On reduction of long-period horizontal seismic noise using local barometric pressure

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SUMMARY

Tilt from atmospheric loading has long been known to be the major source of long-period horizontal seismic noise. We try to quantify these effects for seismic data from the Black Forest Observatory (BFO), which is known to be a very quiet station. Experimental transfer functions between local barometric pressure and horizontal seismic noise are estimated for two long time-series by standard methods. Two simple analytical physical models are developed: the local deformation model (LDM) and the acoustic-gravity wave model (TWM). Subsequently these models, with only two free parameters are fit using least squares to the observed seismic noise for time-series of widely differing lengths. The results are variable, sometimes rather dramatic variance reductions are obtained and sometimes the reduction is hardly significant. The method produces the best results when barometrically induced noise is high. The resulting admittances for the LDM are compared to finite element calculations. Since the methods are simple and can result in conspicuous reductions in noise we provide one more reason for installing barometers at even the best broad-band seismic stations.

Key words: barometric pressure, horizontal seismic noise, modelling, tilt.

1 INTRODUCTION

It is a long-known fact that horizontal seismic noise below \( \sim 50 \) mHz is larger than the vertical noise by factors between 5 and 15 (e.g. Müller & Zürn 1983, Fig. 6). This is confirmed in a recent study by Berger et al. (2004) of the noise at many stations of the Global Seismic Network (GSN). It is also generally accepted that most of this excessive horizontal noise is caused by tilts generated by atmospheric pressure changes and wind (e.g. Webb 2002; Wielandt 2002). Tilts were also invoked as the responsible mechanism by Tsai et al. (2004) who studied the propagation of atmospheric morning glory waves in the Los Angeles basin with speeds between 5 and 25 ms\(^{-1}\), frequencies near 1 mHz, and amplitudes between 0.8 and 1.3 hPa by using records from barometers and seismometers. These authors note also that the amplitudes on the horizontal seismometers were clearly larger.

At sites near coasts loading from the ocean waves causes a temporally varying deformation field (with tilts) which is sensed by seismographs. A fine example of this sensitivity was demonstrated for the load tilts generated at coastal sites in the Indian ocean by the tsunami radiated by the N. Sumatra—Andaman Islands quake on 2004 December 26 as studied by Yuan et al. (2005). These are near-field effects (also invoked in a study of vertical seismic noise by Agnew & Berger 1978) in contrast to the well-known marine microseisms, that is, propagating surface waves excited by waves in the oceans. However, in this paper, we deal with the long-period horizontal noise at the best stations, for well-shielded sensors and far away from the coasts. We note here in passing that the atmosphere also is able to generate propagating surface waves. Manifestations of this could be the background free oscillations first reported by Nawa et al. (1998) and the surface waves observed during the paroxysmal eruptions of El Chichón in 1982 and Mount Pinatubo in 1991 (e.g. Zürn & Widmer 1996).

Barometric pressure changes in the immediate environment of the seismic instruments can lead to noise by mechanisms like buoyancy (vertical component), deformation and tilt of the instrument housing. Air convection has been identified as a major source of noise a long time ago. Another source of noise on seismographs with helical and leaf springs has recently been identified and studied by Forbriger (2007): variations of Earth’s magnetic field. We do not consider these effects here because we are interested in the noise which cannot be avoided by clever construction, shielding and installation of the sensors.

Tilt contributions to the noise in the free mode band associated with changes of barometric pressure were already studied by Große-Brauckmann (1979) in the context of borehole installations...
of Askania tiltmeters in Germany. Such contributions were effectively reduced in horizontal seismograms by Beauduin (1996), Beauduin et al. (1996) and Neumann & Zürn (1999) in order to improve signal-to-noise ratios (SNR). It is highly desirable to understand the physical phenomena producing disturbances in seismograms because such understanding could lead to technical measures or correction algorithms to reduce this noise. Of course, this is also true for noise caused by atmospheric phenomena. Especially the higher noise level in horizontal seismograms has led to a high imbalance in the scientific use of vertical versus horizontal component records at long periods. In this paper we describe simple models for atmospheric disturbances and test their efficiency in noise variance reduction. These physical models are intentionally kept simple with only one free parameter for each of them for two reasons. The first reason is the success of the similarly simple model for reduction of vertical seismic noise below 1–2 mHz as described by Zürn & Widmer (1995). The second reason is that we would like to first learn about the performance of simple models and gain insights into the physical mechanisms of tilt noise generation before more complicated models with more parameters are applied.

A horizontal accelerometer is sensitive to several physical effects associated with a certain geophysical phenomenon. The inertial effect (d’Alembert force) due to its proportionality to frequency squared clearly dominates for high frequency signals and most of body wave seismology. Varying tilts couple a varying component of the gravitational acceleration $g_0$ into the sensitive direction of the seismograph and since $g_0$ is very large compared to seismic accelerations away from the near-field of strong earthquakes, small tilt angles produce significant disturbances. Mass redistributions due to deformations produce varying horizontal gravitational forces on sensor masses. In special cases the source of a phenomenon has a direct gravitational effect on the sensor (like moon and sun in the case of the Earth tides). The relative contributions of these four effects to certain signals at different frequencies are listed in Table 1. Other effects exist but are usually negligible. The four effects are completely independent of the construction details of the sensors. An extensive and enlightening discussion of sensor sensitivities for horizontal seismographs can be found in Rodgers (1968) who investigates special construction features leading to systematic distortions of seismic signals. Most if not all of those are avoided in modern broad-band force-balance sensors (e.g. Wielandt & Streckeisen 1982; Wielandt 2002).

Pendulum tiltmeters and pendulum horizontal seismographs are in principle sensing the same effects, the distinction in the nomenclature arises mainly from the different intentions of the deployers and the frequency range where signals are expected. The idea of measuring only tilts with a tiltmeter and the combination of horizontal inertial accelerations and tilts with a horizontal accelerometer and to subsequently use the two records to isolate the inertial acceleration and to thus remove the tilt noise from seismograms (or similar schemes) is as old as the knowledge about the tilt noise. However, this idea is fallacious because tiltmeters also sense the inertial accelerations. This applies not only to pendulum tiltmeters but also to tiltmeters employing some form of liquid level (e.g. accelerate a full cup of hot coffee horizontally without tilting it and a painful experience will be the result). Examples for this are presented by Ferreira et al. (2006) using records of the free oscillations excited by the great 2004 N. Sumatra–Andaman Islands quake from a 40 m water-tube tiltmeter in Luxembourg and from a 120 m differential-pressure fluid-tiltmeter at Black Forest Observatory (BFO, see below). Comparing the data with predictions demonstrates that these tiltmeters sense predominantly the inertial accelerations associated with the toroidal modes, which on a spherically symmetric earth do not cause tilts. One may devise a scheme to remove the tilt noise in a certain frequency band by a combination of some ‘tiltmeter’ and some ‘inertial seismometer’, however, this will result in removing the signals in this band as well.

In Section 2, we will describe the experimental determination of the transfer-function between local barometric pressure variations and seismograms. We will develop two simple physical models for the atmospheric effects on seismograms in Section 3 and will compare those models with long data sets in the following section. In Section 5, the statistics for multiyear data sets are presented. Improvement of SNR is evaluated for a few examples in Section 6 and work with finite-element models (FE) is briefly outlined in Section 7. The resulting regression coefficients are discussed in Section 8 and conclusions are drawn in the final section.

### 2 EXPERIMENTAL DETERMINATION OF TRANSFER-FUNCTION

All our examples are observed at the GSN-station BFO (48.33°N, 8.33°E, 589 m amsl). The high quality of BFO is mentioned several times in the literature (e.g. Beauduin et al. 1996; Freybourger et al. 1997; Lambotte et al. 2006). This observatory is installed in an abandoned silver–cobalt ore mine excavated into the surrounding granite. The overburden above the instrument vaults is 150–170 m. All seismographs at BFO are installed behind an efficient airlock at a horizontal distance of ~400 m from the adit. This airlock acts as a low-pass filter for barometric pressure variations. Richter et al. (1995) give it’s time constant as ~4 hr, this was increased to ~36 hr since then by improving the sealing. Thus pressure variations in the long period seismic band are efficiently reduced in the galleries and vaults behind the airlock and hence in the vicinity of the sensors. The airlock also reduces temperature fluctuations to less than about 3 mK and prevents air circulation to a large extent. Small-scale convection could still exist due to the little heat created by instruments and electronics. Barometric pressure variations at BFO are sensed by a mechanical microbarograph equipped with an inductive displacement transducer. This unit has a sensitivity of 43.8 mV hPa$^{-1}$ as calibrated by comparison with a precise mercury barometer and a Paroscientific Digiquartz 740-16B. It is installed in the mine for temperature stability but in front of the airlock to measure outside pressure variations.

We attempted to estimate experimentally the transfer-functions at BFO between local air pressure (outside of the airlock) and horizontal accelerations using data from the Streckeisen STS-1/NS and
EW-seismometers (all these data are disseminated through IDA/IRIS). Two continuous time-series from each of the three instruments sampled with a rate of 0.2 Hz from February 1–28, and March 1–27, 2005 were analysed as follows. These time-series were chosen because during these 2 months nobody entered the mine through the airlock (the earthquake activity during these two periods is described in Sections 4.2 and 4.3, respectively). The seismograms were detided while earthquake signals and other disturbances were left in the records (see Figs 13 and 16). The mean values were removed from all series. Segments overlapping by 7/8 with 8192 points (~11.4 hr) were multiplied by a Hanning window and Fourier transformed. Auto and cross power spectral densities were computed and averaged over all these windows resulting in estimates of the transfer-functions and coherencies as functions of frequency. The admittances were corrected for the instrumental responses to represent the admittances between barometric pressure and horizontal accelerations and were further smoothed over 9/10 of a decade. The results for the two components and the two time windows are depicted in Figs 1–4. Inserts show the corresponding coherencies versus frequency. These have to be interpreted with caution (optimistically) because the arrivals of earthquake signals and occasional disturbances of instrumental origin will always cause a drop in the coherency with pressure. There appears to be a plateau in the admittances up to about 1 and 0.6 mHz for the NS- and EW-components, respectively. Above these frequencies the admittances drop into a wide trough with the minima being about half the value of the plateaus and then they rise steeply near about 8 mHz. However, this rise is probably not significant since the coherency is very low. The plateau for the NS-component is near 30, for EW near 15 nm s$^{-2}$ hPa$^{-1}$.

In order to possibly improve the significance of the admittance estimates we selected an interval from the first of the above time-series which had only minor seismic activity and strong barometric pressure variations, from 2005 February 10 to 13 and performed an identical analysis. The results are shown in Figs 5 and 6. The coherencies are much higher now. The plateaus are at similar values as before but extend to higher frequencies, the troughs are shallower (NS) or almost non-existent (EW), and the rises above 8 mHz are much less pronounced.

Lambotte et al. (2006) also estimated admittances between local barometric pressure and horizontal accelerations as observed with the STS-1 seismometers at BFO (Figs 11 and 12 of their paper) without specifying the time period used. They filtered the data between periods of 7 d (~1.6 μHz) and 3 hr (~9.3 μHz) before...
Horizontal seismic noise from barometric pressure

3 TWO SIMPLE MODELS OF ATMOSPHERIC EFFECTS ON HORIZONTAL SENSORS

In the following two simple physical models are described which could be responsible for producing seismic signals as a result of changes in barometric pressure. Both models were already introduced by Neumann (1997), Neumann & Zürn (1999) and Zürn & Neumann (2002). Zürn et al. (1999) utilized these concepts to reduce noise in the free mode records from BFO of the 1998 Balleny Islands earthquake (Mw 8.2). Preliminary tests on longer time-series were described briefly by Exß & Zürn (2002).

The first model is based on observations and modelling of tilts and strains caused by Earth tides: the local deformation model (LDM). The second model was developed because wave-like variations in atmospheric pressure have clear counterparts in horizontal (and vertical) seismic records (e.g. Müller & Zürn 1983; Tsai et al. 2004; Kroner et al. 2005; Zürn & Wielandt 2007): the travelling wave model (TWM). Since the propagation velocity of atmospheric waves is most often less than the speed of sound $c \approx 330 \text{ ms}^{-1}$, that is, small compared to seismic velocities in rocks which are of the order of several km s$^{-1}$, we treat the deformation in the crust quasi-statically in both models.

If we are able to formulate the change in a force on the sensor mass in terms of a change in local barometric pressure we can formally produce ‘pressure seismograms’, which in turn can be compared to recorded seismic traces. In the frequency domain we write

$$s(\omega) = H_a(\omega) \left[ \frac{\delta a}{\delta p}(\omega) \right] \Delta p(\omega),$$

where $H_a$ is the transfer-function of the seismometer with respect to ground acceleration and $\omega$ is the angular frequency. $\delta a/\delta p$ is the proportionality factor or admittance of the physical effect producing an acceleration of the sensor mass due to the pressure change, and $s$ and $\Delta p$ are the Fourier transforms of the seismogram and the pressure variations, respectively.

3.1 Local deformation model (LDM)

Observations of tidal strains and tilts often show significant local variations in amplitude and phase (e.g. Baker & Lennon 1973). This very disturbing result became understood in the 1970s in terms of local modifications of the tidal deformation field due to lateral heterogeneities (cavities, topography, geology; see Harrison 1985, for a summary). King et al. (1976) suggested that these local modifications will occur for seismic displacement fields as well. Beauduin et al. (1996) found different reactions of STS-1 horizontal seismometers to barometric pressure variations on two different piers within the same station. This is a clear manifestation of ‘cavity’ effects, the deformation field including tilts produced by the barometric pressure load and thus the seismometer’s reactions are locally highly variable in space. Neumann & Zürn (1999) invoked such effects in order to explain barometric signals on horizontal seismograph and strainmeter records in addition to direct effects from an acoustic-gravity wave (AGW) model as described in the next subsection. Kroner et al. (2005) and Steffen et al. (2005) used this (LDM) concept in FE models of the cavities, topography and geology at stations BFO and Moxa, Germany, to explain the effects of observed transients in barometric pressure on horizontal seismometers and strainmeters.

For the LDM we assume a horizontally homogeneous atmosphere having only arbitrary density profile with height which is a function of time. The corresponding surface pressure $p$ then represents a varying load on the surface and varying deformation of the crust will result. If we assume also the rocks to behave in an elastic linear fashion, then displacements, tilts, strains, etc. will be proportional to the pressure variation, no matter how complicated the geology, topography and cavity geometry may be at the site under consideration. If anelasticity is negligible the variations are either perfectly in phase or $180^\circ$ out of phase with the pressure variations. Since here we are concerned with accelerations, $a$, we write

$$\Delta a(x, y, z, t) = C(x, y, z) \Delta p(t),$$

where $C$ is a real constant depending on exact location and on component but not on time. Similar equations can be written for displacements, strains, tilts or rotations. In particular, if two orthogonal horizontal components are affected, the direction of the apparent...
acceleration is constant as well completely independent of the direction of travel of the (very slowly) moving air masses. Indeed, Beauduin (pers. comm. 1996) found a very stable direction of polarization for the pressure correlated horizontal signals discussed by Beauduin et al. (1996).

3.2 Travelling wave model (TWM)

According to Hines (1972) AGW are ubiquitous in the atmosphere. Sorrells (1971) calculated the effect of atmospheric pressure waves on seismograms, but since he was concerned with higher frequencies he considered the inertial effect only. Neumann (1997) and Neumann & Zürn (1999) were the first to our knowledge to use the model of AGW to study observed pressure effects in long period seismograms and strainigrams. They were able to model two observed signals with the inertial, gravitational and tilt effects computed from the simultaneous barometric pressure record. Mass redistribution was neglected (for a discussion of this effect in terms of the vertical component see Zürn & Wielandt 2007). Neumann & Zürn (1999) found that in these examples significant contributions corresponding to the LDM had to be added to the ones from TWM in order to get close to the observations in magnitude and phase. In contrast, the simultaneous strain records could be very well modelled using LDM only, that is, strain signals were nearly in phase with the barometric pressure variations.

Our TWM consists of an atmosphere overlying a homogeneous elastic half-space. The surface of the half-space is the x,y-plane with the z-axis pointing upward. The Lamé parameters of the half-space are \( \lambda \) and \( \mu \), but in all applications we let \( \lambda = \mu \). The scale height of the atmosphere is \( H = c^2/\gamma g_0 \), where \( c \) is the sound velocity, \( g_0 \) the surface gravity and \( \gamma = c_p/c_v \), the ratio of specific heats at constant pressure and volume, respectively. It can be shown (e.g. Gossard & Hooke 1975; Neumann 1997; Nappo 2002; Nishida et al. 2005) that the atmosphere supports AGW. If such a wave travels along the surface and its amplitude decays exponentially with height \( z \) it is called a Lamb wave and its density distribution can be described by

\[
\rho(x, y, z, t) = \hat{\rho} \exp\left(-\frac{z}{H \gamma}\right) \exp[i(\hat{k}_h x - \omega t)].
\]

where \( \hat{\rho} \) is the peak density at the bottom of this model atmosphere, \( \hat{k}_h \) the horizontal wavenumber, \( \hat{i} = \sqrt{-1} \), and \( \omega \) the angular frequency. The resulting pressure at the surface has the same distribution over the surface and in time with

\[
\hat{p}(x, y, 0, t) = c^2 \hat{\rho}.
\]

The horizontal phase velocity is \( c_h = \omega/k_h \), in the case of Lamb waves close to the speed of sound \( c \) (Gossard & Hooke 1975). A Lamb wave is well described by these equations. For a general AGW only the loading effects but not gravitational attraction are described well since it travels at an angle to the surface and the density distribution is more complicated. The AGW obey the dispersion relation

\[
k_h^2 = \frac{\omega^2 - \omega_0^2}{c_h^2} + \left(\frac{\omega_0^2}{\omega^2} - 1\right) k_0^2,
\]

with \( \omega_0 = c/2H \) being the acoustic cut-off frequency and \( \omega_0 = \sqrt{g/H} - g_0/c^2 \) the Brunt-Väisälä frequency of the atmosphere (e.g. Nappo 2002; Jones 2005). \( k_z \) is the vertical wavenumber component.

The horizontal phase velocities of AGWs range mostly between 5 and 330 ms\(^{-1}\) (higher horizontal phase velocities are possible, when a high total phase velocity AGW travels under a steep angle with the surface) and are thus much slower than seismic waves with speeds of a few km s\(^{-1}\). Therefore, inertial terms in the elastic equations for the solid half-space are not included, that is, the moving pressure wave does not act as a source of seismic waves but deforms the half-space quasi-statically. This is clearly an approximation in our model. The sensors are located at \( x_a, y_a = 0 \) and \( z_a = 0 \). The right-hand sides of the eqs (7)–(12) have to be multiplied by the factor

\[
\exp(i(\hat{k}_h x_a - \omega t)).
\]

With \( G \) denoting Newton’s gravitational constant the result for the horizontal component of the Newtonian attraction of the sensor mass by the air is (Neumann 1997)

\[
\Delta a_h^N(x_a, 0, 0) = i 2\pi \frac{G}{g_0} \frac{1}{1 + \frac{\omega^2}{c_h^2}}
\]

The displacements are calculated following Sorrells (1971) for the quasi-static case and the following terms are derived. The apparent horizontal acceleration due to tilt is

\[
\Delta a_h^T(x_a, 0, 0) = i \frac{g_0 \lambda + 2\mu}{2\mu} \hat{p}
\]

and the inertial effect from the horizontal acceleration is

\[
\Delta a_h^I(x_a, 0, 0) = i \frac{\mu}{2\mu \lambda + \mu} \omega c_h \hat{p}.
\]

The tilt is independent of frequency but phase shifted by 90° with respect to air pressure. This signal, therefore, corresponds to the Hilbert transform of the air pressure. Möckli (1988) studied horizontal noise at a temporary station at Zürich, Switzerland and found a remarkable similarity of the air pressure induced signals to the Hilbert transform of pressure. The corresponding expressions for the vertical accelerations for the TWM can be found in Zürn & Wielandt (2007). The terms \( a_h^{N}, a_h^{T} \) and \( a_h^{I} \) from eqs (7) to (9) are in phase as can be simply understood using one of the ‘Gedankenexperimente’ in Zürn & Wielandt (2007), which we repeat here. Consider a vertical plane through the atmosphere above a horizontal seismometer sensing accelerations perpendicular to it. Now let the atmosphere to the right-hand side of the plane change its density sinusoidally with time. The Newtonian attraction of the sensor mass will be maximum to the right-hand side when the density has its maximum. The downward deflection of the surface due to pressure loading will be maximum at the same instant, thus the tilt will be to the right-hand side as well and the induced component of the earth’s gravitational acceleration will also pull the sensor mass to the right-hand side. The horizontal ground displacement at the same instant will be maximum to the right-hand side, the corresponding ground acceleration will be to the left-hand side and the d’Alembert force on the sensor mass to the right-hand side. Hence all three contributions are in phase.

To facilitate the comparison with the LDM we also give the strains

\[
\Delta \epsilon_{xx}(x_a, 0, 0) = -\frac{1}{2\mu} \left( \frac{\mu}{\lambda + \mu} \right) \hat{p},
\]

\[
\Delta \epsilon_{zz}(x_a, 0, 0) = -\frac{1}{2\mu} \left( \frac{\mu}{\lambda + \mu} \right) \hat{p},
\]

and

\[
\Delta \epsilon_{xz}(x_a, 0, z_a) = \frac{1}{\mu} k_h z_a \hat{p}.
\]
which vanishes for $z_p = 0$ as it should at the surface to satisfy the boundary condition. The strains are in phase with the pressure variations (and thus with the LDM accelerations) and 90° out of phase with the horizontal accelerations. According to Farrell (1972) for any pressure distribution $p(x, y)$ over an elastic half-space the areal strain is $\Delta e_{\text{areal}} = -1/2 \, p/(\lambda + \mu)$, where $p$ is the pressure. This relation also holds in the case here ($\epsilon_{y} = 0$).

The total admittance for a horizontal sensor for TWM is thus

$$\left( \frac{\Delta a_{h}}{\Delta p} \right) = i \left( \frac{2\pi G}{g_0} + \frac{g_0}{1 + \frac{\omega^2}{c_h^2}} + \frac{g_0}{2\mu} \frac{\lambda + 2\mu}{\lambda + \mu} \right) + i \left( \frac{1}{2\mu} \frac{\mu}{\lambda + \mu} \omega c_h \right),$$

(13)

The terms are the gravitational attraction, the tilt and the inertial effects on the sensor mass. We can relate these terms to each other

$$\frac{\text{tilt}}{\text{inertial}} = \frac{g_0(\lambda + 2\mu)}{\mu \omega c_h},$$

(14)

and

$$\frac{\text{tilt}}{\text{gravitation}} = \frac{\lambda + 2\mu}{2\mu(\lambda + \mu)} \frac{g_0^2}{2\pi G} \frac{1 + \frac{\omega^2 c_h^2}{c_h^2 g_0^2}}{1},$$

(15)

Fig. 7 shows the magnitudes of the transfer-function as functions of frequency for two different parameters $\mu = \lambda$ and three values of $c_h$. Fig. 8 depicts the ratios of the tilt effects to the gravitational and inertial effects, respectively, as functions of frequency for two extreme horizontal phase velocities. Since tilt dominates over most of the frequency range we later use only the tilt contribution (TWT) for the AGW pressure seismograms.

It is clear that all forces from the TWM are perpendicular to the wave crests. Therefore, for a certain accelerometer the right-hand side of eq. (13) has to be multiplied by the cosine of the angle between its sensitive direction and the direction of propagation of the plane AGW, that is, by numbers between $-1$ and $+1$. Unless predominant directions of propagation of atmospheric waves exist at a certain station, for extended time-series a stable experimental admittance cannot be expected simply for this reason.

4 Tests of the Models

With a method for reduction of horizontal noise in mind similar to the one efficiently used for long period vertical noise (e.g. Zürn & Widmer 1995) we performed experiments with seismograms from the horizontal STS-1 seismometers at BFO. Following eq. (1) we computed ‘pressure seismograms’ using the simultaneously recorded local barometric pressure variations for the LDM and for the tilt (TWT) part of the TWM. For the TWM tilt is the dominant contribution (see Fig. 8) and also does not involve the horizontal phase velocity $c_h$ which in reality is probably highly variable in time and cannot be determined without an array. In addition, preliminary tests with the data used in Section 4.1 showed that the other two terms in eq. (13) do not contribute significantly to the variance reductions. Of course, the direction of atmospheric wave propagation is also highly variable. In the pressure seismograms we did not specify the constants in eqs (2) and (8), the coefficients found for the various analyses are discussed collectively in terms of these constants in Section 8 below. Thus the horizontal accelerations representing LDM and TWT were proportional to the pressure variations and their Hilbert transform, respectively. The consequence is that the two model seismograms are orthogonal and the resulting model admittances, therefore, will not depend on whether both models are fit simultaneously or individually.

Three different time-series were selected during which the airlock was not opened. The raw seismograms for NS- and EW-components sampled at 5 s intervals were first decimated after appropriate low-pass filtering to a sampling interval of 20 s and then detided. Since we intended to concentrate on the long period part of the seismic spectrum we subsequently low-pass filtered the seismograms with a cut-off frequency of 10 mHz. The mean was removed from the barometric pressure series, which was then decimated to 20 s sampling, low-passed with cut-off of 10 mHz using the identical filters as for the seismograms and Fourier transformed. The spectrum was multiplied by the complex transfer-function of the STS-1 with respect to acceleration according to eq. (1). This results directly in the spectrum of the pressure seismogram for the LDM and multiplication by $i = \sqrt{-1}$ gives the one for the TWT, except for the constant real factors. Inverse Fourier transform of the spectra provides the corresponding ‘seismograms’. Then one full day of data at either end of the time-series was removed to avoid edge effects completely.
For different time windows within the different time-series least-squares fits of the two ‘pressure seismograms’ (together with a constant accounting for offsets) to the horizontal real seismograms were performed. This results in constant coefficients for each component and model: $c_{LDM}^{NS}$, $c_{LDM}^{EW}$, $c_{TWT}^{NS}$ and $c_{TWT}^{EW}$ which adopt positive values when tilts are to the N and E with increasing pressure. We also obtain residual seismograms $r_{NS}$ and $r_{EW}$ and variance ($\sigma^2$) reductions $R^{NS}$ and $R^{EW}$ were computed

$$R = \frac{\sigma^2(s) - \sigma^2(r)}{\sigma^2(s)} \times 100 \text{ per cent,}$$  
where $s$ represents the low-passed seismograms and $r$ the corresponding residual. It is important to realize that earthquake signals and rare instrumental glitches were not removed from the seismograms. However, in the second and third case those were clipped at the top and bottom before the least-squares fits in order to reduce the disadvantageous effects of large seismic amplitudes on the results. It has to be kept in mind though that the variance reduction can never reach 100 per cent because of seismic arrivals, instrumental noise, and ultimately the incessant free oscillations of the Earth first observed by Nawa et al. (1998) and probably excited by the atmosphere and/or oceans (e.g. Kurrle & Widmer-Schnidrig 2006). The latter have not been identified in horizontal seismograms yet but must be present there with acceleration amplitudes of the order of a few pm s$^{-2}$, since this is their amplitude in vertical records.

The magnetic field induced noise discussed by Forbriger (2007) is shown by that author to be not detectable in the horizontal STS-1 seismometers at BFO. However, the horizontal components of the STS-2 at BFO (Section 5) clearly show this effect, not surprisingly because of the leaf spring suspensions in that triaxial instrument (see discussion in Forbriger 2007).

This imperfection of the models will also lead to biased estimates of the coefficients (e.g. Draper & Smith 1966, chapter 2.12). Another kind of bias probably affects our coefficients: we realize that we fit very noisy functions of time—the pressure seismograms—to very noisy functions of time—the seismograms (e.g. Olsen 1998, section 2.3).

### 4.1 July 2–9, 2000

This time-series was chosen because it was very recent when this work was started and it did not contain very large earthquakes. According to the Harvard Catalogue of moment tensors the 6 (30) largest events had moment magnitudes between 5.5 (5.0) and 5.9. Therefore, the seismograms were not clipped before the least-squares analysis. The original length was 10 full days starting at 0:00 hr UTC on 2000 July 1. Later on, the first and last day were eliminated, as mentioned above. Fig. 9 shows the two seismograms, the two model seismograms, and the barometric pressure. The model seismogram for the LDM is practically a bandpassed version of the barometric pressure itself. Inspection of these records shows that the large disturbances in barometric pressure have their (modified) counterparts in the pressure seismograms, of course, but also impressively in the real seismic records. In addition, the seismic records show a little earthquake activity and especially the NS-component suffers from several one-sided instrumental glitches near the beginning.

These data were then subjected to the least-squares fit of the two models to each component in the time domain. First the total time-series of 192 hr was used. The resulting variance reduction is shown in Fig. 10 and the coefficients are listed in Table 2, case A1. Then windows of lengths between 2 and 144 hr were used and shifted through the whole time-series. For window lengths shorter than 24 hr the time shift was 1 hr; longer windows were shifted by 1 d. The maximum variance reductions obtained for each case are depicted in Fig. 10. Fig. 11 shows the variation with time of the variance reductions and the coefficients for a window length of 8 hr. Variance reductions vary between 0 and 95 per cent, hence the method of noise reduction is often highly efficient in this time-series. Comparison of the seismogram and the variance reductions as functions of time in Fig. 11 suggests the conclusion that the higher the noise the higher the variance reduction obtained. The averages of the coefficients for all windows and for the windows with variance reductions $\geq 40$ per cent (81 and 93 out of 182 for NS and EW) are listed in Table 2, cases A2 and A3. These numbers will be discussed in Section 8. The NS-component responds more strongly to the LDM than to TWT, while the opposite is true for the EW-component. The larger coefficients in both cases ($c_{LDM}^{NS}$ and $c_{LDM}^{EW}$) remain almost negative, while the smaller two ($c_{TWT}^{NS}$ and $c_{TWT}^{EW}$) oscillate more or less around zero. All coefficients appear to be correlated or anticorrelated to the variance reductions. There is a clear tendency for the coefficients to adopt larger magnitudes when the variance reduction is high. This effect (the possible bias mentioned above) is with high probability caused by the...
imperfection of the model, that is (apparent) pressure variations which do not have counterparts in the seismograms, and the noise in the time-series.

Fig. 12 shows the result of the modelling for a section of the seismograms of the three periods 2000 July 2–9 (A), 2005 February 2–27 (B), and 2005 March 2–26 (C) resulted in the first three groups. The magnitudes of the average coefficients in all three cases are always larger when the windows with low variance reductions are excluded. Cases D1 and D2 show coefficients found by minimizing spectral noise between low degree free modes for large earthquakes (see text) and D3, D4 and D5 are the values found for a cold front and other pressure disturbances. Cases E refer to the results of the long-term performance study in Section 5 with the numbers indicating the different seismometers (STS-0, STS-1, and STS-2) now. All coefficients in one column should be identical, except for LDM in cases E0 and E2. The results from finite element models of BFO are given as cases F (see text). Positive (negative) values represent tilts to the N (S) and E (W) for increasing barometric pressure. Units for all coefficients are $10^{-6}$ m s$^{-2}$ hPa$^{-1}$.

<table>
<thead>
<tr>
<th>Case</th>
<th>NS $c_{LDM}$</th>
<th>NS $c_{TWT}$</th>
<th>EW $c_{LDM}$</th>
<th>EW $c_{TWT}$</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>-2.60</td>
<td>-0.39</td>
<td>+0.85</td>
<td>-1.59</td>
<td>Total time-series</td>
</tr>
<tr>
<td>A2</td>
<td>-2.04</td>
<td>+0.13</td>
<td>+0.48</td>
<td>-1.23</td>
<td>Average: all windows</td>
</tr>
<tr>
<td>A3</td>
<td>-2.77</td>
<td>-0.34</td>
<td>+0.87</td>
<td>-1.61</td>
<td>Average: windows with $R \geq 40$ per cent</td>
</tr>
<tr>
<td>A4</td>
<td>-3.21</td>
<td>-0.48</td>
<td>1.02</td>
<td>-1.92</td>
<td>Special 4-d window (Nr. 122)</td>
</tr>
<tr>
<td>B1</td>
<td>-1.51</td>
<td>+0.77</td>
<td>-0.37</td>
<td>-0.39</td>
<td>Total time-series</td>
</tr>
<tr>
<td>B2</td>
<td>-1.82</td>
<td>+0.42</td>
<td>+0.70</td>
<td>-0.00</td>
<td>Average: all windows</td>
</tr>
<tr>
<td>B3</td>
<td>-2.38</td>
<td>+1.37</td>
<td>+1.52</td>
<td>+0.25</td>
<td>Average: windows with $R \geq 40$ per cent</td>
</tr>
<tr>
<td>B4</td>
<td>-1.42</td>
<td>+1.02</td>
<td>+0.20</td>
<td>-0.61</td>
<td>Special 4-d window</td>
</tr>
<tr>
<td>C1</td>
<td>-1.38</td>
<td>+0.66</td>
<td>+0.42</td>
<td>-0.38</td>
<td>Total time-series</td>
</tr>
<tr>
<td>C2</td>
<td>-1.80</td>
<td>+0.51</td>
<td>+0.68</td>
<td>-0.34</td>
<td>Average: all windows</td>
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<tr>
<td>C3</td>
<td>-2.93</td>
<td>+0.53</td>
<td>+1.26</td>
<td>-0.74</td>
<td>Average: windows with $R \geq 40$ per cent</td>
</tr>
<tr>
<td>C4</td>
<td>-1.15</td>
<td>+0.94</td>
<td>+0.20</td>
<td>-0.38</td>
<td>Special 4-d window</td>
</tr>
<tr>
<td>D1</td>
<td>-3.50</td>
<td>+0.50</td>
<td>+1.00</td>
<td>-1.35</td>
<td>Balleny Islands earthquake 1998</td>
</tr>
<tr>
<td>D2</td>
<td>-3.35</td>
<td>+0.60</td>
<td>+0.80</td>
<td>-1.00</td>
<td>N. Sumatra–Andaman Islands earthquake 2004</td>
</tr>
<tr>
<td>D3</td>
<td>-2.62</td>
<td>+0.25</td>
<td>+0.40</td>
<td>-1.62</td>
<td>Cold front May 18, 2006</td>
</tr>
<tr>
<td>D4</td>
<td>-2.70</td>
<td>-1.91</td>
<td>+1.50</td>
<td>+0.04</td>
<td>Pressure waves January 27, 2006</td>
</tr>
<tr>
<td>D5</td>
<td>-3.08</td>
<td>1.03</td>
<td>+0.67</td>
<td>-2.14</td>
<td>Pressure wave train October 13/14, 2002</td>
</tr>
<tr>
<td>E0</td>
<td>2.39</td>
<td>-0.08</td>
<td>+1.50</td>
<td>-0.33</td>
<td>STS-0, $\geq$3 years</td>
</tr>
<tr>
<td>E1</td>
<td>-1.89</td>
<td>0.00</td>
<td>+0.74</td>
<td>-0.70</td>
<td>STS-1, 12 yr</td>
</tr>
<tr>
<td>E2</td>
<td>-1.40</td>
<td>+0.45</td>
<td>+0.21</td>
<td>-0.65</td>
<td>STS-2, 3 yr</td>
</tr>
<tr>
<td>F1</td>
<td>-0.297</td>
<td>0.121</td>
<td>0.121</td>
<td>STS-1 pier, raw model, no airlock</td>
<td></td>
</tr>
<tr>
<td>F2</td>
<td>-0.211</td>
<td>0.108</td>
<td>0.108</td>
<td>STS-1 pier, refined model, no airlock</td>
<td></td>
</tr>
<tr>
<td>F2B</td>
<td>-1.320</td>
<td>0.262</td>
<td>0.262</td>
<td>STS-0 pier, refined model, airlock</td>
<td></td>
</tr>
<tr>
<td>F3</td>
<td>1.113</td>
<td>-0.629</td>
<td>0.671</td>
<td>STS-0 pier, refined model, airlock</td>
<td></td>
</tr>
<tr>
<td>F3B</td>
<td>2.240</td>
<td>0.671</td>
<td>0.671</td>
<td>STS-0 pier, refined model, airlock</td>
<td></td>
</tr>
</tbody>
</table>

4.2 February 2–27, 2005

The second (much longer) time interval was already used in Section 2 (see Figs 1 and 2) to determine experimentally the transfer-

functions. Fig. 13 shows seismograms, pressure seismograms, and pressure for this period. The Harvard catalog lists 1 event with moment magnitude 7.1 (February 5), 5 between 6.5 and 6.9, 10 between 6.0 and 6.4 and 26 between 5.5 and 5.9 in this time period. Hence seismic activity was much stronger (number and magnitudes) in this time-series than in the previous one. Therefore, the seismograms were clipped at $\pm 5$ mV in this case. Otherwise the analysis was carried out as before. The efficiency of our procedure was not as good as in the previous case. In part this is certainly due to the larger seismic activity in this time window. When the total time-series was used for the fit the variance reductions were only 18.2 (NS) and 4.7 per cent (EW). The resulting coefficients are given in Table 2, case B1. In a second analysis we used windows 8 hr long for the fit and shifted those by 1 hr. Fig. 14 depicts the variance reductions and coefficients obtained for the series of windows. Variance reductions exceeding 40 per cent were obtained for only 31 (NS) and 21 (EW) of the 616 windows. The averages of the coefficients for all windows (case B2) and for the windows with variance reductions larger than 40 per cent (case B3) are also given in Table 2. The coefficients will be discussed in Section 8.
Figure 11. Variance reductions and model coefficients (in nm s\(^{-2}\) hPa\(^{-1}\)) for the NS- and EW-seismograms and the two models for the pressure effects for the time-series from 2000 July 2 to 9 inclusively versus window number. Time windows were 8 hr long and shifted by 1 hr. The variance reductions for the EW-component are plotted negatively for reasons of clarity. The coefficients for the LDM are shown by solid lines, for the TWT by dotted lines. The top trace shows the EW-seismogram from Fig. 9 for visual comparison; the horizontal axis is given in elapsed days in July.

Fig. 12. Section of the seismograms and their residuals with strong barometric effects and with high variance reductions (see Fig. 11). Constant coefficients were used for the calculation of residuals (case A4, Table 2).

Fig. 13. Detided and low-pass filtered seismograms in Volts from the STS-1 horizontal seismometers at BFO for the indicated period of time; ‘pressure seismograms’, and barometric pressure \(P_a\) (right-hand scale). The pressure seismograms were multiplied by a factor so their amplitudes have the order of magnitude of the real seismograms.

Fig. 14. Variance reductions and model coefficients (in nm s\(^{-2}\) hPa\(^{-1}\)) for the NS- and EW-seismograms and the two models for the time-series from 2005 February 2 to 27. Windows 8 hr long and shifted by 1 hr were used. The variance reductions for the EW-component are plotted negatively for reasons of clarity. The coefficients for the LDM are solid, for the TWT dotted lines. The top trace shows the EW-seismogram from Fig. 13 for visual comparison (horizontal axis is in elapsed days (UTC) in February).

Fig. 15. Section of the seismograms and their residuals with rather large pressure variations.

4.3 March 2–26, 2005

This long time-series was already used in Section 2. Seismograms, ‘pressure seismograms’, and pressure are shown in Fig. 16. The Harvard catalog lists one event with moment magnitude 7.1 (March 2), 2 between 6.5 and 6.9, 8 between 6.0 and 6.4 and 18 between 5.5 and 5.9. Hence seismic activity was only slightly less than in the previous case and much higher than in the first case. Therefore, the seismograms were clipped at ±4 mV (NS) and ±5 mV (EW) and the same analysis as in the preceding section was carried out. When the total time-series was used for the fit the variance reductions...
obtained were 12 per cent (NS) and 4 per cent (EW) and the coefficients given in Table 2 as case C1 were found. The variance reductions and coefficients found when using windows of length 8 hr and shifted by 1 hr are shown in Fig. 17 as functions of the window series together with the clipped EW-seismogram. The efficiency of the method was even worse than in February 2005. The averages of the coefficients for all windows (case C2) and for windows with variance reductions larger than 40 per cent (case C3) out of a total of 592 are presented in Table 2.

A special 3-d window with stronger barometric pressure variations was also analysed. Variance reductions were 20 per cent (NS) and 5.4 per cent (EW) and the coefficients are presented as case C4 in Table 2. Fig. 18 depicts the seismograms and their residuals. Again the improvement is marginal and by far not as good as in Fig. 12.

Figure 17. Variance reductions and model coefficients (in \( \text{nm s}^{-2} \text{ hPa}^{-1} \)) for the NS- and EW-seismograms and the two models for the time-series from 2005 March 2 to 26. Windows 8 hr long and shifted by 1 hr were used. The variance reductions for the EW-component are plotted negatively for reasons of clarity. The coefficients for the LDM are solid, for the TWT dotted lines. The top trace shows the EW-seismogram from Fig. 16 for visual comparison (horizontal axis is in elapsed days (UTC) in March).

Figure 18. Section of the seismograms of Fig. 16 and their residuals. The coefficients are tabulated in Table 2, case C4.

5 Long-term Performance Statistics

After the successful application of the models to the seismograms from July 2000 we decided to do a long-term study in order to shed more light onto the method and its performance. Three different modern broad-band seismometer sets were or are operating at BFO and all those were installed in the seismic vault about 500 m horizontally into the hill behind the airlock and at a depth of 170 m below the surface. The walls of the nearly square vault are oriented NS and EW. The STS-1s considered so far in this paper were installed in February 1993 and are still in operation. They are sitting on a concrete pier (surface about 20 cm above the floor) directly cemented to the granite at the foot of the southern wall of the vault. Before February 1993 prototypes of the STS-1 (STS-0 in the following) were installed on a pier with the surface about 80 cm above the floor and cemented to the foot of the northern wall, this wall itself and the eastern wall. Finally, an STS-2 is operating since 1990 on a second low pier at the southern wall only a few.cms west of the one with the STS-1s. This STS-2 is a part of the German Regional Seismic Network (GRSN). The horizontal distance between the piers with the STS-1s and the STS-2 is varying by up to 40 nm with the Earth tides (Zürn et al. 1991). Since this is more than the displacement expected from the theoretical body tide strain by a factor of about 8 this is another manifestation of (apparent) strain enhancement due to cavity effects.

We decided to use a window 4 d long (a typical window for computing free mode spectra after large quakes) and shifted this through the data sets in steps of 1 d. Otherwise the analysis followed the one described and used in the previous section. The seismograms were subjected to a simultaneous least-squares fit to the LDM and TWT ‘pressure seismograms’ computed from the simultaneously recorded atmospheric pressure variations. We ignored all disturbances and earthquakes, but tides were removed. Table 3 shows the number of windows for each case for which variance reductions above a certain lower cut-off value were obtained. Figs 19–24 show the distributions of variance reductions (top panel) and coefficients in bins of \( 0.05 \times 10^{-8} \text{ m s}^{-2} \text{ hPa}^{-1} \) for the two models (lower two panels). In the histograms for the model coefficients those windows were excluded for which the variance reduction was \( \leq 5 \) per cent; the corresponding numbers can be found in Table 3.

Figs 19 and 20 show the results for the STS-1 seismometers for the years 1993–2004. Clearly, for the majority of the 3376 windows the variance reduction was less than 10 per cent. However, the...
Table 3. Number of 4-d windows with variance reductions larger than a cut-off value for the three data sets identified by the name of the instruments involved.

<table>
<thead>
<tr>
<th>Cut-off per cent</th>
<th>STS-0 NS</th>
<th>STS-1 NS</th>
<th>STS-0 EW</th>
<th>STS-1 EW</th>
<th>STS-2 NS</th>
<th>STS-2 EW</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>771</td>
<td>3376</td>
<td>643</td>
<td>643</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>479</td>
<td>1983</td>
<td>367</td>
<td>211</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>424</td>
<td>1524</td>
<td>250</td>
<td>113</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>381</td>
<td>1211</td>
<td>155</td>
<td>61</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>330</td>
<td>940</td>
<td>94</td>
<td>37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>293</td>
<td>662</td>
<td>61</td>
<td>24</td>
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<td></td>
</tr>
<tr>
<td>30</td>
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<td>58</td>
<td>34</td>
<td>4</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 19. Histograms of variance reductions (top) and model coefficients (bottom) for the data from the STS-1 seismometers at BFO for the time period from 1993 to 2004. The coefficients were only adopted for windows with variance reductions larger than 5 per cent (see numbers in Table 3). Units for coefficients are in m s$^{-2}$ hPa$^{-1}$.

Figure 20. Same as Fig. 19 for the EW-component of the STS-1.

Figure 21. Same as Fig. 19 for the NS-component of the STS-0 for the time period from 1990 to February 1993.

Figure 22. Same as Fig. 21 for the EW-component of the STS-0.

Figure 23. Same as Fig. 19 for the NS-component of the STS-2 from 2001 to 2003.
The coefficients $c_{TWT}$ phase velocity vector for travelling waves onto the sensitive direction. Since the distribution for EW is one-sided and both positive with rather broad distributions around $-1 \times 10^{-3}$ m s$^{-2}$ hPa$^{-1}$. The coefficients $c_{NS}$, $c_{LDM}$ and $c_{EW}$ both straddle zero now. The time period is simultaneous to part of the time-series for the STS-1 sensors at BFO after the earthquake at the Balleny Islands on 1998 March 25 ($M_\nu 8.2$). Time-series of lengths 36–44 hr were found to provide reasonable raw data for application of the procedure outlined above since these showed some of the lower degree modes above the noise. The resulting coefficients are listed in Table 2 (case D1). Figs 25 and 26 show the spectra computed from raw and corrected data for the NS- and EW-seismograms. In both cases the noise between the modal peaks is clearly reduced in the corrected records. For the EW-record all modes show improved SNR after the correction. For the NS-spectrum the SNR for $aT_4$ (0.766 mHz), $aT_3$ (0.929 mHz) and others is enhanced by the correction, however, in the case of $aT_3$ (0.587 mHz) it appears that the correction does not help at all. This does not depend on the length of the time-series. One possible speculative explanation could be that in the raw data the contribution to the Fourier amplitude at the

maximun $R$ obtained reached 80 per cent (NS) and 70 per cent (EW). The coefficients $c_{NS}$, $c_{LDM}$ and $c_{EW}$ are very nicely distributed around central values of about $-3 \times 10^{-4}$, $+1 \times 10^{-4}$ and $-1.3 \times 10^{-8}$ m s$^{-2}$ hPa$^{-1}$, respectively, but only the latter two distributions have tails reaching values of the opposite sign as seen from the maximum. $c_{EW}$ looks like a bimodal distribution straddling zero with the negative values being less frequent. Such behaviour is basically not unexpected for TWT since the projection of the horizontal phase velocity vector for travelling waves onto the sensitive direction may be positive or negative. Since the distribution for EW is one-sided, one could speculate that the EW-component of the horizontal phase velocity $c_s$ for TWT is most of the time positive, while for NS it fluctuates around zero. Table 2 (case E1) shows the means of the coefficients for all windows with variance reduction larger than 5 per cent.

Figs 21 and 22 show the results for the STS-0 seismometers for the years 1990 to the beginning of 1993. Since these were on a different pier, the LDM could easily produce other values and polarities. The TWT is a model common for all installations within a station; if the coefficients really are representing the assumed underlying physics they should have similar distributions for all installations and piers within one station. As seen in Table 3, the relative number of windows with high variance reduction is higher than for the STS-1s. This could be an effect of the installation but also of the different time period. All four coefficients show broader distributions with the LDM coefficients being clearly one-sided around larger mean values and the TWT-coefficients for both components clearly straddling zero. Table 2 (case E0) shows the means of the coefficients for windows with variance reductions larger than 5 per cent.

Finally, Figs 23 and 24 depict the results for the STS-2 seismometer of the GRSN for the years 2001–2003. $c_{NS}$ and $c_{TWT}$ are now one-sided and both positive with rather broad distributions around $-1 \times 10^{-3}$ m s$^{-2}$ hPa$^{-1}$. The coefficients $c_{NS}$ and $c_{LDM}$ both straddle zero now. The time period is simultaneous to part of the time-series for the STS-1s. In this case the relative number of windows with high variance reduction is smaller than in the other two cases for both components. Table 2 (case E2) lists the mean values for the windows with variance reductions larger than 5 per cent.

As stated before, the LDM model coefficients can vary largely within very short distances, while the TWT model coefficients should be the same for each component independent of the place of installation within one station. Comparing the histograms for the 12 coefficients shows that these properties are approximately obtained in this study. The histograms for the TWT model look somewhat similar to each other, with the ones for $c_{TWT}$ centred near zero and the ones for $c_{TWT}$ centred at negative values. The histograms for $c_{NS}$, $c_{LDM}$ and $c_{EW}$ show much more variation in the three cases.

6 Improvement of Signal-to-Noise Ratio in Seismograms

6.1 Free oscillation spectra

The two models LDM and TWT were used in attempts to reduce the pressure generated noise in free oscillation spectra from horizontal records in the frequency band containing the lowest degree modes. Towards this end for a given horizontal record a grid search in the space of LDM and TWT-coefficients was carried out (a least-squares fit would also be possible) and the minimum of the sum of Fourier amplitudes between the known mode frequencies was sought. Then the coefficients for the minimum were used to form the ‘corrected’ time-series (residuals).

The first two examples are the NS- and EW-seismograms from the STS-1 sensors at BFO after the earthquake at the Balleny Islands on 1998 March 25 ($M_\nu 8.2$). Time-series of lengths 36–44 hr were found to provide reasonable raw data for application of the procedure outlined above since these showed some of the lower degree modes above the noise. The resulting coefficients are listed in Table 2 (case D1). Figs 25 and 26 show the spectra computed from raw and corrected data for the NS- and EW-seismograms. In both cases the noise between the modal peaks is clearly reduced in the corrected records. For the EW-record all modes show improved SNR after the correction. For the NS-spectrum the SNR for $aT_4$ (0.766 mHz), $aT_3$ (0.929 mHz) and others is enhanced by the correction, however, in the case of $aT_3$ (0.587 mHz) it appears that the correction does not help at all. This does not depend on the length of the time-series. One possible speculative explanation could be that in the raw data the contribution to the Fourier amplitude at the

![Figure 24](image-url) Same as Fig. 23 for the EW-component of the STS-2.

![Figure 25](image-url) Spectra of time-series from the STS-1/NS seismometer at BFO starting at 3:00:00.0 hr UTC on 1998 March 25 and 40 hr long computed after multiplication with a Hanning window. Spectral peaks correspond to free oscillations excited by the Balleny Islands quake (bottom: raw data, top: data corrected using the models). Vertical lines indicate the frequencies of fundamental spheroidal modes $aS_0$ to $aS_4$ (dotted) and fundamental toroidal modes $aT_2$ to $aT_7$ (dashed). The reduction of the noise is obvious, but $aT_3$ appears to be lost due to the correction.

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peak frequency from the barometric pressure noise and from the mode itself are nearly in phase and taking the barometer effect away reduces the total amplitude and pushes the peak back into the noise. This is always a possibility with such corrections, but then the peak detection in the raw spectrum is somewhat dubious. Incidentally, a related but contrasting example occurs in vertical component data from the same quake and station as shown in Fig. 1 of Zürn et al. (2000). There the barometric pressure effect apparently pulls the frequency of the Coriolis-coupled mode $\varphi T_3$ away from its correct position in the spectrum and after the correction its location agrees with the long-known frequency.

The third example is the NS-component record of the STS-1 at BFO from the great N. Sumatra–Andaman Islands event of 2004 December 26. The coefficients were found as described above and are listed as case D2 in Table 2. Fig. 27 depicts spectra of the raw and corrected records. The noise after the correction is reduced considerably and the SNRs of the modes clearly improved. The football mode $\varphi S_2$ (0.309 mHz) shows up above the noise level in the corrected data (the record length is too short to see the splitting of this mode). The EW-record was also subjected to this procedure but only marginal improvement could be obtained.

6.2 Other examples

On 2006 May 18 a cold front was passing over BFO with an overall pressure increase of about 3.5 hPa. Clear disturbances in the broad-band seismograms were observed at this time. Fig. 28 shows the barometric pressure variations, the corresponding ‘pressure seismograms’ for the LDM- and TWT-models, the raw and residual horizontal seismograms from the STS-1 seismometers. The two ‘pressure seismograms’ were fit simultaneously to the data for the 10 hr time-series. The noise reductions obtained are impressive, not only during the cold front passage. Variance reductions of 69 per cent (NS) and 71 per cent (EW) were obtained. The corresponding coefficients are listed as case D3 in Table 2.

On 2006 January 27 several disturbances in barometric pressure including a quasi-periodic wave train after 10:00 occurred at BFO with spectral energy within the passband of the STS-1 seismometers. Fig. 29 shows the barometric pressure, the ‘pressure seismograms’ computed for the LDM and TWT models and the detided seismograms and their residuals. The two ‘pressure seismograms’ were fit simultaneously to the data for the 10 hr time-series. The noise reductions obtained were 82.5 per cent (NS) and 57.2 per cent (EW) and the coefficients found are listed as case D4 in Table 2. The reduction of noise is conspicuous, especially for the NS-component.

In the night from 2002 October 13 to 14 pressure disturbances occurred at BFO. An especially nice quasi-periodic wave train can be observed in the pressure record in Fig. 30 between 23 and 24 hr UTC with the counterparts in the ‘pressure seismograms’ and the horizontal records from the STS-1s. Seismic traces were detided and those and the pressure record were low-pass filtered with a cut-off frequency of 10 mHz. Then the model-seismograms for LDM and TWT were computed from the pressure record and fit simultaneously to the 10 hr data shown in Fig. 30. The resulting coefficients are presented as case D5 in Table 2 and the variance reductions were 82.9 per cent (NS) and 78.3 per cent (EW). The improvement of the SNR is again quite dramatic, also around the earthquake signal near
Figure 29. On 2006 January 27 several pressure disturbances occurred at BFO. A wave train can be observed between 10:00 and 10:30 UTC shortly after a cold front like rise in pressure and two other larger transients can be identified at 6:00 and 11:50 UTC. All these have their signatures in the seismograms. From top to bottom are shown: barometric pressure (right-hand scale), ‘pressure seismograms’ for TWT and LDM, detided original and residual STS-1/EW-seismograms, detided original and residual STS-1/NS-seismograms (all in Volts, left-hand scale).

Figure 30. From 2002 October 13 to 14 several wavelike pressure disturbances occurred at BFO. A nice quasi-periodic wave train can be seen in the pressure record between 23 and 24 hr with corresponding counterparts in the seismograms. From top to bottom are shown: barometric pressure (right-hand scale), ‘pressure seismograms’ for TWT and LDM, detided original and residual STS-1/EW-seismograms, detided original and residual STS-1/NS-seismograms (all in Volts, left-hand scale). The two seismic signatures at 22:00 and 22:30 appear with much improved SNR in $P_\text{NS}$ but are almost absent in $P_\text{EW}$, so these waves were polarized in the EW-direction.

22 hr UTC caused by the Samoa Islands quake with $M = 6.0$ and origin time 20:55 hr UTC. When we performed the same analysis for the extended records (October 12, 0:00 hr to October 14, 19:00) we obtained variance reductions of `only’ 54.9 per cent (NS) and 35.4 per cent (EW). When this longer record was low-pass filtered with a cut-off of 2 mHz, the corresponding numbers were 53.3 per cent (NS) and 46.0 per cent (EW). The conclusion can be drawn that shortening the time-series or narrowing the frequency range often may result in improved performance of this noise reduction method. However, this clearly will depend on the coherency of the pressure seismograms with the real ones as a function of time and of the spectral power and range of the pressure disturbances.

7 Finite Element Models

Steffen et al. (2005) subjected a FE model of the geology, topography and cavity geometry of the station BFO and its neighbourhood to different schemes of loading by the atmosphere. In particular, uniform pressure over the whole model and inside the galleries as well as wind-pressure on the flank of the hill (striking NS) were applied. The resulting coefficients for uniform pressure can be compared to $c_\text{NS}$ and $c_\text{EW}$ as estimated from the data. They modified this model in different ways in order to understand the sensitivity of the resulting pressure coefficients to different features of the model. Their model coefficients for tilts produced by uniform pressure for a position in the model corresponding to the location of the STS-1 seismometers as closely as possible are listed as case F1 in Table 2.

The FE coefficients (F1) are smaller than the observed ones by an order of magnitude for the NS-component and also largely underestimated for the EW-component. Therefore, subsequently the model was much refined by introducing details of the piers in the seismic vault and it was found that these details play a significant role. The new coefficients for the pier with the STS-1s are presented as F2 in Table 2 (Steffen et al. 2005, point P8). The NS-coefficient is about 75 per cent of that of the coarser model while the EW-coefficient is slightly smaller (90 per cent). These results are again smaller than the observed coefficients by about an order of magnitude and are, therefore, unsatisfactory. We conjectured that this large discrepancy is due to the fact that in the FE-model the pressure was also acting inside the galleries while in reality the pressure variations inside the inner part of the mine are reduced by at least a factor of 20 by the airlock in the frequency range under investigation.

Therefore, new FE-calculations were performed with no air pressure loading from inside the galleries (i.e. a perfect airlock). The resulting coefficients for the pier with the STS-1s are presented as case F2B in Table 2. For both components the discrepancy with the observed admittances becomes much smaller. The remaining differences are not understood at present but are thought to be related to structural details in the immediate vicinity of the pier not included in the FE-model.

The pier on which the STS-0 was installed was also modelled and resulted in coefficients given in Table 2 as cases F3 and F3B with and without pressure loading from inside, respectively. These can be compared to case E0 and again the agreement is very poor for the case with pressure loading from inside. For both components the magnitudes of the FE-estimates were too small by about 50 per cent and for EW even the sign was different. For the case without internal loading the agreement between data and model is significantly improved. For the NS-component the difference amounts to 6 per cent which is very good considering the experimental variabilities. For the EW-component the signs now agree but the model coefficient is only 40 per cent of the observed one.

Attempts to better understand these remaining discrepancies are under way. An interesting observation here is that according to these models the airlock at BFO increases the sensitivity of the piers to pressure loading. This can be understood as the effect of the missing pressure variations inside the galleries which to some extent would reduce the overall deformation of the rocks. However, the benefits of the airlock remain undisputed, since it acts to reduce the pressure variations in the immediate environment of the sensors by at least a factor of 20 in the long-period seismic band, stabilizes the temperature inside the mine to a few mK (Richter et al. 1995), and reduces air flow.
8 DISCUSSION OF THE MODEL COEFFICIENTS

The coefficients \( c^\text{TWT}_{\text{NS}} \), \( c^\text{TWT}_{\text{EW}} \), \( c^\text{TWM}_{\text{NS}} \), \( c^\text{TWM}_{\text{EW}} \) listed in Table 2 basically all have the same order of magnitude but scatter appreciably from experiment to experiment in the detailed values. With the exception of \( c^\text{TWM}_{\text{NS}} \), they even change polarity. However, the overall pattern of the coefficients (Table 2 and Figs 19–24) is approximately consistent with our models. For the TWM these polarity changes and variabilities can be expected because in a certain time-series the corresponding averages of the parameters \( c_i \) (direction of propagation) can change. The real atmosphere is of course much more complicated than this simple model. However, for the LDM the coefficients should be very stable, since the resulting tilts should not depend on the atmospheric phenomena. Because the seismic data contain many truly seismic ‘disturbances’ which have nothing to do with barometric pressure our estimated coefficients necessarily must be biased in each case by different amounts. Therefore, good stability in the experimental results cannot be expected even in the case of the LDM.

The constant \( C(x, y, z) \) in eq. (2) can immediately be identified with the coefficients \( c^\text{NS}_{\text{LDM}} \) and \( c^\text{EW}_{\text{LDM}} \) for the two components. Assuming the validity of the formula for pressure-induced strain from Farrell (1972) or eq. (10), \( \lambda = \mu \), and strain–tilt coupling coefficients of the order of 1 nrad/10^−9 as estimated for tides (Entner & Zürn 1985) we can derive an effective shear modulus for the crust and we obtain as a minimum 6.9 GPa. For the EW-component the coefficients are smaller by factors of 2–5 and correspondingly higher. In summary, these values are at least providing the right order of magnitude while being a little small. The differences between the components must be generated by the local heterogeneities, that is, different strain–tilt coupling coefficients.

For the TWT-coefficients we have the problem, that the direction of propagation is unknown and with high probability not constant. With all uncertainties in mind we can again determine the order of magnitude of the effective shear modulus using eq. (8) and \( \lambda = \mu \). We get for the maximum in Table 2 a minimum in \( \mu \) of 49 GPa, much more reasonable than the value for LDM.

9 DISCUSSION AND CONCLUSIONS

The comparisons of our two simple physical models to the data from the broad-band seismometers at BFO obviously resulted in vastly different results as far as variance reductions are concerned. This variability is not at all expected for the LDM-model, while for TWM due to temporal variations in the phase velocity and direction of travel it is an inherent property of the model. Our fits suffer to a presently unknown extent from the fact that the model functions are imperfect and noisy. This could possibly cause some of the variability. Another source of variability arises from the fact that the seismic data obviously contain seismic signals and unfortunately also instrumental disturbances unrelated to barometric pressure. While this will definitely always bias low the obtained variance reductions it will also cause variations in the pressure admittances as soon as these additional signals are not perfectly orthogonal to the barometric pressure. However, the order of magnitude of all the coefficients and the general behaviour of each individual coefficient are at least approximately corroborating the physics of the models. Even in the successful cases there appear to be barometrically caused effects left in the residuals, therefore, improvements are probably possible.

Clearly both of our models are not able to accommodate neither frequency dependence (outside of bandpass filtering the time-series) nor time dependence (outside of selection of specific time windows). Since the optimal coefficients for reduction of noise show this high variability one extension of the method could be to determine the coefficients in a data-adaptive way but with some smoothing criterion included and provisions made how to handle seismic waves larger than the noise level. Special frequency dependencies could be prescribed in order to get even more efficient models, however investigating such models will be a subject of further research.

Beauduin et al. (1996) were quite successful using a spectral domain approach for their noise reduction technique. They determined a complex transfer function by finding Fourier coefficients at many frequencies which maximized the coherency between seismic noise and the local barometric pressure, similar to the transfer functions determined in Section 2 of our paper. Their model for correction has many more coefficients than the ones used here. They give their transfer functions in units of m s\(^{-1}\) hPa\(^{-1}\) instead of m s\(^{-1}\) hPa\(^{-1}\) so in order to compare their absolute values with our coefficients we have to multiply theirs with \( \omega \). Their maximum coefficients are factors of between 2 and 10 larger than the largest coefficient in Table 2. This means that they observed larger disturbances than we did for some physical reason, that is, their horizontal components are much more sensitive to barometric pressure than ours at BFO. In passing we note that their maximum values for the vertical component are a little smaller (e.g. at 0.5 mHz) than the values obtained for the well-sealed superconducting gravimeters (between 2.7 and 4.0 nm s\(^{-1}\) hPa\(^{-1}\)) and the LaCoste-Romberg gravimeter at BFO (3.5 nm s\(^{-1}\) hPa\(^{-1}\), Zürn & Widmer 1995). This could be due to either a larger effect due to atmospheric loading at their station SSB with respect to BFO or some instrumental effect opposing the effect due to gravitational attraction.

Considering Beauduin’s (1996) experience with different installations at one site and realizing that our STS-1/NS-seismometer has a rather large sensitivity to barometric pressure one is led to the idea that within one observatory one could attempt to find the position with the lowest coefficients experimentally by doing a study like the one here for sensors at different places. However, in both cases the corrections worked very well when the effects were large. So it is quite uncertain, if an improvement is possible and, therefore, the STS-1/NS seismometer at BFO will not be moved since in general the data quality is among the very best in the world.

Another, often suggested improvement could possibly be obtained by the deployment of a microbarograph array or network around the station in order to get the gradient of the pressure as a function of time and the phase velocity and travel direction of the atmospheric waves or masses (Egger et al. 1993; Tsai et al. 2004; Nishida et al. 2005; Ricciardi et al. 2007). However, the mean distance between barometers in such a network probably should not exceed a few kilometres in order to be helpful in the frequency range considered here.

Despite all these shortcomings we think that our extremely simple models are very successful considering the positive results in the work described. The method can be applied at any station which records local barometric pressure in addition to broad-band seismographs. It is especially promising at times and places where and where barometric disturbances are especially strong. The order of magnitude of our coefficients is not at variance with the physical parameters of the crustal properties of the Earth.
The results of the finite element calculations for BFO are in general underestimating the coefficients. An interesting observation was made with these models: the airlock at BFO possibly increases the sensitivity to outside pressure loading for the horizontal components. This can clearly be seen when comparing the coefficients for cases F2 and F2B, and F3 and F3B in Table 2. However, even if this should be the case the benefits of the airlock overwhelm this effect. The larger effects in the NS-components are clearly reproduced in the FE-model. The remaining discrepancies are not understood at present. One possible conclusion could be that all details in geometry/geology in the vicinity of the seismic vault which are not modelled act to increase the displacements due to barometric pressure loading.

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