Nostradamus: the Radar that wonted be a Seismometer

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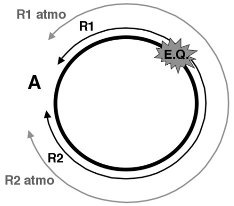
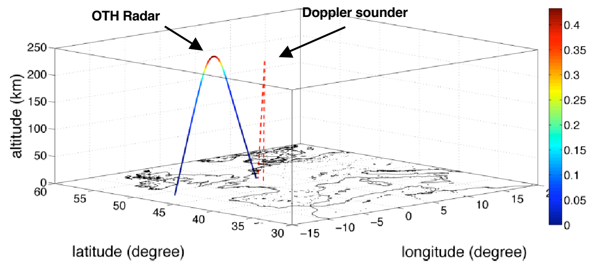
Surface waves emitted after large earthquakes are known to induce, by dynamic coupling, atmospheric infrasonic waves propagating upward through the neutral and ionized atmosphere. Those waves have been detected in the past at ionospheric heights using a variety of techniques, such as HF Doppler sounding or GPS receivers. The HF Doppler technique, particularly sensitive to the ionospheric signature of Rayleigh waves is used here to show ionospheric perturbations consistent with the propagation of Rayleigh wave phases R1 and R2 following the Sumatra Earthquakes on the 28 March 2005 (Ms =8.4). This is in our knowledge the first time the the phase R2 is detected by ionospheric sounding. In addition, we prove here that the ionospheric signature of R2 is also observed by over-the-horizon (OTH) Radar. This latter was never used before to detect seismic signature in the ionosphere. Adding the OTH Radar to the list of the "ionospheric seismometers" we discuss and compare the performances of the tree different instruments mentioned above, nominally HF Doppler sounding, GPS receivers and OTH radar.

Introduction & Tales

The 28 Mars, 2005 the over-the-horizon radar prototype Nostradamus wasn't operative. After the first early seismic information (received in my cell phone) i jump in a cab to go at the radar control centre to catch, at the least, the Rayleigh wave phase R2. Surface waves generated by large earthquakes move around the world several time and if R1 is the first and more energetic wave reaching the observation point A, R2 is the second wave reaching A, after had travelled around the world.



I wasn't interested to measure the Raylegh wave at the surface of the Earth but his signature in the ionosphere. Surface displacement induced by Rayleigh waves is known to produce, by dynamic coupling, acoustic wave that propagating upward in the atmosphere is strongly amplify by the double effect of the degrease of density and the conservation of kinetic energy $Ec=\rho v^2$. Reaching the altitude over 80 km the generated acoustic wave interact with the ionosphere creating strong variation in the plasma velocity and plasma density detectable by ionospheric sounding (*e.g.*, Doppler sounders, Incoherent Scatter Radar, GPS).

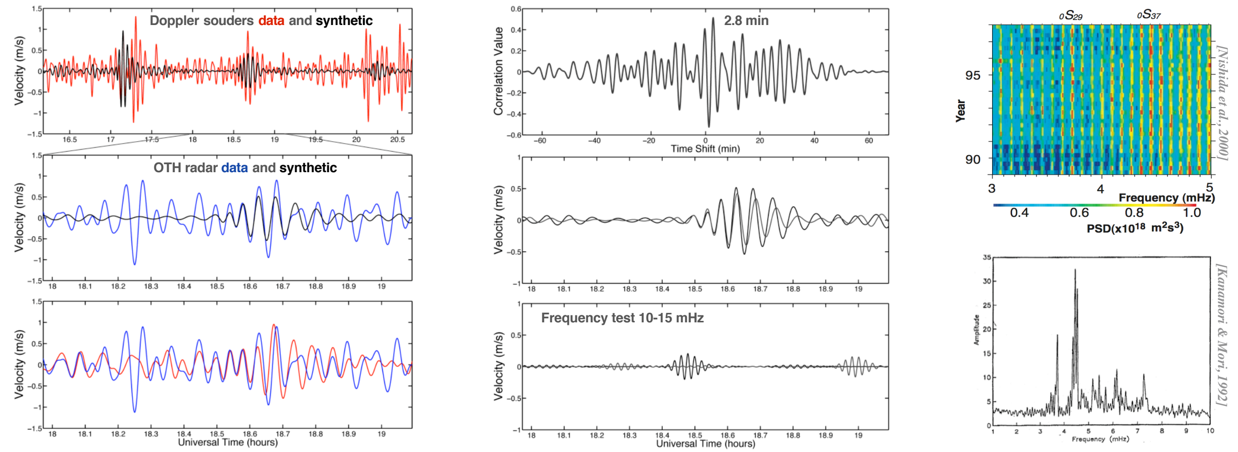


The capability of Doppler sounding to detect the signature of Rayleigh waves in the ionosphere was extensively discussed in the past *[artru et al., 2004]*. Measures of the dispersion of Raylegh waves *[Najita & Yuen, 1979]* performed by Doppler sounding found a clear accord with seismic data, proving that lithospheric proprieties are measurable observing ionosphere at 150 km of altitude. Today, Doppler sounders are able to measure routinely the signature of Rayleigh waves for moderate seismic events (*Ms* ≥ *6.5*).

In this work we principally explore the possibility to detect the Rayleigh wave signature in the ionosphere by over-the-horizon (OTH) radar. This instrument could, in the future, combine the strengths of HF Doppler sounder and GPS dense networks.

The OTH radar is able to sound large region in the ionosphere, consequently, it could images the plasma velocity perturbation, produced in the ionosphere by Rayleigh wave, with a very high spatial resolution (≈ 10 km) and with the same sensitivity of the HF Doppler sounder.

Observatins & Modeling



The Doppler sounder data (red line) show clearly the signature of R1 and R2. The signature of R3 is partially cover by the noise produced by the day/night ionospheric dynamic. The Doppler sounder data are reproduced (black line) by normal mode summation following Lognonné et al. (1998). The first arrival phase of R1 is totally described by synthetics (red and black lines are superimposed). Anyway the synthetics don't arrive to describe the second large phase of R1, probably cause the limit of the 1D model used to compute the synthetics (PREM+USSA). Blue line show the vertical velocity observed by OTH radar. Here the data are also reproduced by synthetics; we observe that the phase arriving around 18.6-18.7 UT is well explained by synthetics.

We highlight that here we treat a OTH radar in the same way of a Doppler sounder, in essence we analyse only the formed signal coming from the more energetic part of the emission beam. This hypothesis his equivalent to consider a narrow beam. The limit of this hypothesis show up in the phase arriving around 18.2-18.3 UT that remain unsolved by the model. This signal could be induced by a secondary lobe of the emission beam.

Signatures of Rayleigh wave in Doppler sounder and OTH radar are strictly in accord and show a time shift that we can quantify by cross correlation. The observed time shift (2.8 min) correspond to the propagation time from the OTH radar observation point to the Doppler sounder observation point (synthetics superimposed taking account this time shift). Data and synthetics presented here were filtered between 3 mHz and 7 mHz. If we filter data in a different frequency range (e.g., 10-15 mHz) we obtain a maximum correlation value of 0.3 and an incoherent time shift. This simple frequency test is in accord with previous observation suggesting that the transfer of energy between the solid Earth and the atmosphere go through fundamental modes ${}_0S_{29}$ and ${}_0S_{37}$, at 3.68 and 4.40 mHz respectively *[Kanamori & Mori, 1992; Nishida et al., 2000]*.

Conclusion & References

In this work we show the clear signature of Raylegth phase R1 and R2 observed by ionospheric sounding during the Sumatra event (28 March 2005). We demonstrated here the capability of OTH radar to measure the signature of Rayleigh waves in the ionosphere. Detection of Rayleigh wave by OTH radar could open new perspective in (ionospheric) seismology combining the sensitivity of Doppler sounding and the imaging capability of GPS dense network. Consequently, OTH radar could measure the arrival time of Rayleigh wave on large regions (200x200 km^2) with an high spatial resolution (10 km). In the future these measurements could be included in the seismic dataset to improve the resolution of velocity maps and lythospheric tomography.

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