Spatiotemporal features of the Earth’s background oscillations observed in central Europe

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Received 10 October 2006; revised 10 November 2006; accepted 14 November 2006; published 19 December 2006.

[1] We present a continuous analysis of the background oscillations of the Earth. We processed five years of vertical recordings from the German Regional Seismic Network (GRSN) and estimated the directions of arrival (DOA) of the background Rayleigh waves in the frequency range between 5 and 8 mHz. We find clear seasonal variations in the direction of propagation and a striking rate of recurrence in these seasonal patterns. This seasonality provides evidence of an excitation of the background oscillations by large-scale atmospheric and/or oceanic processes which confirms previous studies. Citation: Kurrle, D., and R. Widmer-Schnidrig (2006), Spatiotemporal features of the Earth’s background oscillations observed in central Europe, Geophys. Res. Lett., 33, L24304, doi:10.1029/2006GL028429.

1. Introduction

[2] Since the first reports about the continuously excited fundamental spheroidal oscillations of the Earth [Nawa et al., 1998; Suda et al., 1998], which are also known as the seismic hum, these oscillations have been observed at many seismic stations all over the world [Suda et al., 1998; Tanimoto et al., 1998; Kobayashi and Nishida, 1998].

[3] The amplitudes of these oscillations were found to be rather constant in time (modal amplitudes ≈0.4 ngal [Nishida and Kobayashi, 1999]) with small seasonal variations of a few percent [Tanimoto and Um, 1999; Ekström, 2001; Tanimoto, 2005]. Due to the very small signal amplitudes, the background oscillations of the Earth can only be observed at the quietest stations which are mainly stations of the global seismic networks.

[4] However, the stations of these networks are distributed all over the world, and the station density is much too low to utilize a subset of these stations as a seismic array, even in the very long period range to be considered in this paper.

[5] Since the fundamental spheroidal modes of the Earth can also be viewed as interfering Rayleigh waves and this is also true for the Earth’s background oscillations [Ekström, 2001; Nishida et al., 2002], it is possible to investigate the origin of this Rayleigh wave background with the well-known methods of array seismology [e.g., Rost and Thomas, 2002], provided the existence of an array of suitable size with low enough noise levels in the normal mode band.

[6] In this way, Rhie and Romanowicz [2004] identified the northern Pacific and the southern oceans as the main source regions of the hum during the corresponding winter months.

[7] Besides the two broadband seismic networks in California (Berkeley Digital Seismic Network, BDSN) and Japan (F-net) used in that study, one of very few networks suitable to study the background Rayleigh waves is the German Regional Seismic Network (GRSN). While the quietest records in the BDSN and the F-net originate from Streckeisen STS-1 broadband seismometers [Wielandt and Streckeisen, 1982], the GRSN stations are uniformly equipped with STS-2 seismometers. Even though the sensor noise levels of STS-2 seismometers are higher than those of the STS-1, the GRSN data are still suitable for studies of the Earth’s hum due to the special seismometer shielding used in that network [Wielandt and Widmer-Schnidrig, 2002; Widmer-Schnidrig, 2003].

2. The GRSN as Array for the Very Long Period Rayleigh Wave Background

[8] The GRSN currently consists of 22 stations distributed all over Germany. The distance between stations ranges from 80 to 800 km, so the size of the network allows us to use the GRSN as an array to study Rayleigh waves with wavelengths of several hundred kilometers. The suitability of the GRSN as an array for long period waves was already shown by Krüger and Stammel [1996].

[9] To identify the stations recording the background oscillations, we computed power spectral densities (PSDs) for several years of LHZ (vertical component, 1 sample per second) data of the GRSN and stations in neighboring countries. Since the aim was to obtain a homogeneous data set with a uniform array configuration, only stations set up before the year 2000 were considered. We continuously detected the hum at eight stations in the GRSN (BFO, BRG, CLI, CLZ, FUR, RGN, TNS, WET) and one GEOFON station (WLF, Luxemburg). By restricting the Rayleigh wave analysis to data from these stations we make sure that our findings apply to the background oscillations. The first quartile of the PSD for these stations in 2000 and a station map are depicted in Figure 1.

3. Methods

[10] After filtering the data between 100 and 500 sec period, we split the seismograms into segments of 3 h length with an overlap of 2 h. All segments containing large earthquakes or other disturbances were sorted out.

3.1. Data Selection

[11] Due to the very small signal amplitude and allowing for the fact that removing earthquakes mentioned in catalogs does not suffice, we preferred a data driven selection.
This data selection was based on total signal power and on the ratio between short term and long term average of this value (STA/LTA).

For our data selection, each three hour window was divided into seven sub-windows, then for each of the \( N \) stations the total signal power and the maximum STA/LTA ratio for the seven sub-windows were calculated. To obtain robust mean values for signal power and STA/LTA, we rejected the minima and maxima and averaged over the remaining \( N - 2 \) stations. The resulting time series for a 20 day period in 2000 are shown in Figure 2. Only if both signal power and STA/LTA were below the empirically determined thresholds of 0.15 and 1.7, respectively, the particular time window was used for the DOA estimation. In doing so, about half of the data was retained.

As can be seen from Figure 2, even the occurrence of moderate earthquakes with magnitudes \( \geq 5.5 \) did not necessarily lead to a rejection of the respective time span. Two events of this kind on days 92 and 108, both deeper than 500 km, did not give rise to a significant excitation of modes below 10 mHz and thus, there was no reason to exclude those data.

### 3.2. DOA Estimation for Very Long Period Rayleigh Waves

From the studies of large earthquakes, the dispersion properties of surface waves are well known, especially in the very long period range. At frequencies below 10 mHz, it is justifiable to neglect the effects of lateral heterogeneities on surface wave dispersion within the GRSN and to apply the dispersion relation according to PREM [Dziewonski and Anderson, 1981] to determine the direction of arrival (DOA) of the background Rayleigh waves.

For every data segment left after the selection procedure, we calculated the Fast Fourier Transformations \( X_n \) of the records (tapered by a Hanning window) and performed a frequency-wavenumber analysis to compute the beam power \( E \) as a function of the back azimuth \( \vartheta \).

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### Figure 1.
(a) Station map and (b) first quartile of power spectral density (PSD, measured in dB relative to 1 m²/s³) for the nine stations in 2000. Vertical lines indicate the frequencies of the fundamental spheroidal modes \( oS_l \). In spite of the small signal-to-noise ratio, all spectra show the background oscillations of the Earth.

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### Figure 2.
Example of data selection for 20 days in 2000. (a) Earthquake magnitude from CMT catalog, (b) STA/LTA ratio of signal power, (c) rejected (black) and selected (white) data windows, (d) total signal power. Only data segments with both STA/LTA and signal power below the thresholds were retained.
Taking into account the dispersion of the Rayleigh waves across the array, we calculated the beam power in the frequency interval \([\omega_1, \omega_2]\) for the \(N\) station array according to

\[
E(\mathbf{K}_0) = \int_{\omega_1}^{\omega_2} \int_{t_0}^{t_1(\omega)} \left| \frac{1}{N} \sum_{n=1}^{N} \hat{X}_n(\omega) e^{-i\omega \mathbf{u}_n \cdot \mathbf{r}_n} \right|^2 \, \mathrm{d}u \, \mathrm{d}w,
\]

where the slowness limits \(u_1\) and \(u_2\) (in case of surface waves simply the reciprocal of the phase velocity) were chosen corresponding to a ±10% deviation from the PREM velocity. The \(\mathbf{r}_n\) are the station vectors of the array with the station CLL chosen to be the central station. \(\mathbf{K}_0 = (-\sin \vartheta, -\cos \vartheta)^T\) symbolizes a unit vector pointing in the assumed propagation direction defined by the back azimuth \(\vartheta\) which is measured clockwise from North.

\[16\] To get statistically stable results, the outcomes of (1) were averaged over 10 days and then, for a better visualization, normalized to relative scales between 0 and 1. When studying signals as small as the background free oscillations, the extreme data quality requirements make it difficult to find enough adequate stations, even in Europe where currently more than 200 VBB stations are in service. It has to be pointed out that with a sparse nine station array, one can not expect to get a unique plane wave decomposition of the Rayleigh wave background which is likely to be caused by multiple simultaneous sources. Instead, the results will be biased by interference effects and by the array configuration.

\[17\] However, we can still draw some important conclusions about the respective wave field from the results of our analysis.

### 3.3. Example: A Moderate Earthquake

\[18\] Figure 3 shows an example of the capability of our method to determine the propagation direction of an incident Rayleigh wave. In the upper panel, the nine recordings of a shallow, moderate earthquake are depicted, filtered between 2 and 10 mHz. Two of the traces (FUR,WLF) are distorted by some glitches but are nonetheless included in the analysis. The lower panel displays the bearings for four Rayleigh wave arrivals, R2, R4, R6 and R8. Up to R6, the beam power maximum is very close to the theoretically expected back azimuth of 102°, whereas R8 can not be detected any more. Instead, the beam power distribution for the respective time span resembles the 10-day average for the Rayleigh wave background in that period, suggesting that the background waves dominate over R8.

\[19\] We note that the sidelobes get larger with decreasing signal amplitude. This can be due to additional Rayleigh wave sources as well as unwanted random processes, and a clear distinction is not possible. To minimize random effects, we only consider averages over many time windows in our analysis of the Rayleigh wave background.

### 4. Results and Discussion

\[20\] By the method described above, we analyzed the Rayleigh wave background from the beginning of 1999 to the end of 2003. Figure 4 shows the normalized beam power between 5 and 8 mHz, calculated from the vertical recordings of the nine stations shown in Figure 1. The peak width of the beam power maxima is \(\approx 60^\circ\) for the background waves and only slightly smaller (\(\approx 50^\circ\)) for the large

![Figure 3](image.png)

**Figure 3.** Example for DOA estimation: \(M_w = 6.4\) earthquake Off Coast of Costa Rica, July 21, 2000, 01:53, depth = 33 km. (top) Vertical recordings, bandpass filtered from 2 to 10 mHz. Arrival times for Rayleigh waves R1–R8 are indicated above. (bottom) Beam power distributions for R2, R4, R6 and R8 as well as the corresponding background average. Back azimuth is measured clockwise from North.

![Figure 4](image.png)

**Figure 4.** (a) Beam power distribution of Rayleigh wave background 1999–2003; (b) corresponding display of array response function. Back azimuth is measured clockwise from North.
earthquake signals shown in Figure 3. Thus the peak width is dominated by wavelength and station spacing and does not allow any conclusions on the dimensions of the source regions. Even localized point sources cannot be ruled out. Most remarkably, there are clear seasonal variations and obvious annual patterns in the angle of incidence.

[21] This complements the seasonal amplitude variations with a period of six months reported before [Tanimoto and Um, 1999; Ekström, 2001; Tanimoto, 2005]. However, a spectral analysis of Figure 4a exposed the dominant period to be 12 months, whereas a semiannual component could not be found.

[22] While in northern hemisphere winter, the strongest waves seem to arrive from northern directions around 30°, the most energetic waves during the summer months come from the opposite direction with back azimuths of about 210°. In summer, further periodically occurring arrivals could be detected around 120°, albeit with varying relative amplitudes.

[23] An unexpected feature might be the lack of arrivals from the opposite direction, because at very long periods, the Rayleigh wave R2 is not necessarily small against R1. However, the superposition of two Rayleigh wave trains R1 and R2 with unequal amplitude, excited by a continuous source, leads to both a standing wave of twice the amplitude of the smaller (R2) wave and a propagating wave with reduced amplitude from the R1 direction.

[24] Since the beam power distribution differs significantly from the array response shown in Figure 4b, we can conclude that the Rayleigh wave background in this frequency range is never completely isotropic. Instead, these background Rayleigh waves, and thus the background oscillations of the Earth, seem to be excited by sources whose distribution depends only on the respective season.

5. Conclusions

[25] In order to constrain the regions where the hum is being excited, we analyzed five years of GRSN data. Due to the constantly low noise levels at a part of the stations, the GRSN offers an excellent data base to carry out long term studies of the long-period background noise.

[26] We demonstrate the suitability of the GRSN for array based hum studies. Provided a similarly efficient shielding from environmental thermal and barometric noise as in the GRSN, the comparatively large number of globally deployed STS-2 seismometers could be a great help to better localize the hum sources in space and time.

[27] From the frequency-wavenumber analysis of the quietest time windows, we found the long-period Rayleigh wave background with periods between 120 and 200 sec to be non-isotropic with back azimuths near 30° in winter and around 210° as well as 120° in summer. These bearings, pointing to the northern Pacific, the southern Atlantic and the Indian Ocean, respectively, are consistent with the study of Rhie and Romanowicz [2004] who located the dominant sources in the northern Pacific in winter and in the southern oceans in summer.

[28] Even though our analysis does not allow us to distinguish between atmospheric and oceanic sources, the observed seasonal patterns which differ only slightly from year to year are evidence in support of a near surface excitation of the background oscillations of the Earth.

[29] Acknowledgments. We thank W. Zürn and M. Joswig for valuable discussions. B. Romanowicz and an anonymous reviewer are gratefully acknowledged for their critical comments. We also want to thank the network operators of the GRSN (SZGRF, Erfangen) and the GEOFON Network (GFZ Potsdam) for freely distributing their high quality data. All figures were prepared using the GMT software [Wessel and Smith, 1991]. This work is granted by the Deutsche Forschungsgemeinschaft (DFG).

References


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