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The horizontal hum of the Earth: A global background of spheroidal and toroidal modes

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[1] It is well known that the fundamental spheroidal modes of the Earth are continuously excited. The vertical motions of this 'hum of the Earth' can be observed at many stations all over the world. However, there exists no hum observation based on horizontal seismic data yet. In this article, we present observations of continuous horizontal background oscillations of the Earth at four exceptionally quiet seismic stations and show the existence of a so far unknown global background of long-period Love waves and, equivalently, fundamental toroidal modes. Spheroidal and toroidal modes exhibit similar horizontal amplitudes which, for the spheroidal modes, agree with those expected from the vertical component data. Neither earthquakes nor spheroidal-toroidal mode coupling can explain a permanent excitation of toroidal modes at this level. **Citation:** Kurrle, D., and R. Widmer-Schnidrig (2008), The horizontal hum of the Earth: A global background of spheroidal and toroidal modes, *Geophys. Res. Lett.*, *35*, L06304, doi:10.1029/2007GL033125.

1. Introduction

[2] It is now widely accepted that the fundamental spheroidal modes of the Earth, ${}_0S_l$, are continuously excited, even at times devoid of large earthquakes [*Nawa et al.*, 1998; *Kobayashi and Nishida*, 1998; *Suda et al.*, 1998]. Since the first reports on this phenomenon, which is often referred to as the 'hum of the Earth', several groups tried to identify the origin of the permanent mode excitation, but a definitive answer has not been given yet. At first, the atmosphere was considered to be the most likely source [*Kobayashi and Nishida*, 1998; *Tanimoto and Um*, 1999; *Nishida et al.*, 2000]. Most recent publications [*Rhie and Romanowicz*, 2004, 2006; *Tanimoto*, 2005; *Webb*, 2007] favor long-period surface waves in the oceans, so-called infragravity waves [e.g., *Webb et al.*, 1991]. However, an atmospheric excitation is not ruled out yet [*Nishida and Fukao*, 2007]. Attempts to model the excitation of the hum have shown that atmospheric pressure variations [*Tanimoto*, 1999; *Fukao et al.*, 2002] as well as infragravity waves [*Tanimoto*, 2005, 2007; *Webb*, 2007] are viable sources.

[3] All observational hum studies are hampered by the very small amplitudes of the background oscillations, and due to the low signal-to-noise ratio, only vertical component data from the quietest seismic stations have been considered so far. Thus, the horizontal accelerations predicted for the spheroidal modes (about 70% of the vertical amplitudes) have not been observed up to now. Moreover, a much more important question could not be answered yet: Is there also a permanent excitation of toroidal modes and, if so, at what level? An answer to these questions is highly desirable because this could lead to further insights into the mechanisms responsible for the permanent mode excitation.

[4] At periods greater than 30 sec, horizontal component seismic data are much noisier than the vertical component. This seems to make them unsuitable for the detection of the weak background oscillations. The enhanced noise level of horizontal seismic data is predominantly caused by tilting of the ground when the surface around a station is deformed by atmospheric loading [*Wielandt*, 2002]. This major contribution to horizontal seismic noise, although generated in the vicinity of a seismic station, cannot be eliminated by instrumental measures. Recently *Zürn et al.* [2007] suggested a method to reduce long-period horizontal seismic noise by the computation and subtraction of 'pressure seismograms'. However, this method only works efficiently for the rare case of strong local pressure variations. Despite these shortcomings, we examined horizontal long-period data to search for signs of continuously excited normal modes of the Earth.

2. Data and Methods

[5] While for the study of the vertical background oscillations, more than hundred seismic broadband stations provide sufficiently quiet data, this number is dramatically reduced in the horizontal case. We used data from the four stations we found to have the lowest horizontal long-period noise: The Black Forest Observatory (BFO), Takato (TTO), Baijiatuan (BJT) and Matsushiro (MAJO). All stations are equipped with Streckeisen STS-1 VBB seismometers, and at BFO, there is in addition an STS-2. The station coordinates, data channels and time periods are specified in Table 1.

[6] We first divided the whole data sets into time windows of 24 h length with an overlap of 12 h. For these time windows we calculated estimates of the acceleration power spectral densities (psd) using the FFT after multiplication by a Hanning taper. We calculated the mean signal power for each window in the frequency band between 3 and 7 mHz and selected the 1000 quietest time windows for each channel. The data from these time windows were the basis of our subsequent analyses.

[7] For each of the five channels, we merged the quietest 1000 spectra to create a quasi-spectrogram, a spectrogram-like gray-scale plot with a discontinuous time axis. To facilitate the association of possible spectral lines with

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Table 1. Overview of Seismic Stations and Quietest Horizontal Data Channels

Station	Network	Latitude	Longitude	Sensor	Channel	Period
BFO	IRIS IDA	48.33°N	8.33°E	STS-1	VHE	1997–2006
BFO	GRSN	48.33°N	8.33°E	STS-2	LHE	1996–2006
TTO	F-net	35.84°N	138.12°E	STS-1	LHN	1999–2006
BJT	CDSN	40.02°N	116.17°E	STS-1	VHN	1994–2006
MAJO	IRIS USGS	36.54°N	138.21°E	STS-1	VHE	1996–2006

normal modes of the Earth, robust spectral estimates were obtained by computing the median psd at each frequency.

[8] To distinguish between spheroidal and toroidal mode energy, we made use of the duality between fundamental spheroidal modes and Rayleigh waves and between fundamental toroidal modes and Love waves. In the case of a detection of fundamental modes of the Earth, it should also be possible to detect the respective kinds of surface waves in the same data. To search for these surface waves, we applied a method introduced by *Ekström* [2001]. To detect background surface waves, he applied an inverse great circle dispersion operator to the seismograms. In the case of Rayleigh waves, this operator should ideally transform a R3 wave train into R1, R4 into R2 and so on. An operator for Love waves, which is different from that for Rayleigh waves, transforms G3 into G1 and G4 into G2. The detection of multi-orbit surface waves is then performed by cross correlating the original seismogram with the transformed one. A zero lag correlation significantly larger than zero indicates the presence of the respective kind of surface waves. After band-pass filtering the data between 2.5 and 10 mHz, we calculated such cross correlations for the 1000 quietest time periods of each channel and computed the median for each time lag to obtain a robust estimate of the correlation functions.

3. Results and Discussion

[9] The quasi-spectrogram and the respective median for the quietest of the five horizontal data channels, the VHE channel of the STS-1-E seismometer at BFO, are shown in Figure S1 (see auxiliary material[1]). While no modal structure is evident below 3 mHz even after the selection of the quietest periods, it is possible to discern several persistent spectral lines at higher frequencies. The regularity and the spacing of these lines resemble the hum observations made with vertical component data [e.g., *Suda et al.*, 1998; *Widmer-Schnidrig*, 2003]. The psd in this frequency band reaches the hum detection threshold of ≈ -178 dB which we have found for vertical component data.

[10] Figure 1 shows the median spectra for all five channels (see Table 1). To illustrate the quality difference

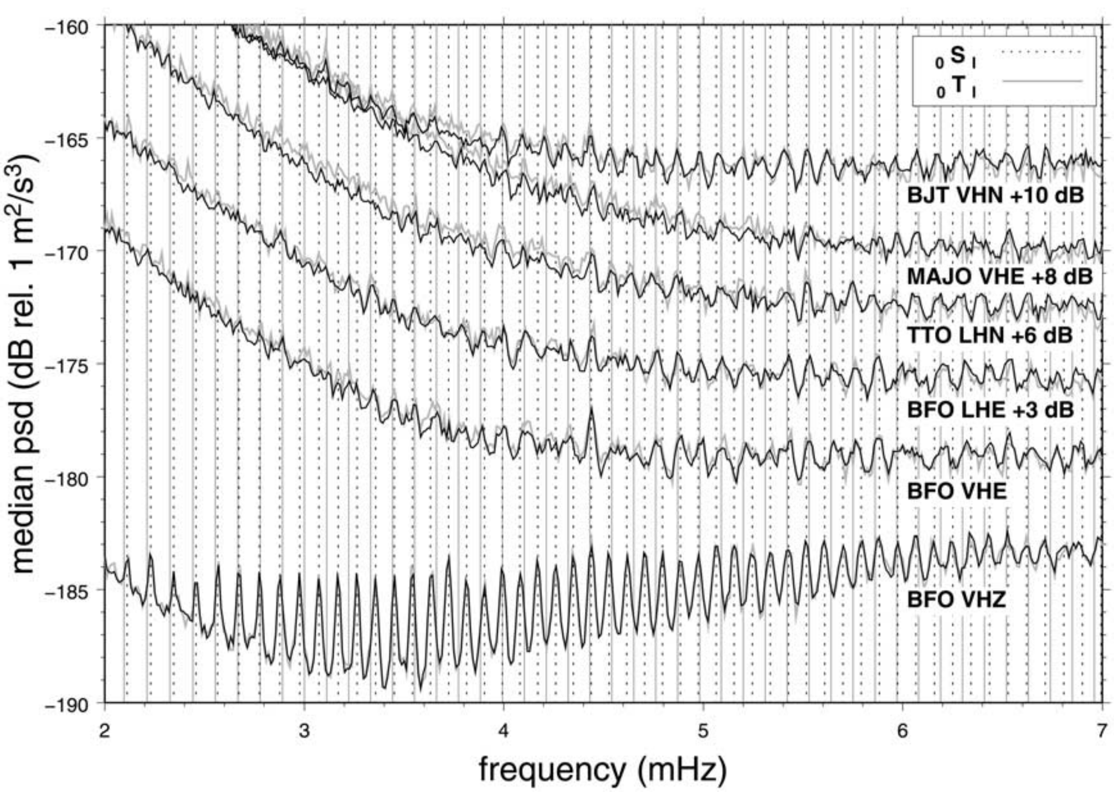

Figure 1. Comparison of median power spectral densities of the 1000 least noisy time windows from each of the sensors. For clarity, the spectra have been vertically shifted. Vertical lines mark the frequencies of fundamental spheroidal and toroidal modes. The underlying gray spectra were computed after the rejection of time windows affected by earthquakes with $M_W \geq 5.5$.

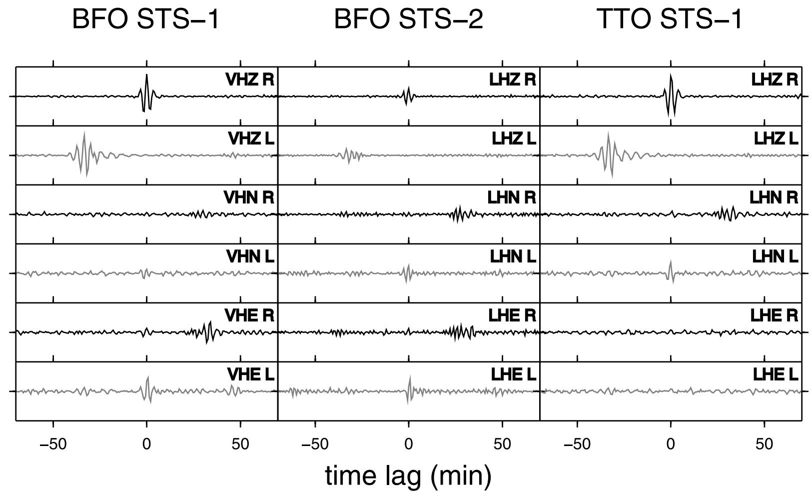

Figure 2. Correlation functions after inverse great circle propagation. For each chart, the data channel and the kind of surface wave (R-Rayleigh, L-Love) tested for are indicated. The ordinates range from −0.1 to 0.1 for the vertical and from −0.05 to 0.05 for the horizontal components. Rayleigh waves are evident in all vertical and at least two horizontal datasets. We detect Love waves in no vertical and five horizontal components.

between vertical and horizontal data, a spectrum for the vertical STS-1 at BFO (channel VHZ) is included. The vertical lines mark the frequencies of the fundamental spheroidal and toroidal modes from the Earth model 1066A [*Gilbert and Dziewonski*, 1975]. An unambiguous attribution of all observed spectral peaks to the fundamental spheroidal mode frequencies, as it is easily done for the vertical component spectra of quiet stations, is not possible in the horizontal case. This might be due to the extremely low signal-to-noise ratio as well as the presence of additional modes.

[11] Nonetheless, the five horizontal spectra exhibit a high similarity, indicating that the observed spectral structure is a property of the global seismic background and not a local effect.

[12] The data selection based only on signal power does not guarantee the exclusion of significant mode excitation through earthquakes. For the horizontal components, the total signal power is mainly determined by atmospheric conditions, so that even on a day of a large or moderate earthquake, the signal power can be relatively low when there are only small atmospheric disturbances. To make sure that the observed spectral structure is not due to earthquakes, we rejected all time windows affected by earthquakes with $M_W \geq 5.5$ and computed again the median spectra. These spectra which are also shown in Figure 1 (gray curves) are very similar to those computed from the 1000 quietest spectra. However, only 43%–46% of the data remained after this rejection procedure, and as a consequence, the median spectra are less smooth. Because of the small differences between the spectra before and after the elimination of earthquakes, we decided to refrain from rejecting more than half of the data hereinafter but to benefit from the enhanced statistical robustness provided by a larger dataset.

[13] Upon further inspection, we find that most of the spectral peaks which do not correspond to fundamental spheroidal mode frequencies, are located at fundamental toroidal mode frequencies. In the quietest horizontal spectrum, from the STS-1-E seismometer at BFO, we can assign all but three minor spectral peaks between 3 and 5 mHz to fundamental modes of the Earth, if we take spheroidal and toroidal modes into account. There is no clear indication for the presence of overtones. Due to the different spacings of spheroidal and toroidal modes, some toroidal modes lie between two adjacent spheroidal modes, whereas others coincide with a spheroidal mode. Although spheroidal and toroidal modes cannot be separately identified at such spheroidal-toroidal mode junctions, the particularly clear peaks and troughs near the junctions at 3.5, 4.0, 4.4, 5.0 and 5.4 mHz as well as the rougher psd in between argue for the assumption that the observed spectra are composed of the full set of spheroidal and toroidal fundamental modes.

[14] A few frequency bands where spheroidal and toroidal modes are clearly separated (near 3.2, 3.8 and 4.2 mHz) allow a comparison of the amplitudes for the two types of modes. In these bands, the amplitudes of spheroidal and toroidal modes agree within a fraction of 1 dB. For the continuous spheroidal oscillations, the noise-corrected vertical amplitude of an individual multiplet was shown earlier to be approximately 0.4 ngal [*Nishida and Kobayashi*, 1999]. Taking into account the theoretically predicted ratio of horizontal to vertical accelerations of about 0.7 in this frequency range, we infer that the horizontal amplitudes of the spheroidal hum should be around 0.3 ngal. Thus we estimate the spectral amplitudes of the continuous toroidal oscillations to be about 0.3 ngal, too.

[15] A striking feature of the spectra in Figure 1 is the raised amplitude of the peak at 4.4 mHz. An obvious explanation for this might be the coincidence of two fundamental modes, ${}_0S_{37}$ and ${}_0T_{35}$, at this frequency. However, at other spheroidal-toroidal mode junctions, we cannot observe such an enhanced spectral amplitude. An alternative explanation might come from previous observations of narrowband mode excitations due to resonant coupling between the atmosphere and the solid Earth near 3.7 and 4.4 mHz. Two well documented cases are the Mount Pinatubo eruption in 1991 [*Kanamori and Mori*, 1992;

Widmer and Zürn, 1992] and the vertical hum [*Nishida et al.*, 2000].

[16] The spectra in Figure 1, however, show no amplification at 3.7 mHz. Since these two resonances are always observed together, we consider it unlikely that the prominent spectral peak at 4.4 mHz is due to a resonant coupling between the atmosphere and the solid Earth. Thus the enhancement at 4.4 mHz remains to be explained.

[17] To further verify that both spheroidal and toroidal modes are permanently excited, we applied inverse great circle dispersion operators for Rayleigh and Love waves to the data from BFO and TTO and correlated the obtained seismograms with the original ones, as described in section 2. To appraise the significance of the correlation functions, we performed this analysis for all three components and for both kinds of surface waves. As a robust representation of the correlation function, we chose again the median. The resulting cross correlations are shown in Figure 2.

[18] As expected, the zero lag correlation is maximum for the case Z component/Rayleigh waves and vanishes for the case Z component/Love waves. However, there are also positive correlations for the quietest horizontal components.

[19] We see indications of Love waves on five horizontal channels (BFO VHE, VHN, LHE and LHN; TTO LHN) and, moreover, signs of Rayleigh waves for at least two horizontal channels (BFO VHE and LHE). The wave trains at a time lag of approximately ±30 min which can be seen in some correlation functions result from the application of the inappropriate inverse dispersion operator to the data: A Rayleigh wave operator for data containing Love waves or vice versa. The lack of any surface wave detection for TTO LHE is due to a higher noise level. These data were only included for completeness.

[20] Thus there is twofold indication that not only the fundamental spheroidal modes but also the fundamental toroidal modes of the Earth are continuously excited: We found (1) numerous toroidal mode peaks in the median spectra and (2) seismic waves circling the globe with the dispersion properties of Love waves.

[21] Since the physical mechanisms giving rise to the continuous spheroidal mode excitation have not been unambiguously identified up to now, any discussion of possible sources of the toroidal hum must necessarily remain speculative. However, the spectral amplitude of ≈0.3 ngal estimated above is too high to be caused solely by spheroidal-toroidal mode coupling through the Coriolis force or heterogeneous structure. Furthermore, we can rule out cumulative effects of small earthquakes because these were shown to be at least one order of magnitude too small for the permanent spheroidal mode excitation [*Kobayashi and Nishida*, 1998; *Suda et al.*, 1998; *Tanimoto et al.*, 1998; *Tanimoto and Um*, 1999]. As it has already been stated for the spheroidal hum, the dominance of fundamental modes argues for an excitation near the surface [e.g., *Suda et al.*, 1998].

[22] None of the theoretical models for the excitation of the hum has predicted the excitation of toroidal modes so far. All these calculations were focused on the excitation of fundamental spheroidal modes or Rayleigh waves, respectively, by pressure variations exerted on the surface or the seafloor. *Tanimoto* [2007] found also a horizontal forcing term, though for Rayleigh waves instead of Love waves. Given the topography and bathymetry of the Earth's surface, pressure forces which act normal to the surface necessarily also involve a horizontal component that can potentially lead to a toroidal mode excitation. However, in light of the small average slope of the Earth's surface, this mechanism most likely does not lead to comparable excitation levels for toroidal and spheroidal modes as they are observed in the data. Future studies will have to show whether shear stresses exerted on the Earth's surface by winds in the atmosphere or bottom currents in the oceans, surf beats on the coasts or yet another mechanism can produce the toroidal hum amplitudes reported here.

4. Conclusions

[23] For the first time, we showed that it is possible to detect the continuous excitation of normal modes with data from horizontal seismometers. We demonstrated the presence of persistent spectral lines between 3 and 7 mHz in horizontal long-period spectra at four very quiet observatories. Although we could not unambiguously assign Earth modes to all observed spectral lines, we see indications for a superposition of fundamental spheroidal and toroidal background oscillations of the Earth.

[24] In addition, we searched the data for globe-circling surface waves and found indications for a long-period horizontal seismic background made up of both Love and Rayleigh waves together. This further supports our finding that, besides the intensely studied spheroidal background oscillations, there is also a toroidal hum of the Earth. Even though it is not clear if the spheroidal and the toroidal hum have a common source, it will be necessary to develop new theoretical models to explain the permanent excitation of the fundamental toroidal modes of the Earth.

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