# Theory and observation of acoustic coupling between the solid Earth and its atmosphere

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Introduction: The atmosphere of the Earth is generally considered decoupled from the solid Earth. Earth's solid surface is then considered either as a free surface, by seismologists, or a rigid surface by atmosphericists. However, it has been recognized that solid earth sources, such as earthquakes, can excite the atmosphere, and vice-versa; atmospheric sources, such as nuclear, meteoritic or volcano explosions or even continuous turbulence near the surface can excite the solid Earth. We describe here the mean features of a theory able to take into account these coupling effect by an explicit calculation of the normal modes of Earth model with realistic atmospheric model. We then applied this theory with two examples: the first one is the analysis of the Pinatubo eruption, which can be foreseen as an example of excitation of the solid earth with source in the atmosphere. The second one is the recording of surface waves in the ionosphere, and therefore the excitation of atmosphere by seismic sources in the solid earth.

Theory: The theory is described in details in Lognonné et al., 1998. The atmosphere of the Earth (or other planets) changes the boundary conditions of the elastodynamic operator. The atmosphere is indeed such that no specific boundary can be defined, due to the exponential decay of the density. However, acoustic waves are not reflected when propagating upward at high altitude, and loose their energy due to viscosity and non-linear effects. These effects can be modeled by using a radiative boundary condition instead of the usual free surface boundary condition.

Normal modes for such boundary condition are computed with a variational method, which uses a basis of test functions found by mapping the normal modes with free surface toward functions verifying explicitly the radiative boundary conditions. All normal modes of the Solid Earth-Ocean-Atmosphere coupled system are then found (Spheroidal Solid Earth Normal modes, Acoustic, Gravity and Lamb atmospheric modes, Gravity-Tsunami gravity modes).

The main perturbation, for the spheroidal normal modes are found in the amplitude of normal modes rather than in the frequency or quality coefficient perturbations, which appears to small to be detected. Two regimes for the fundamental spheroidal modes are found: below 3.68 mHz (the exact frequency depending on the model), the atmospheric part of the mode is trapped and decay exponentially with altitude. At higher frequency in contrary, the energy propagates upward [Figure 1].

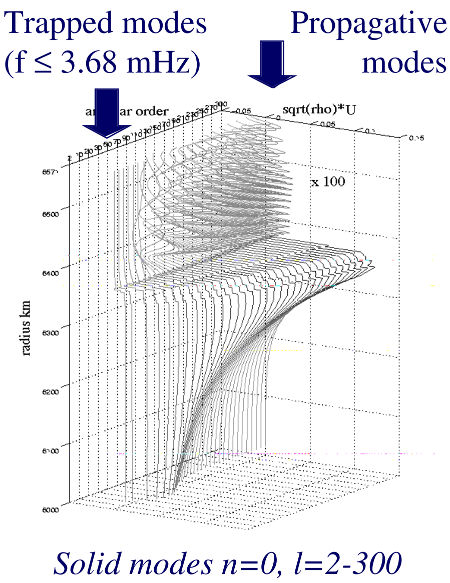


*Figure 1: Amplitude of the Solid spheroidal normal modes in the upper mantle and atmosphere.*

Seismic signals from atmospheric sources: the pinatubo eruption: Strong unusual seismic signals were reported following the 1991 volcanic eruption of Pinatubo [Kanamori and Mori, 1992; Zürn et al., 1996 Kanamori et al., 1984] and El Chichon, 1982 eruption [Zürn et al., 1996]. The 1991 eruption of Mount Pinatubo excited harmonic fundamental-mode Rayleigh waves with periods of about 230 and 270 sec, which were believed to be caused by acoustic coupling of the solid Earth and the atmosphere. A very detailed study of this data set is given by Watada [1995].

We present the results of a source inversion, where we invert for the pressure glut history with a source located either in the solid earth or in the atmosphere. Despite the relatively low signal to noise ration, good results in variance reduction are found and we match well the main feature of the waveform. A comparison between our source history and the eruption history and amplitude is given.

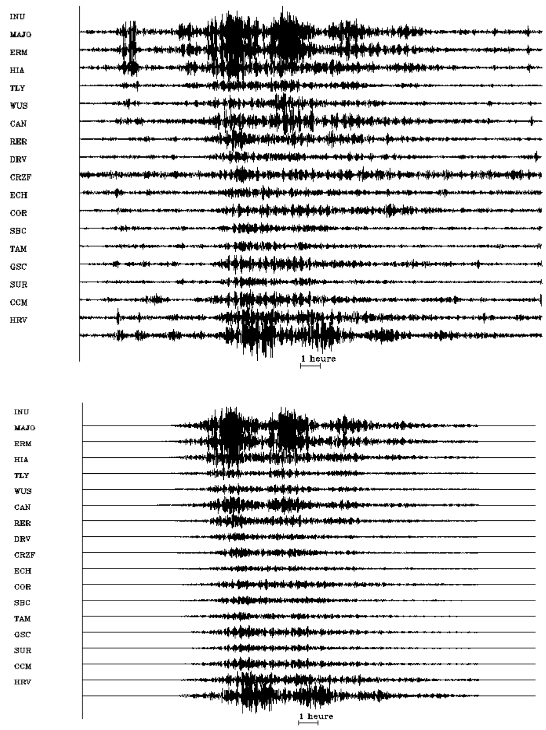


*Figure 2: Top, bandpass filtered data recorded after the Pinatubo eruption by several station of the global network. Bottom: synthetics found in the study*

Atmospheric signals from seismic sources: We finally presents data of ionospheric oscillations recorded in France by an ionospheric sounder developed by CEA. This instrument performs the measurement of the Doppler shift between a HF EM wave emitted from the ground and its counterpart reflected by ionospheric F layer and provides a direct measurement of the vertical velocity of the ionosphere. 3 receivers are located 50-100 km apart from the emitter, located in Francourville, France.

The network has been working continuously since August 1999, most of M>6.5 earthquakes have been observed.

| | | SEISMOGRAM | | | DOPPLER | | |
|---|---|---|---|---|---|---|---|
| Date | | | Ms | Prof | Df | Altitude (km) | Tmax |
| 17/08/99 | 00:01 | Turquie | 7.8 | 10 | 0.5 | 240 | 100 |
| 20/08/99 | 10:02 | Costa Rica | 6.7 | 33 | 0.4 | 170? | 40 |
| 20/09/99 | 17:47 | Taiwan | 7.6 | 10 | 0.3 | 180 | 70 |
| 30/09/99 | 16:31 | Mexique | 7.5 | 33 | 0.15 | 170? | 100 |
| 16/10/99 | 09:46 | Californie | 7.3 | 10 | 0.7 | 180? | 40 |
| 12/11/99 | 16:57 | Turquie | 7.2 | 10 | 0.4 | 170 | 40 |
| 15/11/99 | 05:42 | Ocean Indien | 7.0 | 10 | * | * | * |
| 28/01/00 | 14:21 | Iles Kouriles | 6.8 | 33 | 0.15 | ? | 40 |
| 25/02/00 | 01:43 | Iles Vanuatu | 7.1 | 33 | * | * | * |
| 28/03/00 | 11:00 | Japon | 7.7 | 116 | 0.8 | ? | 50 |
| 4/05/00 | 04:21 | Minahassa | 7.3 | 33 | 0.3 | ? | 100 |
| 12/05/00 | 18:43 | Chili | 7.0 | 240 | <0.05 | ? | 300 |
| 4/06/00 | 16:28 | Indonesie | 7.9 | 33 | 0.4 | ? | 50 |
| 17/06/00 | 15:40 | Islande | 6.6 | 10 | 0.7 | ? | 50 |
| 18/06/00 | 14:44 | Ocean Indien | 7.5 | 10 | 1.05 | ? | * |

*Table 1: List of the events recorded during the first year of operation. Amplitude of the doppler signals are given, as well as the altitude of the reflection for all recorded events.*

We present the comparison of synthetics with these data [Figure 3]. Significant differences in amplitude are found. Even if non-linear effects are not taken into account here, they should represent about 10% of the signal at 150km and can be neglected in first approximation. In contrary, we found that attenuation due to viscosity is important above 100 km height and strongly constraints the attenuation of waves: our data can therefore be used to constrain the relatively poorly known profiles of the atmospheric viscosity. Future works will also combine this method with the modeling of the interaction of the wave with ionospheric plasma, together with thermal effects.

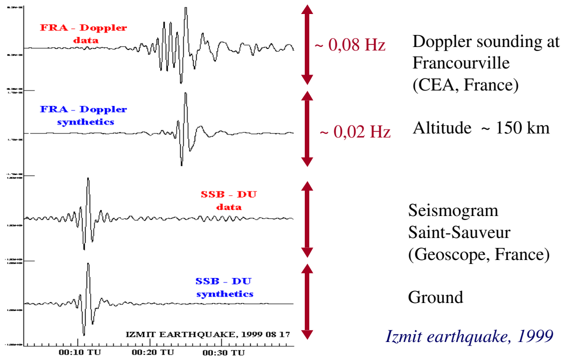


*Figure 3 : Observation of ionograms at Francourville and seismograms at the nearby Geoscope SSB station, with their synthetics for the PREM model with US standart atmospheric model.*

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