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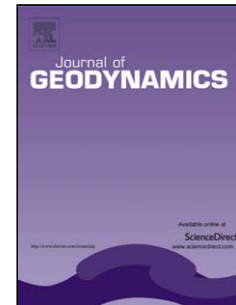
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Clear evidence for the sign-reversal of the pressure admittance to gravity near 3 mHz

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SUMMARY

The influence of the atmosphere on gravity measurements by Newtonian attraction and vertical displacements due to surface loading is well known and studied especially at frequencies below 1 mHz. Less work has been done at the higher seismic frequencies where inertial effects come into play. The sensor mass of a vertical accelerometer responds to several forces caused by the atmosphere, on global, regional and local scales. For the seismic frequencies the atmosphere above the observation site has the largest influence. A simple "Gedankenexperiment" demonstrates that the gravitational effect on one hand and the free air and inertial effects due to deformation on the other have opposite sign. Since the inertial effect is strongly frequency-dependent there should be a crossover-frequency where the pressure admittance to gravity changes sign. Simple analytical models clearly show this property near frequencies of a few mHz and are used here to amplify the variance reduction of the gravity residuals. The crossover-frequency depends on the properties of the models of the atmospheric phenomena and the elasticity of the Earth's crust. Therefore in reality it must be expected to vary in time and space.

We show one extremely clear example of this sign-reversal detected in the gravity data from the superconducting gravimeter GWR-C025 in Vienna among other examples which demonstrate the reality of this effect.

Key words: gravity variations, barometric pressure, long seismic periods, modelling

1 INTRODUCTION

Gilbert (1980, Table I) and Dahlen and Tromp (1998, Table 10.1) show in their discussions of vertical accelerometer response to low-frequency seismic signals, that seismic phenomena (like free vibrations of the Earth) generate several different accelerations of the sensor mass: the changes in the local gravity field due to vertical displacement (the free air effect), disturbance of the local gravity field due to large scale mass displacements in the Earth and the inertial effect (d'Alembert force) due to the motion of the accelerometer's frame. Zürn and Wielandt (2007, Table 1) extend the list to other phenomena (e. g. tides) recorded by vertical accelerometers and add Newtonian attractions of the sensor mass arising from changes of the density distribution in the source region as an additional acceleration. The relative magnitude of these contributions depends on frequency and on the characteristics of the phenomenon which is observed. The d'Alembert force completely dominates at the high frequencies of body wave seismology.

It is well known that high quality observations of vertical acceleration at long periods include contributions from the atmosphere (e. g. Warburton and Goodkind, 1977; Müller and Zürn, 1983) which cannot be shielded. It is also known from modeling that the major effect in this case is the direct Newtonian attraction of the sensor mass by the changing air masses especially above the accelerometer but also on a global scale, an effect usually not considered by seismologists. Significant research effort has been devoted to atmospheric effects on gravity records at very long periods (e.g. Hinderer et al., 2007). In contrast, Zürn and Widmer (1995) pointed out that noise reduction is also possible in the frequency band of the lowest degree free oscillations using a simple regression method and locally recorded barometric pressure. The regression factor is about $3.5 \text{ nm}\cdot\text{s}^{-2}/\text{hPa}$ and is now routinely applied for noise reduction in records from (superconducting) gravimeters (e. g. Hinderer et al., 2007). Examples are presented for instance in Zürn and Widmer (1995), Virtanen (1996), Van Camp (1999), Zürn et al. (2000), Rosat et al. (2003) and Zürn and Wielandt (2007, Fig. 1). It is possible to reduce the noise variance with this simple method up to frequencies of about 1 to 2 mHz (10 - 15 min periods). Beauvuin et al. (1996) also succeeded in reducing the noise in long period seismic records using locally recorded barometric pressure albeit using a different method and without a realistic physical interpretation.

Sorrells (1971) studied seismic noise caused by barometric pressure variations at frequencies higher than about 0.1 Hz. However, he took only the inertial effect into account in his theoretical derivations. Zürn and Wielandt (2007) considered gravitational, free air and inertial effects together and showed in a "Gedankenexperiment" and with very simple models of the atmospheric influence on vertical acceleration sensors that the air pressure admittance as a function of frequency should be zero near a few mHz . This results in a notch of the magnitude of the transfer function between air pressure and sensor acceleration and a sign-reversal of the

admittance associated with it. This notch is caused by a cancellation of the gravitational effect by the free air and inertial effects induced by density variations in the air above the accelerometer. Free air and inertial effects are directly caused by the air pressure loading of the Earth's surface, while the Newtonian attraction is due to the changing density distribution. The simultaneously recorded air pressure serves as a measure of the changes of the total mass of the atmosphere above the station.

If the effects described above would be the only causes of noise in long period accelerograms there would be a deep hole near 3 mHz in the noise power spectral densities for the best vertical seismographic and gravity stations. Of course, because seismic waves and noise of instrumental and other origin (e. g. Forbriger, 2007) will provide some energy at these frequencies thus the best one can expect is to see a minimum. Peterson (1993) and Berger et al. (2004) show in their studies of broad-band seismic noise at many stations of the Global Seismic Network for many time windows that the lower envelope of vertical acceleration noise power spectral densities (PSD) has a minimum near 3 mHz not present in the horizontal components. This minimum in the vertical PSD and the difference between vertical and horizontal noise at these frequencies is nicely explained by the contributions from the atmosphere as described in detail by Zürn and Wielandt (2007) and Zürn et al. (2007). This special feature in the vertical noise PSD allows the clear detection of the Earth's background free oscillations ("Hum") in the vertical component records of many stations (e. g. Nawa et al., 1998; Suda et al. 1998; Tanimoto et al. 1998; Nishida et al. 2002; Ekström, 2001; Fukao et al., 2002; Rhie and Romanowicz, 2004; Kurrle and Widmer-Schmidrig, 2006), while in contrast the horizontal hum can only be detected at barely a handful of them (Kurrle and Widmer-Schmidrig, 2008).

Zürn and Wielandt (2007) were not able to directly demonstrate the reversal in the sign of the pressure admittance for vertical acceleration in real records. They show two examples in which the experimentally found admittances of 2.65 (their Fig. 13) and $1.5\text{ nm} \cdot \text{s}^{-2}/\text{hPa}$ (their Fig. 12) for best variance reductions are clearly lower than the $3.5\text{ nm} \cdot \text{s}^{-2}/\text{hPa}$. In another example (their Fig. 10), they argue that the atmospheric signal from a pressure wave train is probably missing in the vertical component because the frequency coincides with the notch, while it is prominent in the horizontal components. These observations were interpreted by Zürn and Wielandt (2007) as indications of strong frequency dependence of the admittance near a few mHz and therefore as evidence for the existence of the notch. A very clear example is described in the next section.

2 A VERY CLEAR EXAMPLE: MARCH 4, 2006, VIENNA

2.1 Observations

On March 4, 2006 between 19:00 and 22:30 UTC, oscillations of local barometric pressure with frequency near 3.5 mHz and their counterpart in the gravity record from the superconducting gravimeter GWR - C025 in Vienna were observed. Fig. 1 shows high-pass filtered (cutoff frequency $75\ \mu\text{ Hz}$) versions of these records and the attempts to attenuate these effects in the gravity data by subtracting the barometric pressure multiplied by $\pm 3.53\text{ nm} \cdot \text{s}^{-2}/\text{hPa}$ from the gravity record. The polarity successful for the long period disturbances has the

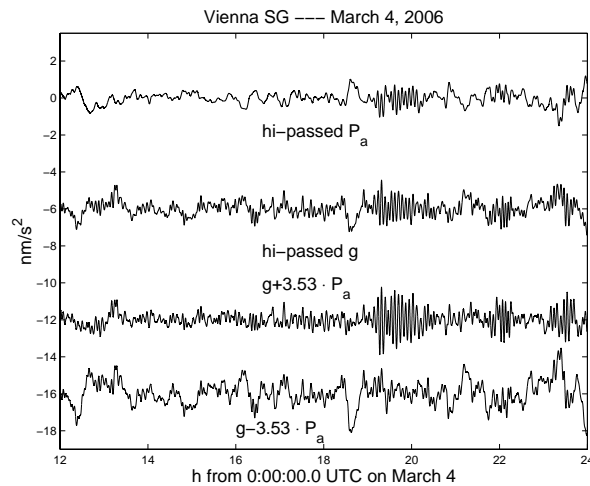


Fig. 1. Time series from Vienna on March 4, 2006 (top to bottom): High-pass filtered records of (1) the locally recorded barometric pressure scaled by $3.53 \text{ nm} \cdot \text{s}^{-2}/\text{hPa}$, (2) gravity from the superconducting gravimeter GWR-C025 at Vienna, gravity with the scaled pressure signal added (3) and subtracted (4). The amplification of the high-frequency oscillations in trace (3) and the attenuation of those in trace (4) are conspicuous. In contrast the longer period variations are attenuated in trace (3) and amplified in trace (4).

opposite effect on the high-frequency oscillations, namely an amplification of these oscillations. In contrast, the “wrong” polarity attenuates the high-frequency oscillations but amplifies the long period disturbances. If these oscillations are really occurring in the atmosphere above Vienna then the observation is a clear indication of a sign-reversal in the pressure admittance to gravity as predicted by Zürn and Wielandt (2007).

However, other possibilities have to be ruled out. Since both pressure and gravity are recorded at the same station the possibility of common ambient disturbances exists, i. e. sources other than an atmospheric phenomenon. Therefore pressure records from nearby weather stations were acquired and inspected for the presence of the oscillations shown in Fig. 1. Two such records could be found from the meteorological stations Hermannskogel and AKH, in distances of 5.3 and 3.2 km and azimuths of $\text{N}290^\circ\text{E}$ and $\text{N}194^\circ\text{E}$, respectively, from the site of GWR-C025 and are shown in Fig. 2.

They clearly show the high-frequency oscillation at about the same time and with very similar waveform and amplitude (about 0.3 hPa). These observations clearly rule out a source other than the atmosphere. Assuming a plane wave and applying crosscorrelation techniques the apparent horizontal phase velocity and direction of travel could be estimated from this small network. Unfortunately the timing of the two records from the neighbouring stations is not accurate enough to extract this information reliably. Thus it is not even clear whether this is a horizontally traveling wave or a vertical oscillation in phase at all three stations. It was also not possible to obtain a clear identification of the phenomenon from meteorologists. According to the meteo-

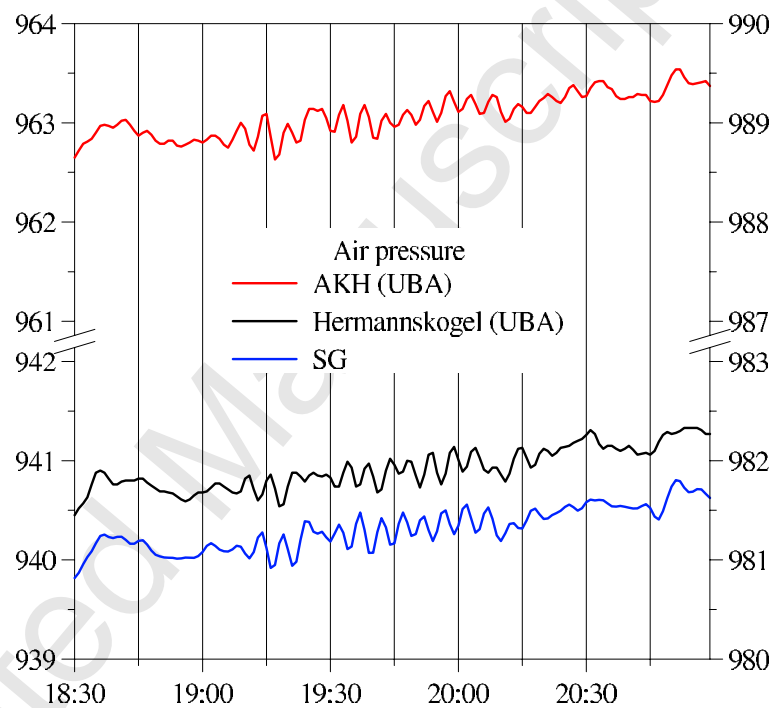


Fig. 2. Absolute air pressure records in hPa from three sites in Vienna showing the high-frequency oscillation. From top to bottom these are from AKH (UBA), Hermannskogel (UBA) and the site of GWR-C025. UBA = Umwelt-Bundesamt, AKH = Allgemeines Krankenhaus. Time is UTC on March 4, 2006 .

rological summary of the ZAMG (Zentralanstalt für Meteorologie und Geodynamik) in Vienna for March 4, 2006 a low pressure system over Poland drove cold air from the NE against the Alps causing rain and then snowfall spreading all over Austria. One meteorologist suggested that the observed oscillation could possibly be "seiches" of a mass of cold air lying north of the Alps.

We isolated the high-frequency oscillation in the filtered gravity series from the longer period gravity variations in the record using a Hanning window (such windows or tapers also reduce spectral leakage but this is not a problem here). Then we computed the Fast Fourier Transform (FFT) of this modified signal to identify the frequency of the conspicuous oscillation. The tapered time series (thick solid line) and its spectrum are depicted

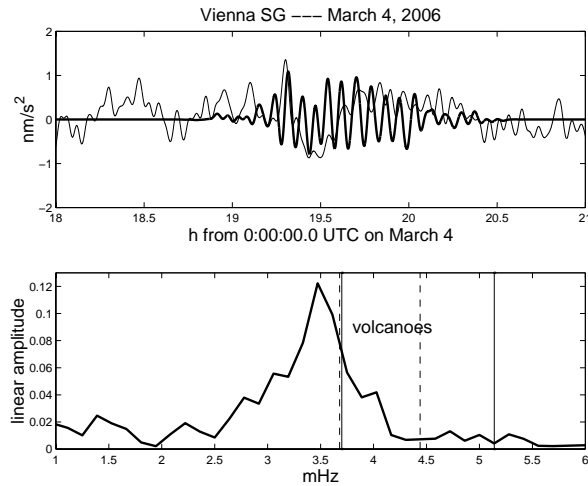


Fig. 3. Upper panel: high-pass filtered gravity (thin line) and the same time series after multiplication with a Hanning window. Lower panel: linear amplitude spectrum of the tapered time series. Vertical lines indicate the frequencies radiated during the eruptions of El Chichón (1982, dashed) and Mount Pinatubo (1991, solid). These are the eigenfrequencies of vertical oscillations of the atmosphere (e. g. Lognonné et al., 1998).

in Fig. 3. The peak frequency is very close to the frequencies of harmonic signals radiated as Rayleigh waves by the powerful volcanic eruptions of El Chichón in 1982 and Mount Pinatubo in 1991.

With high probability these waves were caused by fundamental free vertical oscillations of the atmosphere excited by these volcanoes (Widmer and Zürn, 1992; Kanamori et al., 1994; Zürn and Widmer, 1996). Vertical oscillations in the ionosphere with 3.7 mHz were also observed above convective storms in the United States of America (Georges, 1973) by Doppler sounding. In principle, the observed oscillation could just be such a vertical oscillation of the atmosphere above Vienna with unknown excitation. Without counterparts in barometer records 3.7 mHz signals lasting about 1.5 h were observed in several vertical seismic records in Central Europe on June 10, 1991 with unidentified source (Zürn et al. 2002).

It is of interest to estimate roughly the vertical ground displacement associated with the 3.5 mHz-oscillation in gravity caused by the air pressure oscillation. Naively, the observed peak-to-peak amplitude of about 2 nm/s^2 can be converted into a vertical ground displacement by assuming that the whole signal is caused by the inertial acceleration. This results in a peak-to-peak displacement of $3.9 \mu\text{m}$. For the usual free-air gravity gradient at the surface of the Earth the corresponding free-air effect contribution amounts to only 0.6% of the gravity signal. However, another contribution results from the Newtonian attraction and this is dependent on the atmospheric phenomenon. For instance, using the IBPM-model of Zürn and Wielandt (2007; Bouguer plate model including the inertial effect) we obtain about $6 \mu\text{m}$ peak-to-peak of vertical displacement from the observed gravity amplitude. This value is almost twice as large as the naively determined displacement. The inertial (and free

air) effects have to cancel the attraction effect and produce a signal with the "wrong" polarity, therefore the displacement necessary to explain the observed gravity signal must be larger.

2.2 Model performance

We selected the part of the high-pass filtered gravity and pressure records ranging from 18:00 to 23:00 UTC on March 4, 2006 (not tapered) and made an attempt to optimize several models in the sense that for this part of the time series the variance of the residual gravity time series should be minimum. Referring to gravity and pressure series in the following always implies the high-pass filtered versions of these variables. To form the residual gravity the "pressure accelerograms" for the different models computed from the pressure signal were subtracted from the gravity time series. The filtered gravity series is shown as the thin solid line in Fig. 3. We use the variance reduction $R_{\sigma^2} = (\sigma^2(o) - \sigma^2(r))/\sigma^2(o)$ to describe quantitatively the apparent reduction of the noise by the subtraction of our pressure accelerograms, where $\sigma^2(o)$ is the variance of the gravity series and $\sigma^2(r)$ the variance of the residual gravity series.

First we determined the optimal admittance in a least squares sense by fitting pressure to gravity. The minimum in variance was obtained with a factor of $-1.0 \text{ nm} \cdot \text{s}^{-2}/\text{hPa}$ and a variance reduction of 5%. The nominal correction using $-3.5 \text{ nm} \cdot \text{s}^{-2}/\text{hPa}$ in the case here increases the variance by 28%. The frequency-independent model implicitly used here is basically just a Bouguer plate atmosphere changing its density. The small regression coefficient obviously results from the mix of frequencies contained in the air pressure signal to both sides of the notch predicted by Zürn and Wielandt (2007). The resulting residual gravity is shown in Fig. 4 (trace 4) together with pressure, gravity and gravity residuals resulting using constant admittances of $\pm 3.53 \text{ nms}^{-2}/\text{hPa}$ and the models described below.

The three frequency-dependent simple models used by Zürn and Wielandt (2007) are described as admittances of vertical gravity changes to local barometric pressure as functions of frequency. Therefore the pressure accelerograms are computed as follows: Fast Fourier Transform of the air pressure variation, multiplication of the transform with the transfer function of the models, and inverse Fourier Transform. These pressure accelerograms are then subtracted from the simultaneously recorded gravity variations.

The first simple frequency-dependent model used by Zürn and Wielandt (2007; called IBPM, inertial Bouguer plate model, in that paper) corresponds to the one above but including the strongly frequency-dependent inertial effect. The deformation by the atmospheric pressure is calculated analytically for an elastic layer over a rigid halfspace. Zürn and Wielandt (2007) show, that in this model the location of the notch on the frequency axis depends only on the ratio of the thickness D of the elastic layer over its shear modulus μ . Therefore a reasonable (crustal) shear modulus was assumed ($\mu = 45 \text{ GPa}$) and the "crustal" thickness D varied and again the variances of the residuals were calculated. Fig. 5 shows the resulting variances as a function of crustal thickness. The minimum is obtained for $D = 27 \text{ km}$ with a variance reduction of 67%.

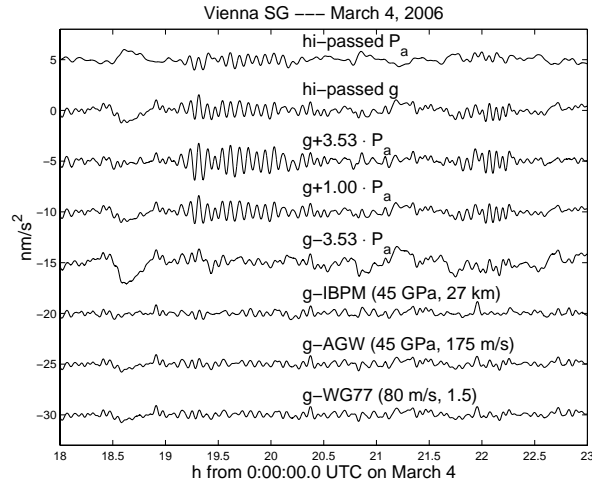


Fig. 4. Time series from Vienna, March 4, 2006 (top to bottom): High-pass filtered records of (1) local barometric pressure scaled by $3.53 \text{ nm} \cdot \text{s}^{-2}/\text{hPa}$, and (2) high-pass filtered gravity from GWR-C025, gravity residuals obtained by subtraction of $-3.53 \cdot P_a$ (3), $-1.00 \cdot P_a$ (4), and $+3.53 \cdot P_a$ (5), and gravity residuals obtained by subtraction of pressure accelerograms computed with optimized frequency-dependent models IBPM (6), AGW (7), and WG77 (8). For the parameters of these models see text and trace labels. Clearly the frequency-dependent models perform better than any frequency-independent one .

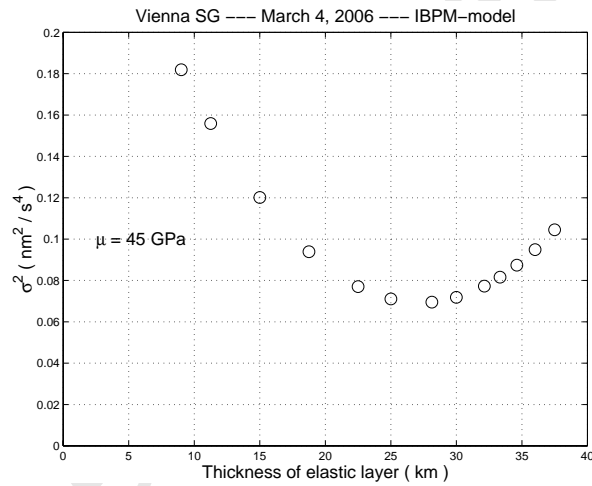


Fig. 5. Variance of the gravity residuals after subtraction of the pressure accelerogram produced using the inertial Bouguer plate model (IBPM) as a function of the thickness of the elastic layer D with a shear modulus of 45 GPa .

The resulting residual gravity is shown in Fig. 4. The transfer function magnitude of this model is depicted in Fig. 6 together with the ones from the models described below.

In this model and the previous one the atmosphere extends laterally to infinity and therefore becomes the higher the frequency the more unrealistic. The pressure accelerograms for all frequency dependent models were

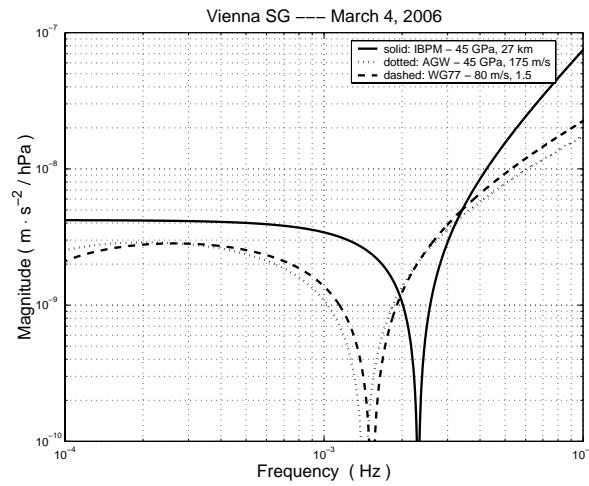


Fig. 6. Transfer function magnitudes as functions of frequency for optimal IBPM-, AGW-, and WG77-models. The notch occurs at different frequencies but the admittances coincide at about 3.2 mHz, the frequency where most of the signal is concentrated (see Fig. 3) .

lowpass-filtered at 20 mHz because of the steep rise of the admittances with frequency (Fig. 6) and because at higher frequencies the models cannot describe the physics properly (the models do not incorporate propagation of the elastic disturbances).

The following two models possess limits for the sizes of their pressure cells which decrease with increasing frequency. Zürn and Wielandt (2007) consider a pressure wave in the atmosphere traveling with horizontal phase velocity c_h over an elastic halfspace with shear modulus μ (called acoustic-gravity wave, AGW). The air density decays exponentially with altitude (scale height H). In addition to the shear modulus used above we tested a higher value of 90 GPa. c_h was varied and pressure seismograms computed and subtracted from the gravity record. Fig. 7 depicts the variances of the gravity residuals as functions of q_h for these two cases. For the case with $\mu = 45$ GPa a minimum was obtained for a phase velocity of about 150 m/s with a variance reduction of 64%.

The resulting residual gravity series with the indicated parameters is presented in Fig. 4 and the corresponding transfer function magnitude is shown in Fig. 6. For the case with the doubled shear modulus no minimum is reached in the range of c_h considered. It is possible that acoustic-gravity waves have horizontal phase velocities larger than the speed of sound, as a matter of fact c_h can reach infinity for a simple vertical oscillation. However, in these cases the assumptions for the derivation of the formulae in Zürn and Wielandt (2007) for AGW are certainly violated. The gravitational effect for AGW was calculated with the assumption that air density vertically is described by an exponential decay from the (laterally varying) value at the bottom of the atmosphere and no other dependence on height.

The last model (called WG77) employed by Zürn and Wielandt (2007) is derived from Warburton and Goodkind (1977) and consists of a cylindrical pressure cell centered on the sensor location. Parameters of

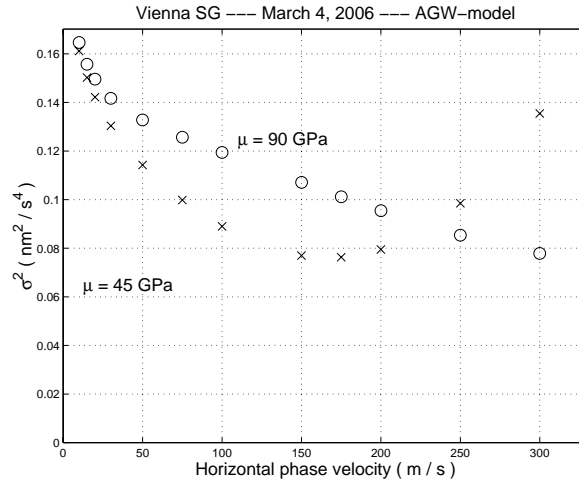


Fig. 7. Variance of the gravity residuals after subtraction of the pressure accelerograms produced using the atmospheric gravity wave model (AGW) as functions of the horizontal phase velocity c_h . Shear moduli used were 45 (x) and 90 (o) GPa .

this model are the ratio of the radius of the cylinder to the period of the pressure variation (dimension of a velocity) and a multiplier modifying the deformation caused by the pressure cell as computed by Warburton and Goodkind (1977) for an Earth model. The atmosphere can be described by either constant or exponentially decaying density and a scale height H . Exponential decay is more realistic and a scale height of 6.6 km was chosen following Kanamori et al. (1994). For the three spatial-temporal scale ratios of 15, 80 and 330 m/s, which can be considered realistic, the deformation multiplier was varied from 0.1 to 22 and pressure accelerograms calculated and subtracted from the gravity data. The resulting variances of the residuals are plotted in Fig. 8 against the deformation multiplier. Nearly identical minima were obtained for all cases at multipliers of 0.35, 1.5 and 5.0, respectively, corresponding to a variance reduction of 65%.

The residual gravity with parameters indicated is presented in Fig. 4. We prefer multipliers near to one in order to stay close to the model used by Warburton and Goodkind (1977). The shear modulus they used is 22 GPa corresponding to a crustal shear velocity of 3 km/s. The corresponding transfer function magnitude is depicted in Fig. 6.

Clearly the frequency dependent models all perform better than when a simple regression with whatever factor is used. Amongst those the ranking is IBPM (67%), WG77 (65%), and AGW (64%) in the optimized cases. These numbers will to a certain extent depend on the time interval chosen for this analysis and therefore the differences between these variance reductions are not significant, but the differences to the models with frequency independent admittance certainly are. In Fig. 4 the residual gravity time series after subtraction of the pressure accelerograms are shown together with pressure and uncorrected gravity. Three frequency independent admittances are used and the three optimal models including frequency-dependence. The optimal parameters

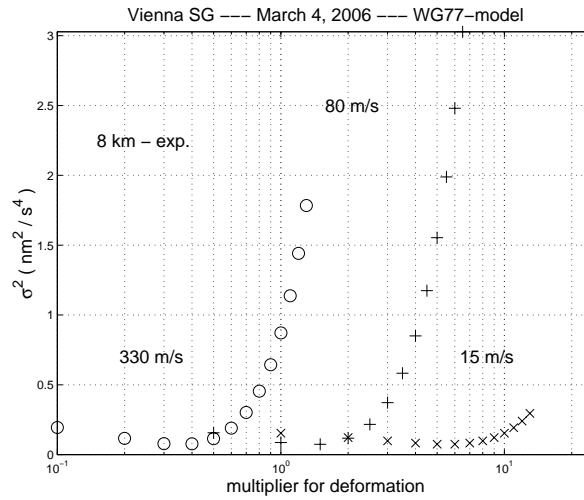


Fig. 8. Variance of the gravity residuals after subtraction of the pressure accelerograms produced using the Warburton and Goodkind (1977) model of a spherical cylinder centered above the sensor as modified by Zürn and Wielandt (2007) as a function of the multiplier for the deformation contribution. Spatio-temporal scale relations of 15, 80 and 330 m/s were used .

are given next to the traces. Visually the three frequency dependent models appear to perform equally well as indicated by the insignificant differences of the variance reductions.

In Fig. 6 the magnitudes of the transfer functions (or the admittances) of the three models are depicted. The most conspicuous feature is the fact that the locations of the notch are different. While AGW and WG77 are very close to each other with the notch near 1.5 mHz, IBPM has its notch at 2.2 mHz and rises much more steeply for high frequencies. However, all three models have very similar admittances of about $+4 \text{ nm} \cdot \text{s}^{-2}/\text{hPa}$ at about 3.2 mHz near the peak in the spectrum of the high frequency oscillations in the records (Fig. 3) and therefore removed the two wave trains equally efficiently (Fig. 4) from the gravity by our optimization of model parameters.

3 FURTHER EXAMPLES

3.1 July 30, 2007, Vienna

Another record section in the data from the same instruments as in the previous case where the nominal barometer correction failed to work well was found during a few hours on July 30, 2007. We performed a similar optimization of our models as in the case above for the identically high-pass filtered time series from 4:00 to 14:00 h UTC on July 30 without showing the details. The variance reductions in the gravity residuals for constant admittances of -3.53 , -2.7 (the optimum for this case), and $+3.53 \text{ nm} \cdot \text{s}^{-2}/\text{hPa}$ were 59.6, 66.7, and -294% , respectively. The IBPM-model with $\mu = 45 \text{ GPa}$ assumed had a minimum for $D = 36 \text{ km}$ and a variance reduction of 76.5%. The AGW was optimized for shear moduli of 25 and 45 GPa with resulting optimal hori-

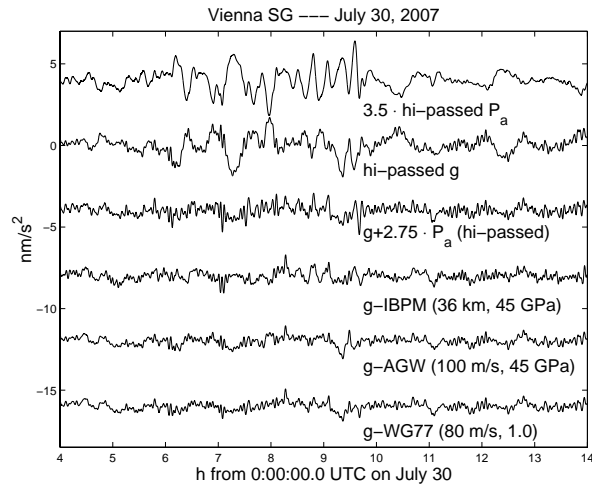


Fig. 9. Time series from Vienna on July 30, 2007 (top to bottom): High-pass filtered records of (1) local barometric pressure scaled by $3.53 \text{ nm} \cdot \text{s}^{-2}/\text{hPa}$, and (2) high-pass filtered gravity from GWR-C025, gravity residuals obtained by subtraction of $-2.75 \cdot P_a$ (3), and gravity residuals obtained by subtraction of pressure accelerograms computed with optimal frequency-dependent models IBPM (4), AGW (5), and WG77 (6). For the parameters of these models see text and trace labels. The frequency-dependent models perform better than any frequency-independent one .

zonal phase velocities c_h of 60 and 100 m/s, respectively. 45 GPa is the value used above and 25 GPa is also a reasonable value for sedimentary rocks. The second model performed slightly better than the first and resulted in a variance reduction of 79.5%. Finally, the WG77-model was optimized for spatio-temporal scale relations of 15, 80, and 330 m/s with the variance minima at deformation multipliers 0.3, 1.0, and 4.0, respectively. The variance reductions of all three were very similar near 81.4%. The original and residual time series for the optimal cases are shown in Fig. 9.

3.2 Examples from the Black Forest Observatory, SW Germany

We searched and continue to search the data archives at the Black Forest Observatory (BFO 48.33°N, 8.33°E) for similar events. The gravity records from LaCoste-Romberg Earth Tide Gravimeter ET-19 and the relative air pressure records P_a were inspected. The search (Vienna and BFO) so far was not performed in a systematic way but examples were selected from notes made by routinely inspecting the pressure and gravity records (among others). We had noted four examples, where pressure variations with frequencies above 3 mHz occurred. We applied the same analysis as for the examples from Vienna to these four examples. The results are summarized in Table 1 together with the corresponding results from the examples from Vienna.

For all these examples it was possible to amplify the variance reduction by using one of the frequency-dependent models rather than a linear regression. In two of the cases this is probably rather insignificant, but these are the ones (4, 6) in which the linear regression works very well and the admittances are close to the long period value. In turn, this means that the pressure variations occur mostly below the notch in the frequency

Table 1. Summary of information and variance reductions R_{σ^2} for the six examples of high-frequency air pressure variations examined in this paper.

Case		1	2	3	4	5	6
Station		VI	VI	BFO	BFO	BFO	BFO
Date		4.3.2006	30.7.2007	25.1.1995	22.7.1995	19.3.2002	1.7.2003
Lin. regr. coeff.	$\text{nm} \cdot \text{s}^{-2}/\text{hPa}$	-1.0	-2.7	-1.1	-3.5	-2.5	-2.85
R_{σ}^2	%	5.0	66.7	16.4	92.2	41.9	80.7
Freq.-dep. model		IBPM	WG77	AGW	WG77	WG77	AGW
R_{σ}^2	%	67.4	81.4	26.5	93.6	53.6	83.9

domain. Our best case (1) was optimized for frequencies above the notch, of course, to demonstrate the sign reversal and therefore the improvement with the frequency-dependent models is highly significant.

The geological structure is quite different at the two stations: the site of the superconducting gravimeter in Vienna is located close to a deep sedimentary basin while BFO is located in the granite of the Black Forest in Southwestern Germany. Therefore the displacements caused by the same air pressure variation could be appreciably larger in Vienna than at BFO. This conjecture could be tested by looking at a variety of stations with different geology.

4 DISCUSSION AND CONCLUSIONS

The examples demonstrate that the mutual cancellation of the vertical accelerations exerted by local atmospheric density variations in the frequency range near 3 mHz proposed by Zürn and Wielandt (2007) is real. Especially the first example from Vienna is convincing, because there the lower and higher frequencies in the pressure variations are nicely separated in time. For this reason the high-frequency train of oscillations was detected while performing the usual linear regression correction on the gravity data. For the second example from Vienna and for the four examples from BFO this temporal separation does not exist and it is probably rarely the case. The amplification of the variance reduction by using one of the frequency-dependent models is not as large in these cases as for the first one.

It is clear from these observations and common sense that no inferences can be made about what happened in the atmosphere in each case just because one model performed better than the others. All the models are extremely simple compared to the real atmosphere. However, basic physical considerations (see "Gedankenexperiment" in Zürn and Wielandt, 2007) clearly require the cancellation effect and the associated sign-reversal in the pressure admittance for gravity near frequencies of a few mHz for many different real atmospheric phenomena. The observations reported here support this conjecture. That property of all the frequency-dependent

models is certainly correct. This alone explains the minimum near 3 mHz of the vertical seismic low-noise models and the difference to the horizontal low-noise models at these frequencies.

We note here in passing that observations reported by Meurers (2000) and Simon (2002) show that the atmosphere causes gravity variations without associated variations in barometric pressure just by strictly vertical mass displacements. In this case the apparent pressure admittance to gravity would become infinite. This underlines the complexity of the phenomena going on in the real atmosphere and also points out limitations for the models used in this paper and by Zürn and Wielandt (2007).

Very interesting questions arise from the observations in the first example (section 2). Were the pressure oscillations caused by a traveling wave or by a simple vertical oscillation (or something else)? Over what area can they be observed in barometer records? What and where was their source of excitation? If it was a traveling wave, what was its propagation velocity and direction? Did the vertical deformation of the crust caused by the pressure oscillation excite observable seismic surface waves and can those be detected in broadband seismic records and how far away from Vienna? The answer to the last question depends on the area on which pressure acted coherently. Air pressure variations of 3 hPa peak-to-peak acting over a circular area with a radius of 38 km were invoked to explain the globe-circling Rayleigh waves (Kanamori et al., 1994) during the eruption of Mount Pinatubo in 1991. However, the investigation of these problems is beyond the scope of this paper and needs more work.

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