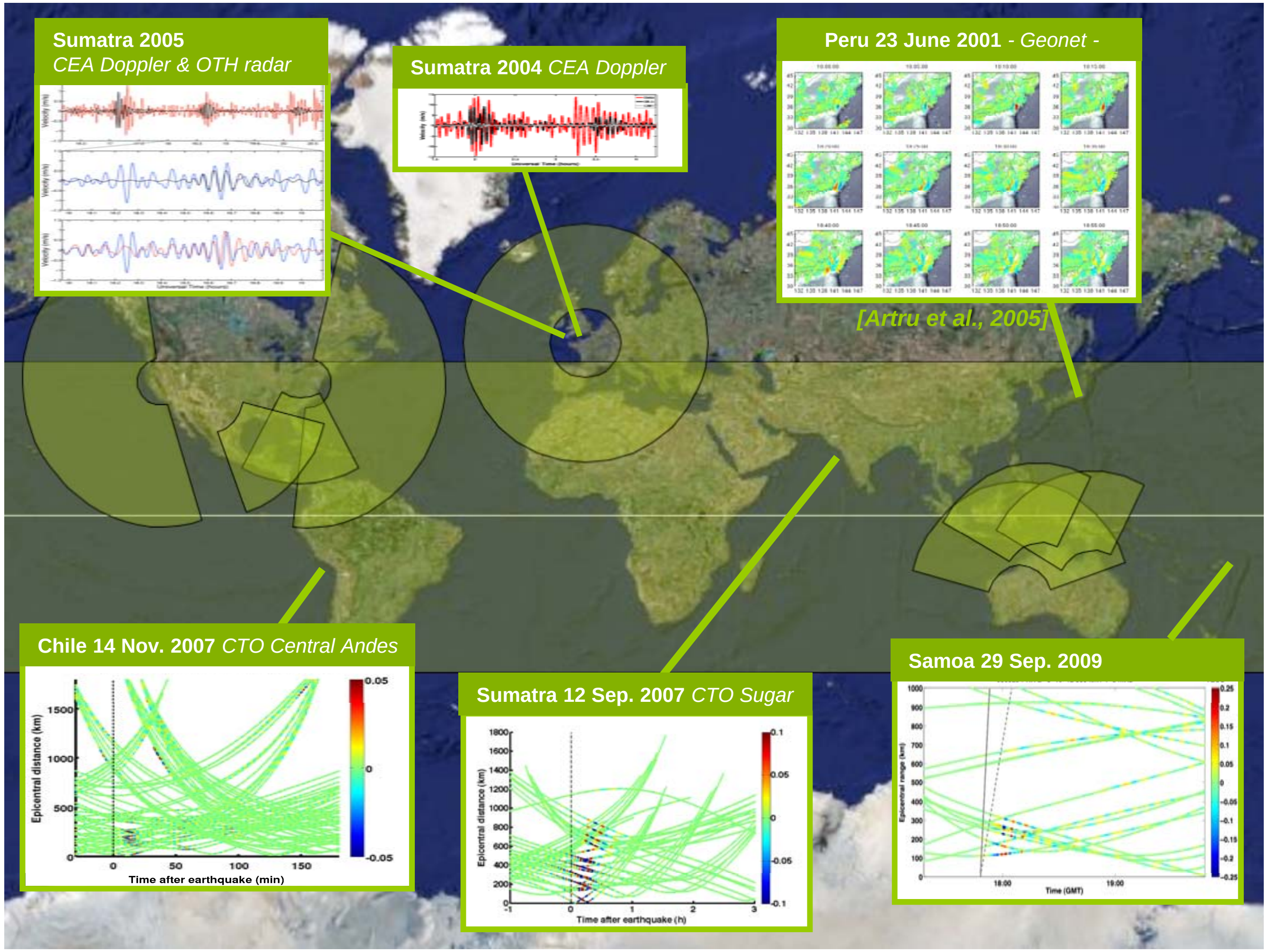


The South-North tsunami propagation



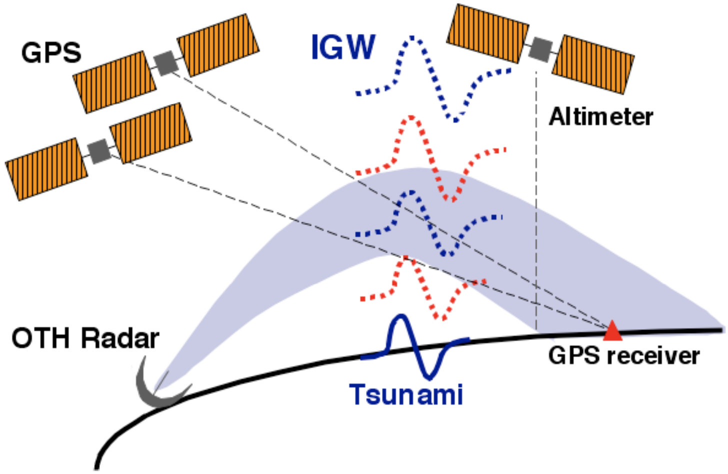
We observe that the horizontal component of the ion velocity is strongly affected by the magnetic field term n_i B. This latter is driven by the value of ion density increasing with altitude. As a consequence of this effect, the horizontal component of ion velocity in the F-region decreases with the latitude increasing. Contrary, in the E-regions the neutral-ion coupling is independent of magnetic field term and the horizontal velocity is invariable. The same equatorial effect is observed in the electron density variation that is strongly amplified in the equatorial F-region.

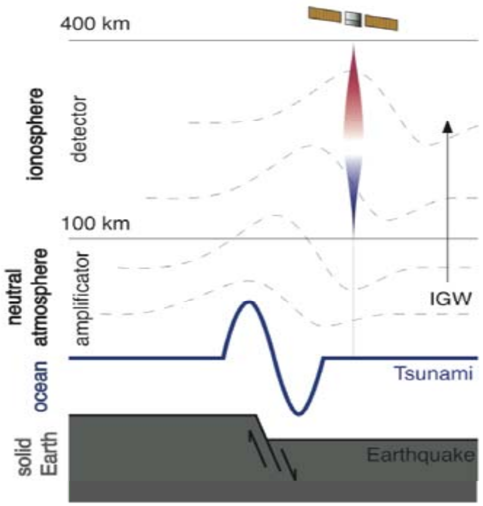




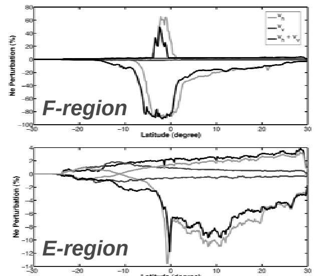
Sumatra 2005
CEA Doppler & OTH radar
Sumatra 2004 CEA Doppler
Peru 23 June 2001 - Geonet -
[Artru et al., 2005]
Chile 14 Nov. 2007 CTO Central Andes
Epicentral distance (km)
Time after earthquake (min)
Sumatra 12 Sep. 2007 CTO Sugar
Epicentral distance (km)
Time after earthquake (h)
Samoa 29 Sep. 2009
Time (GMT)

A series of ionospheric anomalies following the Sumatra tsunami has been reported in the scientific literature (e.g., Liu et al. 2006; DasGupta et al. 2006; Occhipinti et al. 2006). Similar anomalies were also observed after the tsunamigenic earthquake in Peru in 2001 (Artru et al., 2005). All these anomalies show the signature in the ionosphere of tsunami-generated internal gravity waves (IGW) propagating in the neutral atmosphere over oceanic regions. The strong amplification mechanism of atmospheric IGW allows to detect these anomalies when the tsunami is offshore where the see level displacement is still small. In addition, the dense coverage of ionospheric sounding instruments over the oceans increases over time and more instruments will be able to provide ionospheric measurements: i.d., Doppler sounding, over-the-horizon radar (OTH) and space-based GPS data. Most of the ionospheric anomalies are also deterministic and reproducible by numerical modeling (Occhipinti et al., 2006, 2008) via the ocean/neutral atmosphere/ionosphere coupling mechanism. In addition, the numerical modeling supplies useful helps in the estimation of expected anomalies The sensitivity of altimeters, OTH radar, ground-based and space-based GPS measurements is analyzed in this work by the way of the modeling and data. T



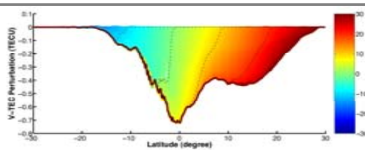


Vertical and horizontal effects



	Equatorial Region			Mid Latitude		
	v_h	v_v	$v_h + v_v$	v_h	v_v	$v_h + v_v$
E-region	−2 : 2%	−2 : 10%	−2 : 10%	−2 : 2%	−2 : 10%	−2 : 10%
F-region	−2 : 2%	−80 : 60%	−80 : 50%	−2 : 2%	−20 : 2%	−20 : 2%
V-TEC		−0.7 : 0.01 TECU			−0.4 : 0.01 TECU	

The table and figures resume Ne perturbation induced by the IGW neutral motion in the equatorial and mid- latitudes. Here the Ne perturbations produced by horizontal and vertical component of IGW have been computed separately for academic purpose. We can deduce that the plasma density variation in the high ionosphere are mainly driven by the horizontal component of IGW and that it is strongly influenced by the geomagnetic field. In the E-region the role of the geomagnetic field is less perceptible and the contributions of horizontal and vertical components of the IGW are comparable. We deduce the feeble B-dependence of vertical component: no differences are observed between E and F, equatorial and mid-latitude regions. A North-South dichotomy appears, probably driven by



The perturbation is shown in terms of TEC. The modeling shows a TEC perturbation in order of a fraction of TEC-unit (TECU) coherent with the GPS observation.

We must consider here that the tsunami-geometry is not taken into account and the amplitude of vertical displacement at the sea surface is in order of 25 cm this can be a good estimation of the mean displacement produced by Sumatra tsunami in the indian ocean. In accordance with the result of realistic modeling of Sumatra tsunami [Occhipinti et al., 2006], the amplitudes of TEC and electron density perturbations shown here are strongly enlarged in the equatorial latitude. The geometrical heterogeneity induced by the tsunami waveform [Occhipinti et al., 2006] adds to the latitude dependence highlighting the difficulties in the identification of tsunami signature in the ionosphere without numerical simulation.