Simplistic models of atmospheric effects in horizontal seismograms

by

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1 Introduction

It is common knowledge, that horizontal seismic noise at a given station is larger by factors between five and fifteen than the vertical noise at essentially all frequencies. A typical example is presented by Müller and Zürn (1983) in their Fig. 6. This fact definitely contributes to the large difference in use of horizontal and vertical seismographs and seismograms. It is also well known that at low frequencies tilts are an important mechanism for production of noise signals on the horizontal components. Tilts associated with changes in atmospheric pressure have been effectively removed from signals by Beauduin et al. (1996) and Neumann and Zürn (1999) in order to improve the quality of the seismograms. It is very desirable to understand the physics of the horizontal noise in order to possibly take measures against it or devise correction algorithms to remove noise from the already recorded seismograms. This and the companion paper by Exss and Zürn (2002, this volume) take steps to identify the physical mechanisms leading to horizontal noise.

A horizontal accelerometer senses several forces on its mass. Some sources of deformation have a changing direct gravitational attraction on the sensor mass like the sun, moon (tides) and the atmosphere, mass redistribution in the earth leads to secondary changes in gravitation, the local displacement field causes tilts and inertial effects. There are other effects which are usually of minor importance. Table 1 shows for different phenomena the relative contributions of these effects to the total recorded signal. An enlightening discussion of sensor sensitivity for horizontal seismographs can be found in Rodgers (1968). He took special design features into account, which are to some part avoided in modern broadband feedback seismometers (e. g. Wielandt and Streckeisen, 1982).

Note that the tilt effect is the largest contribution to ${}_oS_2$, while for the fundamental toroidal mode ${}_oT_2$ on a laterally homogeneous earth tilt does not exist. In the following

Table 1: Relative contributions to signals sensed by a horizontal accelerometer.

Signal	Frequency	Inertial effect	Tilt effect	Mass redistr. effect	Gravitation
M_2-tide	22.4 μHz	0.0042	-0.6	0.30	1.00
${}_oS_2$	0.30 mHz	-0.118	2.13	-1.015	0.0
${}_oT_2$	0.38 mHz	1.000	0.0	0.0	0.0
${}_oS_{10}$	1.725 mHz	0.87	0.14	-0.008	0.0
P-wave	1.0 Hz	1.00	0.0	0.0	0.0

we are not concerned with purely instrumental effects and we only consider effects of local atmospheric pressure.

2 Two simplistic models for horizontal noise

Both of our models are quasistatic in the sense, that we assume that there are no elastic waves excited by the changing pressure field. At higher frequencies this will not be the case, of course (e. g. Sorrells, 1968; Kanamori and Mori, 1992; Widmer and Zürn, 1992).

The first model is extremely simple. It assumes that the surface near the station is loaded by a laterally homogeneous pressure field changing with time. The station underground is assumed to be elastic, so clearly there are displacements, tilts and strains which have the same time dependence as the barometric pressure without phase leads or lags. The amplitudes of these signals will depend strongly on the local geology, topography and geometry of the station and the pier on which the instrument sits. In tidal tilt and strain measurements such local effects from stressing the locality with tidal stresses were clearly observed and they hamper the interpretation of tidal signals in terms of Love numbers (e. g. King et al. 1976). The pressure admittance for this case can be written as follows:

$$\left(\frac{\Delta a_h}{\Delta p}\right)_L = C_p \tag{1}$$

where Δa_h is the change in acceleration in the horizontal direction indicated by h, Δp is the change in atmospheric pressure and C_p is a positive or negative constant strongly dependent on the position and sensitive direction of the sensor but not on frequency or on the propagation direction of atmospheric masses or waves. We believe that the results by Beauduin et al. (1996) were due to such effects, because they obtained results strongly dependent on the position of the sensor within one observatory and independent of time.

Our second model was described by Neumann and Zürn (1999) and by Zürn (2002) and consists of a horizontally propagating plane wave with horizontal phase velocity c_h, horizontal wave number k_h and angular frequency ω in the atmosphere over an elastic halfspace with Lamé constants λ and μ. We assume $\lambda = \mu$ in the following:

$$\Delta p(x,t) = p_o \cdot exp(i \cdot (k_h \cdot x - \omega \cdot t)) \tag{2}$$

p_o is the peak pressure of the sinusoidal variation. The density decreases exponentially with height z and with scale height H from the surface value:

$$\Delta \rho(x,z,t) = \frac{p_o}{c^2} \cdot exp(i \cdot (k_h \cdot x - \omega \cdot t)) \cdot exp(-z/H) \tag{3}$$

where c is the speed of sound. These equations describe the properties of a Lamb wave with imaginary vertical wavenumber $k_z = i/H$, while they only approximate the behavior at the surface of an acoustic-gravity wave with real vertical wave number k_z (Gossard and Hooke 1975). For a horizontal accelerometer on the surface (x = 0, z = 0) of the halfspace we have the pressure admittance:

$$\left(\frac{\Delta a_h}{\Delta p}\right)_W = i \cdot \frac{2 \cdot \pi \cdot G}{g} \cdot \frac{1}{(1 + \frac{\omega \cdot c^2}{c_h \cdot g})} + i \cdot \frac{3}{4} \cdot \frac{g}{\mu} + i \cdot \frac{1}{4 \cdot \mu} \cdot c_h \cdot \omega \tag{4}$$

with $k_h = \omega / c_h$ and $H = c^2/g$ and $i = \sqrt{-1}$. c_h can assume values from 10 m/s up to the sound velocity c (330 m/s). The three terms represent the gravitational attraction, the tilt and the inertial effect, respectively. Note that all three contributions are in phase with each other, but in quadrature with the pressure signal. All three have a different dependence on frequency. The tilt term surprisingly does not depend on the wavelength for this model, so the amplitude of the sinusoidal surface deformation must be proportional to the wavelength (then tilt = amplitude/wavelength is constant). Thus the tilt term does not correspond to the pressure gradient but to the Hilbert transform of the pressure variation, a result noticed by Möckli (1988).

The relative importance of the effects can be obtained from the terms in eqn. (4):

$$\frac{tilt}{inertia} = \frac{3 \cdot g}{c_h \cdot \omega} \tag{5}$$

This ratio increases with ω^{-1} for constant c_h and equals one for frequencies of 0.468 and 0.014 Hz for horizontal phase velocities of 10 and 330 m/s, respectively.

$$\frac{tilt}{gravitation} = \frac{3}{8 \cdot \pi} \cdot \frac{g^2}{\mu \cdot G} \cdot \left(1 + \frac{\omega \cdot c^2}{c_h \cdot g}\right) \tag{6}$$

The second term in the parentheses is always larger than 1 and only increases as frequency increases. To underestimate the ratio we use μ = 100 GPa and the factor in front of the parentheses results in the value 1.7, so the tilt is for all frequencies and model parameters larger than the gravitational effect, except when the halfspace is unrealistically stiff.

We compute (in the frequency domain) from an observed time series of local atmospheric pressure p(t) the pressure induced "signal" (noise) deterministically as a time series (pressure seismogram). The spectrum of the "pressure seismogram" is:

$$A_h(\omega) = \frac{1}{i \cdot \omega} \cdot H_v(\omega) \cdot \frac{\Delta g}{\Delta p}(\omega) \cdot \Delta p(\omega) \tag{7}$$

where H_v is the transfer function of the accelerometer for output a_h (in volts or counts) w. r. t. ground velocity, as normally used in seismology for broadband seismometers. After application of inverse Fourier transformation the "pressure seismograms" can be compared to real ones (between earthquake signals). The model seismograms can be fit by least squares to the data for different time windows and/or atmospheric phenomena or situations and the regression factors found may be interpreted in terms of the parameters in eqns. (1) and (4). First results will be reported by Exss and Zürn (2002, this volume).

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