Can OTH radar help tsunami warning systems?

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Introduction

A series of ionospheric anomalies following the Sumatra tsunami has been reported in the scientific literature from GPS and altimeter observations (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) and after the recent earthquakes in Sumatra and Chile in 2007. All these anomalies show the signature in the ionosphere of tsunami-generated internal gravity waves (IGW) propagating in the neutral atmosphere over oceanic regions.

Most of these ionospheric anomalies are 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 to explore and identify new techniques to detect the tsunami signature in the ionosphere, other than GPS and altimeters.

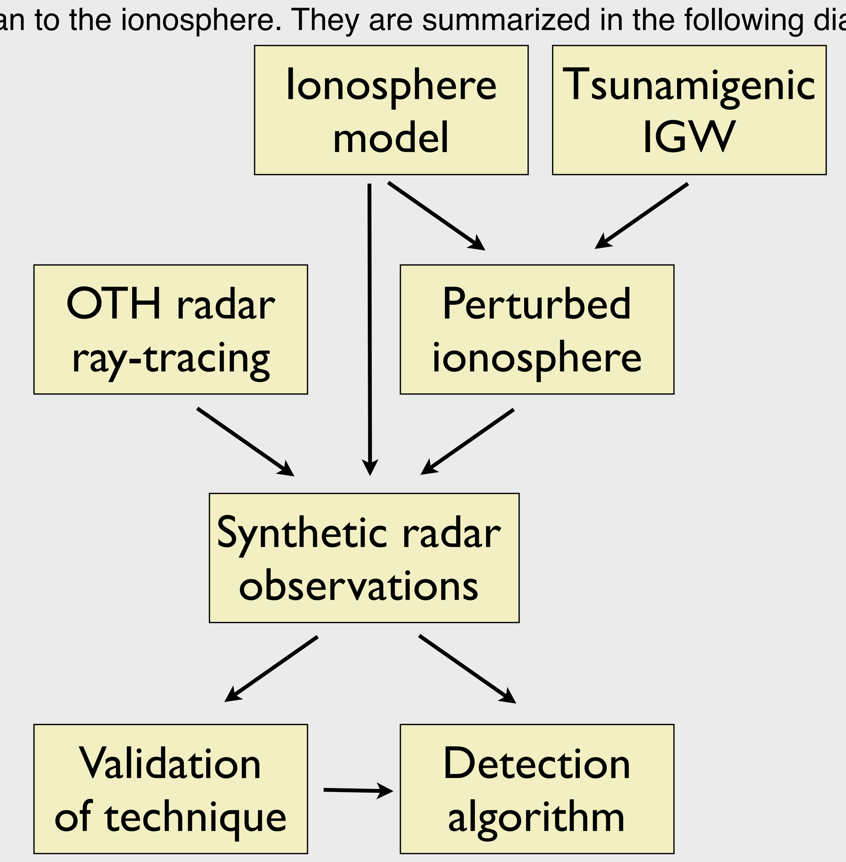
Here we present an overview of the mechanism highlighting the advantage of Over-The-Horizon (OTH) radar in the tsunami detection by ionospheric sounding. The large coverage of OTH radar and its sensitivity to plasma anomalies can open new perspectives in the future oceanic monitoring and tsunami warning system.

Building a synthetic OTH radar

Over-The-Horizon radars operate in HF radio band (from 3 to 30 MHz). This frequency range covers the range of frequency that can be reflected down by the Earth ionosphere. OTH radars signals are tuned in elevation and azimuth to observe areas up to few thousands km from the source.

These instruments can be also used to sound the ionosphere and we want to develop a technique that enable the detection of the ionospheric signature of tsunamigenic IGW.

We are building a full 3D simulation tool to model all the elements involved in the system OTH radar - tsunamigenic internal gravity wave propagating from the ocean to the ionosphere. They are summarized in the following diagram:



- **Ionosphere model**: it provides the climate conditions of the quiet ionosphere. At present IRI 2007 and NeQuick 2 models are included.
- **Tsunamigenic internal gravity wave**: it is modeled in two steps: first the tsunami propagation is computed using a realistic ocean bathymetry, then its displacement is used as excitation source of IGW in the neutral atmosphere.
- **Perturbed ionosphere**: the response of the ionosphere induced by the neutral atmospheric motion is computed and a 3D-time varying distribution of electron density in the ionosphere is obtained.
- **OTH radar ray-tracing**: a ray-tracing program, coupled with the radar emission lobe, simulate the radar operation in the frequency range 3-30 MHz.
- **Synthetic radar observations**: combining OTH radar ray-tracing with a selected ionospheric environment (nominal or including IGW) we obtain the synthetic response of the system.
- **Validation of the technique**: the next step of our research is to validate the synthetic radar observation with OTH radar measurements to check the ray-tracing module and select the most suitable ionospheric model.
- **Detection algorithm**: the synthetic data will be used to develop an algorithm for OTH radar operations to detect tsunamigenic IGW in the ionosphere and provide support for tsunami warning systems.

Ray-tracing

Ionospheric ray-tracing

We developed an 3D electromagnetic wave ray-tracing program based on the geometric optic linear theory and including a heterogeneous ionosphere above an ellipsoidal Earth (WGS-84). It is used along with a 3D model of electron density in the ionosphere in order to calculate the index of refraction at any point of the propagation path. Two options for the ionosphere have been included in the program to check rays response to different ionospheric representation: IRI 2007 (Bilitza, 2008) and NeQuick 2 (Nava et al., 2008). They present different characteristics that have to be tested to understand the ability of the ray-tracing program to predict the propagation behavior of radar signals.

- **IRI 2007**: it includes all ionospheric bottomside layers (D, E, F1, F2), but can have electron density spatial discontinuities when F1 layer appears. The default foF2 model is based on URSI coefficients.
- **NeQuick**: it is spatially continuous, with continuous spatial first derivatives, but does not include D layer and E layer height is fixed. It uses ITU-R coefficients for foF2.

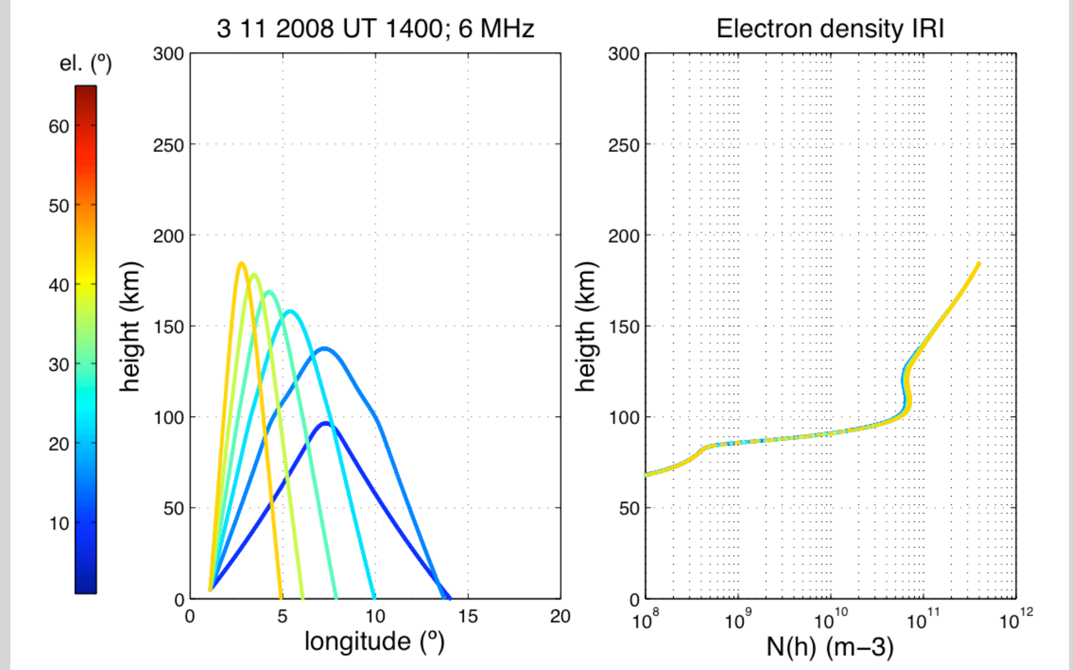


Figure 1: Ray-paths for different elevation angles through IRI ionosphere, from middle latitude location, day-time, low solar activity, azimuth 90°.

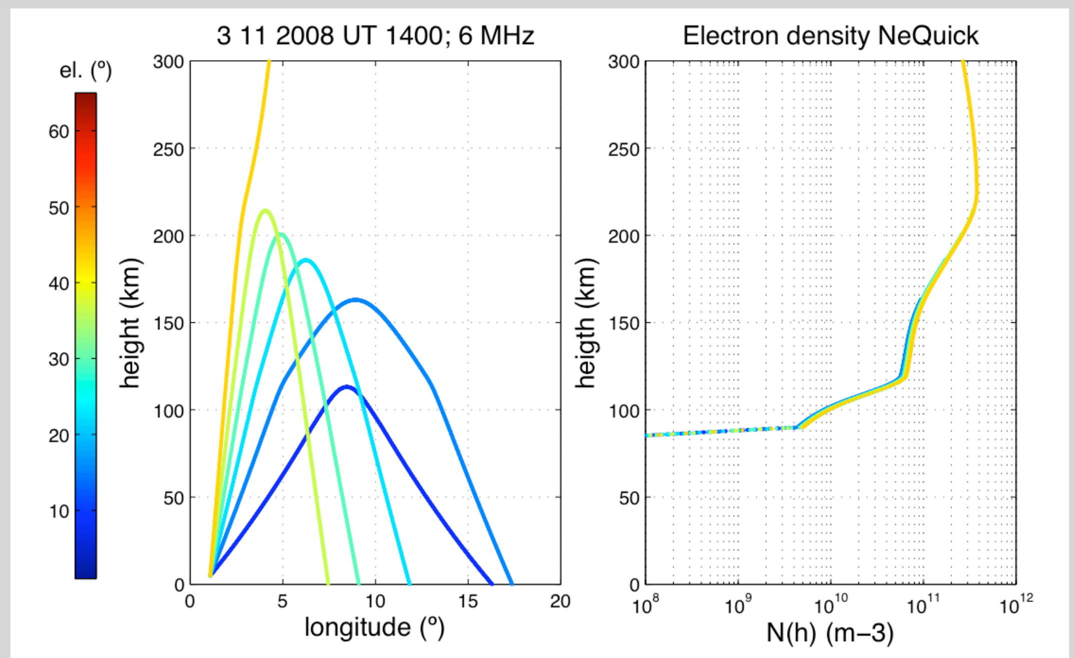


Figure 2: Ray-paths for different elevation angles through NeQuick ionosphere, from middle latitude location, day-time, low solar activity, azimuth 90°.

Figures 1 and 2 show examples of ray-tracing calculations using IRI or NeQuick models for day-time conditions during low solar activity for rays emitted at elevation angles between 10° and 60° from a radar located in France (Nostradamus).

Since NeQuick electron density is always lower than the corresponding IRI density, all the rays have a higher reflection point and reach more distant locations.

It is possible to have rays emitted at different elevation angle that have ground reflections in the same point, since they are reflected by two different ionospheric layers (E and F).

In this example the ray at 60° elevation is not reflected down by NeQuick ionosphere, while for IRI it still have a ground reflection. This is an indication that the NmF2 value computed by the models is a critical parameter to determine rays behavior.

OTH radar simulations

Echo time calculation using ray-tracing technique

The use of two ionospheric models allows the identification of issues related to their different representation of the Earth ionosphere. In the low solar activity example shown in fig. 3 NeQuick echos are always arriving later than IRI echos (up to 1 ms for low elevations). For frequencies above 6 MHz the signals emitted at high elevation are not reflected down by NeQuick ionosphere, while most of them produce echos for IRI.

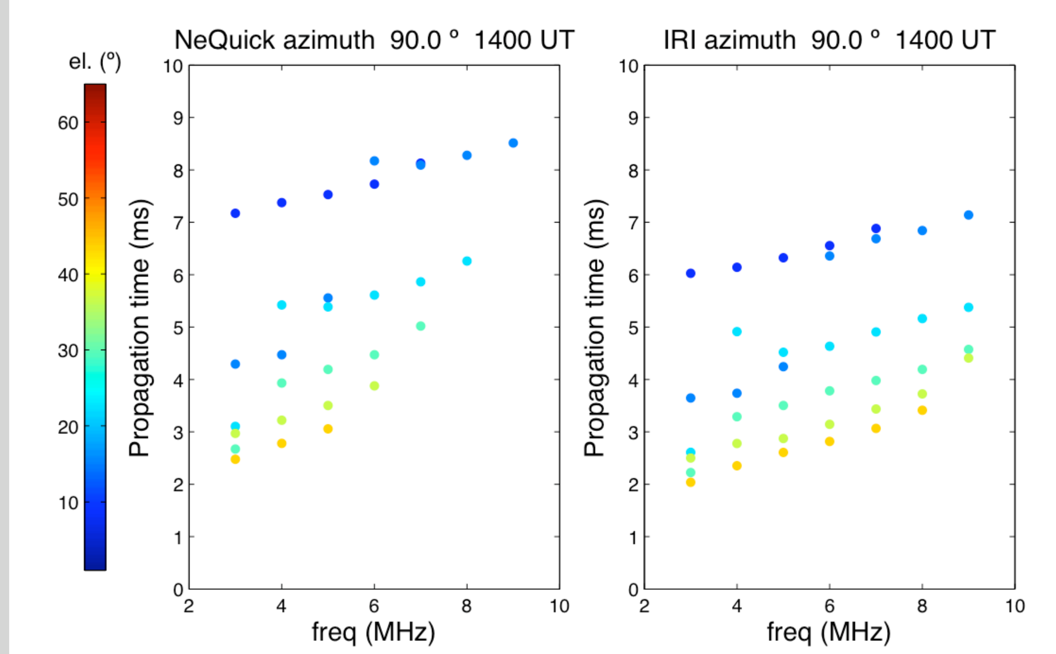


Figure 3: Propagation time of signals emitted at various frequency for elevations angles between 10° and 60°: left NeQuick ionosphere, right IRI ionosphere.

OTH radar emission lobe

Figure 4 shows a simulation of the radiative diagram of a typical OTH radar at 30° elevation. It cannot be approximated by a single ray: the central part of the beam has been divided here into 121 rays. Figure 5 shows an example of ray-tracing using NeQuick model for the ionosphere (Occhipinti, 2006).

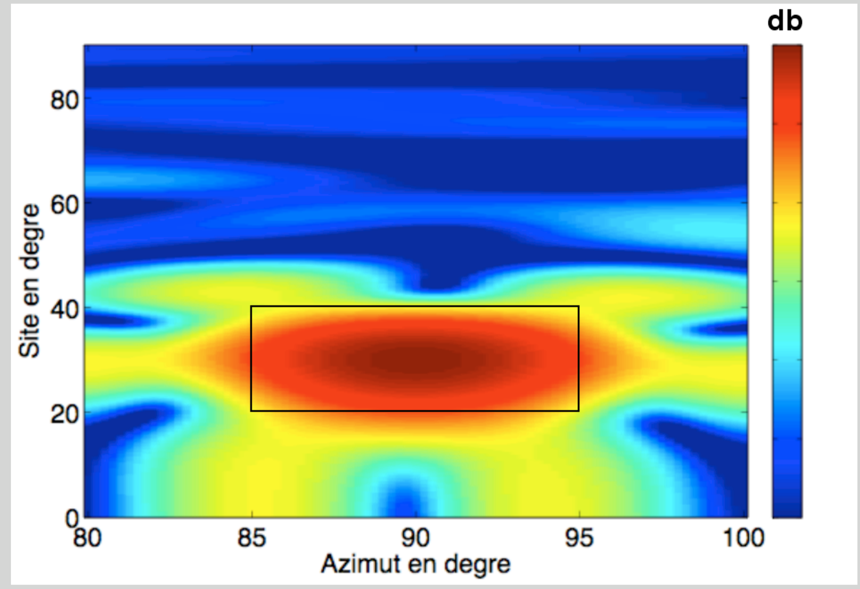


Figure 4: Theoretic radiative diagram of OTH radar at 30° elevation and 90° azimuth.

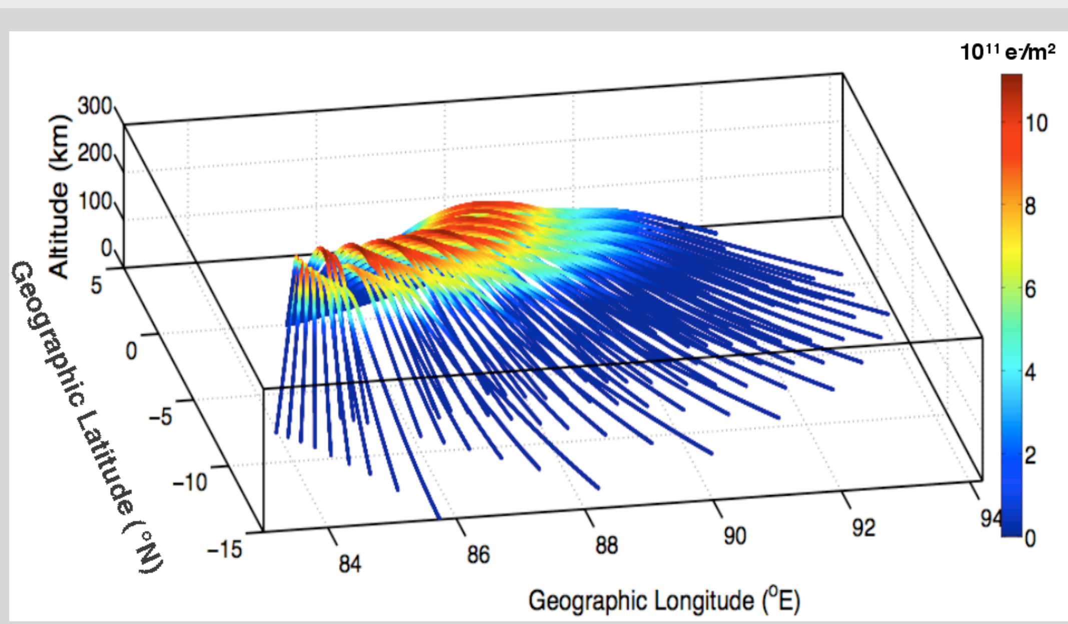


Figure 5: 121 rays computed for calculating the synthetic emission lobe of the radar, using NeQuick model for the ionosphere.

Preliminary results

Simulation of OTH radar detection of Sumatra 2004 tsunami

The tsunami occurred on 12/26/2004 after the giant M_w=9.3 Sumatra earthquake has been chosen to simulate the detection of its ionospheric signature by OTH radar.

The tsunamigenic IGW produced by the tsunami has been calculated and coupled with the ionosphere to produce disturbed ionospheric conditions.

The synthetic OTH radar has been located at (0°N, 85°E) and emitted rays have been calculated at 80s time interval.

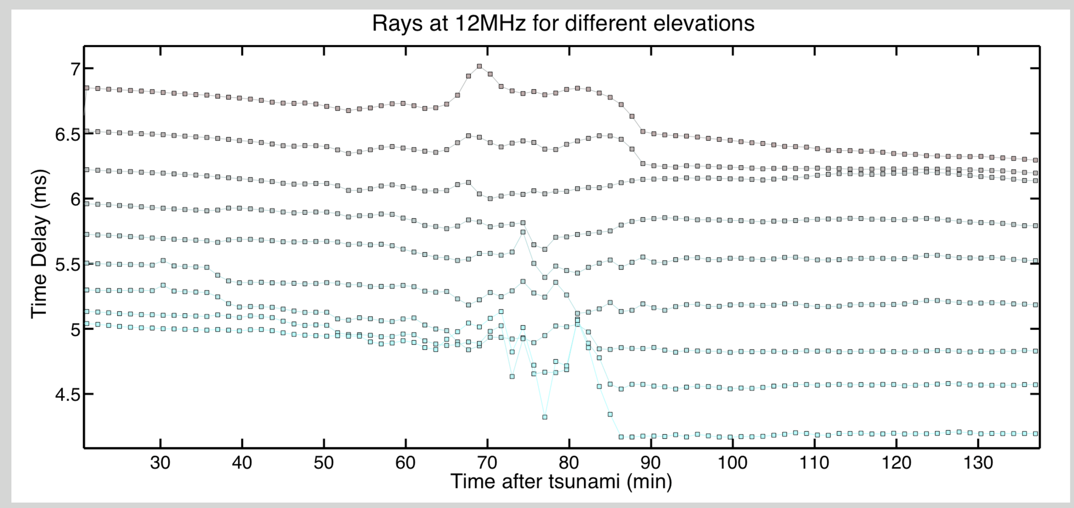


Figure 6: Propagation time of rays emitted every 80 s at 9 elevation angles, between 22° and 40°, step 2°, propagating through an ionosphere affected by tsunamigenic gravity waves.

Figure 6 shows the clear signature of IGW observed by successive measurements of narrow rays echoes at different elevations angles after tsunami generation. To apply this technique to OTH radar, 121 rays corresponding to the radar emission lobe have been computed every 80 s, considering their energy to verify if the tsunami signature is not attenuated by the three-dimensionality of the radar measure. Figure 7 shows the synthetic image of the radar received energy for a time resolution of 200 μs, with a clear indication of the tsunami IGW. These results are in agreement with altimeter observations by Topex/Poseidon and Jason satellites (Occhipinti et al, 2006).

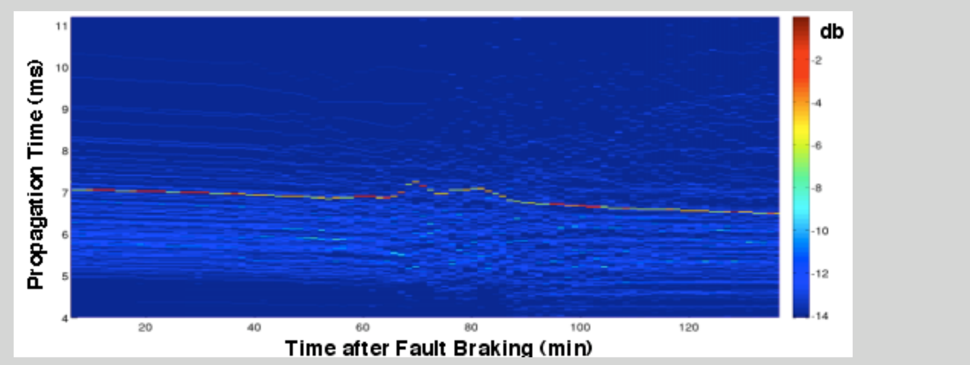


Figure 7: Syntetic OTH radar measurements for Sumatra event. Time resolution 200 μs.

Conclusions and Perspective

OTH radar can be regarded as a very promising instrument to detect tsunamigenic gravity waves, due to its capability to observe the ionosphere over very large area.

The preliminary tests performed confirm the possibility of detecting these waves.

Validation of the different elements involved in the synthetic detection has to be performed with experimental data. The first step will be a validation of the ray-tracing program with OTH radar measurements.

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