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On noise reduction in vertical seismic records below 2 mHz using local barometric pressure

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Abstract.
We propose a simple method for the reduction of noise in vertical seismic recordings at frequencies below 2 mHz. The method consists in subtracting the locally recorded, scaled, atmospheric pressure signal from the gravity record. The scale factor is frequency independent and can be linearly estimated from the data. While such a pressure correction was previously only used in the analysis of tidal records, it is equally efficient at the low-frequency end of the normal mode band and we use gravity recordings of the big 1994 Shikotan and Bolivian quakes to demonstrate this point. Our examples also show that this correction permits to achieve noise levels well below the New Low Noise Model (NLNM) [*Peterson*, 1993]. The success of the correction also sheds some light on the physical processes responsible for the generation of low-frequency seismic noise at quiet observatories.

Introduction

The frequency band below 2 mHz contains the eigenfrequencies of many free oscillations of the Earth. The very gravest modes below 0.8 mHz can very rarely be observed with good signal-to-noise ratio (SNR), because even the very strongest quakes excite them only at the most quiet station-instrument combinations to observable amplitudes. Several of the lowest order spheroidal modes, ${}_1S_1$ and ${}_2S_1$ for example have never been observed. A reduction of the noise in this frequency range, whatever its physical reasons are, would certainly help to improve our knowledge of the Earth's large-scale mechanical structure.

It is well known, that meteorological phenomena cause noise at long periods in all three components of seismic records through a set of physical influences of the invariably moving air masses like (1) Newtonian attraction of the sensor mass, (2) deformation of the Earth's crust (involving free air potential change and inertial effects associated with it) (3) buoyancy of the sensor mass and (4) deformations of the instrument casing due to the very local atmospheric pressure changes, among others. It is also well known, that horizontal components show five to ten times larger levels of meteorologically caused noise than vertical components [e.g. *Peterson*, 1993]. In a study of vertical seismic transients in the free mode band caused by the passage of cold fronts in the atmosphere above a sensor, *Müller and Zürn* (1983) demonstrated that Newtonian attraction alone explains these signals very well in magnitude, while the detailed waveforms in many cases could not readily be modeled using only local measurements of barometric pressure and air temperature.

In modern investigations of earth tide gravity variations at much longer periods it has become a standard method to fit local atmospheric pressure records simultaneously with a theoretical tidal model to the observed data in order to reduce the variance of the post-fit residuals by an appreciable percentage and to obtain better estimates of the gravimetric factors and phases for the tides [e.g. *Warburton and Goodkind*, 1977; *Merriam*, 1994;]. Therefore modern earth tide analysis programs include this option [e.g. *Wenzel*, 1994]. For long periods the effect of atmospheric pressure variations has also been studied theoretically due to its clearly observable contributions to the noise in gravity and deformation observations [e.g. *Slichter et al.*, 1979; *Spratt*, 1982; *Rabbel and Zschau*, 1985; *VanDam and Wahr*, 1987; *Niebauer*, 1988]. Experimentally it turns out that large variance reductions (of the order of at least 50 %) can be obtained by simply subtracting the simultaneously recorded barometric pressure multiplied by a linearly estimated factor from the tidal gravity record. These factors are around -3.5 nms^{-2}/hPa, but vary from record to record [e.g. *Richter et al.*, 1995] and station to station by around ±20%, unless severe instrumental problems modify it significantly. Several modifications of this simple method were recently attempted, but the additional gains achieved in variance reduction in comparison with the simplistic method were marginal [e.g. *Merriam*, 1994, *Crossley et al.*, 1995]. Theoretically it is understood, that the major contribution to this effect is the Newtonian attraction of the sensor mass by the changing density of the atmosphere above the instrument while the contribution from deformation of the crust through atmospheric loading is smaller. In searches for the elusive core modes in gravity records this method is also applied routinely, since it is hopeless to detect signals at and below the *ngal*

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($1 ngal = 10^{-11} m/s^2$) level without application of this 'correction' [e.g. *Hinderer et al.*, 1994]. However, to the best of our knowledge this simple method has never been tested with records of the seismic normal modes, because at frequencies above 0.1 mHz it was not expected to work.

Application of the local barometric pressure correction to vertical component seismic records

Our best example for successful noise reduction so far stems from the records of local barometric pressure and the tide channel of LaCoste-Romberg earth tide gravimeter ET-19 at the Black Forest Observatory (BFO) Schiltach in Southwestern Germany after the big Shikotan event of October 4, 1994. The observatory and its instruments are described by *Richter et al.* (1995) and were also used in the studies by *Müller and Zürn* (1983) and *Zürn et al.* (1991). The gravimeter is principally very similar to the accelerometers used in the IDA-network [*Agnew et al.*, 1986]. Fig. 1 compares discrete Fourier transforms after application of a Hanning window of a seismogram from the tide channel of ET-19 with and without the pressure correction. The tide channel data were calibrated to give nms^{-2}, then the calibrated (hPa, relative) atmospheric pressure record was multiplied by the factor -3.51 nms^{-2}/hPa and simply added to the seismogram to produce the correction. During seismically quiet times the factor can be estimated by linear regression over a broad frequency band (*e.g.* 0.1 - 1.0 mHz) whereas in the days following a large quake the regression has to be restricted to frequency bands devoid of seismic normal modes. The improvement of the SNR near mode ${}_0S_3$ is quite dramatic and ${}_0S_2$ is brought out from the noise by this method. Modes ${}_0S_2$, ${}_0S_3$ and ${}_0S_4$ are conspicuously split by the Earth's rotation. Previously not recognizable modes ${}_1S_2$ at 0.68 mHz and ${}_3S_2$ at 1.107 mHz begin to show up above the noise. As frequencies increase, the amount of improvement to the SNR is reduced, most probably caused by the decrease of the power in the barometric pressure spectrum with frequency, but possibly also by more complicated dynamics of the atmosphere at the higher frequencies. No effect of this simple correction could be seen above about 2 mHz. It is also quite dramatic to see the mode-like peak in the uncorrected spectrum just above 0.2 mHz be reduced by a factor of 4 to 5. Peaks like this one in spectra from gravimeter records have often been misinterpreted as theoretically possible signals from the Earth's core. A famous example (period 86 minutes) after the great Chilean quake led *Slichter* (1961) to postulate the existence of translational oscillations of the inner core (experimentally still controversial). The effects responsible for the efficiency of this correction as mentioned above produce forces (or apparent accelerations) on the sensor mass which are proportional to local barometric pressure. The proposed noise reduction method therefore only works, if instrument output is proportional to ground acceleration, which is the case for tide channels on gravimeters. In other cases the transfer function of the instrument has to be corrected for.

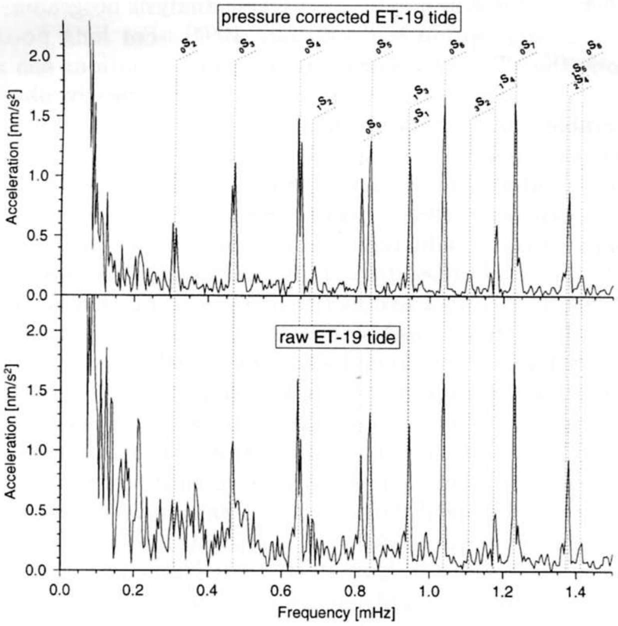

Figure 1. Linear amplitude spectra of the gravimeter series starting at 0:00 hrs, October 6, 1994 (1.5 d after the Shikotan quake) and 68 hrs long. Barometric pressure correction was applied to the gravity record in the time domain before application of a Hanning window and the Fourier transform. The vertical dashed lines show the degenerate frequencies of selected spheroidal modes as predicted for earth model 1066A.

We sucessfully applied this technique also to the mode channel of the ET-19. However, with the STS-1 vertical component seismometer at BFO we achieved noticeably smaller improvements to the SNR with ${}_0S_2$ remaining hidden in the noise. The conclusion must be drawn, that in this instrument other noise sources are active at the same level as the barometric noise while the latter noise source dominates in the ET-19. As will be shown below, we are operating at extremely low noise levels.

In a second example we apply the method to two a-priori selected, seismically quiet, 24 hr intervals, one with very small and one with appreciable variations in barometric pressure. Selecting quake free time windows allows us to demonstrate the effect of this barometric correction in an absolute sense by comparison with *Peterson*'s (1993) model for least expected seismic noise (NLNM). Fig. 2 shows the power spectral densities of the gravity records with and without the barometric correction. The factors for the correction were found experimentally (see above) and turned out to be 5 % higher than the best factor for the data in Fig. 1. In both cases a significant noise reduction is achieved for frequencies lower than approximately 1.8 mHz and below 0.7 mHz we have a factor of two to three between the two curves. In the case of the quieter time window the noise spectrum runs well below the NLNM for frequencies lower than 1.0 mHz.

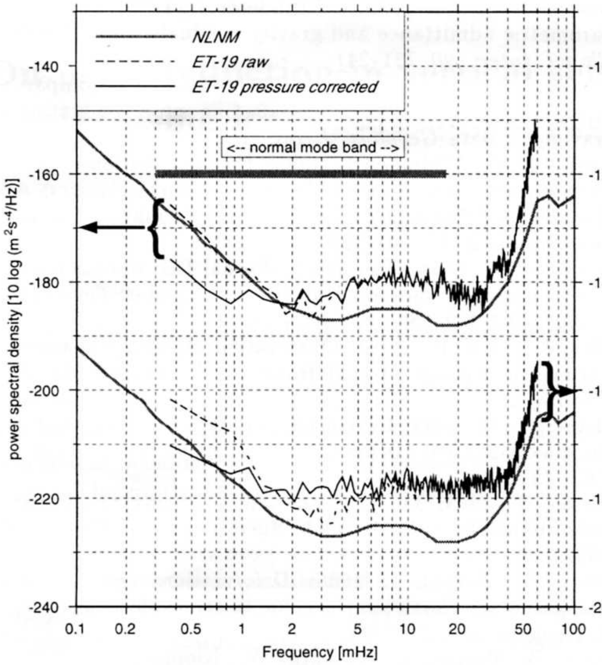

Figure 2. Power spectral density of two 24 hr gravimeter series with and without the simple pressure correction. Time series were selected for seismically quiet days in March 1995. Noise due to atmospheric pressure was large on March 27/28 (starting at 12:00 UT) and small on March 10/11 (starting at 13:00 UT). The New-Low-Noise-Model (NLNM) of *Peterson* (1993) is also shown. Note that the top three curves are for the quieter day and go with the axis on the left. Similarly, the bottom three curves are for the noisier day and go with the axis on the right. It appears to be clear that our correction becomes effective from about 1.8 mHz on downward while at 0.7 mHz there is already a factor of 3 between the corrected and uncorrected data.

For frequencies above 2 mHz the barometric correction leads to a raised noise level out to at least 4 mHz at which point the power of the correction becomes vanishingly small. In order not to contaminate the record by the pressure correction the barometric record could be low-pass filtered at 2 mHz. In particular, this would leave the noise level in the vicinity of the 3-4 mHz minimum of the NLNM unchanged.

We note also that the noise level in the corrected record for the stronger barometer variations is only slightly below the noise level in the record with the more quiet atmosphere whithout the correction: this is probably an indication of the fact that our underlying physical model is too simple.

For completeness we mention that in order to suppress spectral leakage in the noise spectra we have (1) removed most of the tidal energy by a least squares fit of harmonics with the major tidal frequencies (2) used a Hanning taper.

It was interesting to apply the same method to the records of another big quake with relatively high excitation of low frequency eigenmodes, the deep quake under North Bolivia on June 9, 1994. *Richter et al.* (1995) compared records of the same quake and different vertical seismic instruments at BFO but unfortunately the efficiency of the barometer correction was not known then. Fig. 3 shows a comparison of the tide channel of the gravimeter ET-19 with and without the barometer correction. The factor used here was found by minimizing the noise power in narrow frequency bands immediately above and below the mode ${}_0S_2$ and turned out to be about 5 % higher than the one which was used in Fig. 1. This variability is known from tidal work, where even for much longer records the factor for the best fit of local barometric pressure to gravity variations varies from record to record at the same station, most probably due to the variability of the atmospheric mass distributions. Although it is doubtful if the peak near the predicted frequency of ${}_0S_2$ is an indication of observation of this mode, clear reduction of noise by the correction in the whole frequency range of Fig. 3 is observed.

Finally we mention that the barometric correction was equally successful for the July 12, 1993 Hokkaido event where we observe ${}_0S_2$ with SNR of 2.

Conclusions

While the uncorrected spectrum in Fig. 1 is among the ones with the highest SNRs when compared with the records from the global seismic networks (IRIS, GEOSCOPE, IDA), the corrected spectrum has the highest SNR for ${}_0S_2$ and ${}_0S_3$ that we know of for this earthquake and is only rivalled by a few IDA recordings of the 1977 Indonesian event (e.g. Fig. 8 of *Masters and Widmer*, 1995) and some records from the great Chilean (1960) and Alaskan (1964) quakes. For studies of free oscillations with frequencies below 1.5 mHz this sim-

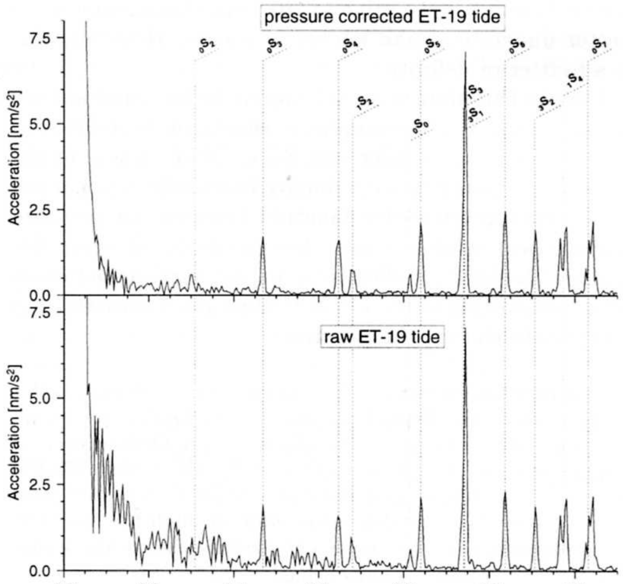

Figure 3. Same as Fig. 1 but for a gravimeter series starting at 06:00 hrs, June 9, 1994 (5.5 hrs after the deep North Bolivia quake of June 9, 1994) and 80 hrs long.

ple correction appears to be very useful. This includes searches for the notoriously elusive Slichter modes. It is therefore suggested that quiet long period seismic stations should be equipped with digital barometers with high enough resolution in amplitude and time to enable this correction.

From Fig. 2 we conclude, that it is highly probable that the shape of the NLNM at frequencies below 0.3 mHz is controlled by the Newtonian attraction of the seismometer mass by the atmosphere above the station. With a simple correction using local barometric pressure we could achieve noise levels below the NLNM by an appreciable margin and were able to extract signals from the noise. So far we have proven the efficiency only for one instrument, however, in the tidal frequency band the method is known to work at all stations for excellent gravimeters, including the Geographic South Pole [*Rydelek and Zürn*, 1986]. Clearly the method has to be tested for other stations and instruments in the free mode band. However, if no noise reduction is obtained for a given data set, other noise sources probably overwhelm the one we are dealing with in our method. In other words, the Newtonian attraction by the atmospheric masses is a signal which should be observed with good instrumentation. For seismographs with a strong direct influence of barometric pressure (e.g. buoyancy) the method could reduce the noise levels too, however, this would most likely occurr at much different regression coefficients than the fairly well understood 3.5 nms^{-2}/hPa.

If the NLNM can be beaten by this correction, the question arises, whether the NLNM should be modified accordingly. From the work in the tidal band it is understood, that most of the effect treated by the correction is due to a direct force on the sensor's mass, and only to a lesser extent due to vertical ground motion. In this way it is an effect similar to the earth tides, which are better understood and known of course. However, this is a matter of definitions.

Clearly this simple model cannot be the final answer to the problem of atmospheric effects on vertical seismic records [e.g. *Müller and Zürn*, 1983]. There might be improvements by introducing frequency dependence and a complex transfer function between air pressure and vertical seismic noise. For example, at some frequency the inertial effect due to the vertical deformation, proportional to ω^2, will start to dominate and completely change the picture.

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