Origin of Earth's ground noise from 2 to 20 mHz

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[1] Long-period seismology probes the Earth's interior through the seismic passband in a period range from 50 to 500 s. The limitation of seismic transparency in this band is known but the source of limitation has been a long-standing puzzle. Here we report evidence that the transparency is limited, over the entire passband, by fundamental Rayleigh waves excited by global and random sources in a thin layer just above the Earth's surface. *INDEX TERMS:* 7255 Seismology: Surface waves and free oscillations

1. Introduction

[2] Earth's vertical ground noise spectrum at a quiet site is not flat in acceleration but possesses a marked minimum in a frequency range from 2 to 20 milli-Hertz (mHz) [*Agnew and Berger*, 1978]. Long-period seismology has been developed in this seismic passband, where the highest S/N ratio can in general be achieved for waveform analyses [*Agnew et al.*, 1986; *Gilbert*, 1980]. Broadband seismometers have been designed so that they can record the lowest ground noise in this band [*Wielandt and Streckeisen*, 1982; *Wielandt*, 1983]. Such instrumental development has established the lowest level of vertical ground noise (not of instrumental origin), leading to the New Low Noise Model (NLNM), yet it remains to be answered what vertical ground noise in the passband is and how it is excited [*Peterson*, 1993]. A hint to answer these questions comes from the recent discovery of Earth's background free oscillations in a frequency range from 2 to 7 mHz [*Kobayashi and Nishida*, 1998; *Nawa et al.*, 1998; *Suda et al.*, 1998], where the vertical ground noise spectra at quiet sites show distinct peaks of the fundamental spheroidal modes with modal amplitudes on the order of 1 nano gal (=10^{-11} m s^{-2}). Amplitudes of the modes vary annually and some of them are acoustically coupled with modes of atmospheric free oscillations [*Nishida et al.*, 2000; *Tanimoto and Um*, 1999]. These observations indicate that Earth's free oscillations mark the lowest level of ground noise in a frequency range from 2 to 7 mHz and that they are likely to be excited by atmospheric disturbances in the lowest part of the convection zone of the troposphere. However, the observations have been limited to only the lowest one forth of the seismic passband. In the rest of the passband, identification of individual free oscillation modes, if they exist, is hampered by peak broadening of the modes due to Earth's anelasticity and asphericity. A time-domain detector of long-period surface wave energy was also used to investigate Earth's background free oscillations [*Ekström*, 1998] but the detection was limited in a frequency range from 2.5 to 6 mHz. We, for the first time, report evidence that the ground noise in the entire passband consists of globally and randomly generated fundamental spheroidal modes or, equivalently, Rayleigh waves.

2. Analysis

[3] We analyze continuous records sampled every 10 seconds in a time period from 1988 to 2000 through the very-long-period high-gain channel from the vertical STS-1 seismometers at 49 stations at the lowest ground noise level (slightly less than 10^{-18} m^2 s^{-3} in the seismic passband). The records are provided by the Incorporated Research Institutions for Seismology Data Management Center (IRIS DMC) [*IRIS*, 1994]. For each station, we remove glitches and divide the whole record into about 5.6 hour segments with an overlap of 1 hour. The 5.6 hour window corresponds to the travel time of a Rayleigh wave traveling about twice around the Earth. Each time segment is Fourier-transformed to obtain the power-spectrum. The spectrum might have been disturbed by transient phenomena such as earthquakes and local nonstationary ground or instrumental noise. We discard all the seismically disturbed segments which are defined in terms of the mean power spectral densities (PSDs) greater than 10^{-18} m^2 s^{-3} in a frequency range 2.5–7.5 mHz. We also discard noisy segments if their mean PSDs over the four frequency ranges, 2.5–7.5, 7.5–12.5, 12.5–17.5, and 17.5–22.5 mHz, are greater than 3×10^{-18} m^2 s^{-3}.

[4] The free oscillation approach in the previous studies [*Kobayashi and Nishida*, 1998; *Nawa et al.*, 1998; *Suda et al.*, 1998] is essentially a single station analysis. Lack of spatial information in this approach limits detection of relatively high frequency modes above 7 mHz. Our multiple station analysis differs from the previous one in that we utilize both temporal and spatial information contained in the records with the assumption of stationary stochastic waves [*Aki*, 1957, 1965]. We calculate the cross-spectra $\Phi_d(\Theta, f)$ between every pair of different stations for their common record segments, where Θ is the separation distance between a station pair, and f is frequency. The cross-spectra are then stacked for each pair of stations, assuming that $\Phi_d(\Theta, f)$ at f depends only on Θ. This assumption presumes ground noise to be stationary stochastic waves generated by laterally homogenous and horizontally isotropic random excitation sources. Figure 1 plots the stacked cross-spectral value at 3.71 mHz as a function of Θ, indicating a characteristic oscillation of $\Phi_d(\Theta, f)$ with respect Θ. This oscillation is reasonably well modeled by the 29th-order Legendre function, a curve shown in Figure 1 as a reference. A better modeling may be done by a linear combination of the Legendre functions with different orders:

$$\Phi_m(\Theta, f) = \sum_{l=0}^{l_0} \alpha_l(f) P_l(\cos \Theta), \qquad (1)$$

where P_l is the Legendre function of the l'th order (l is the number

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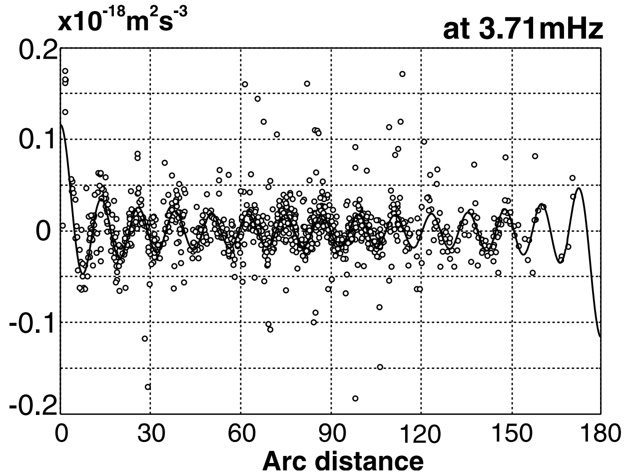

Figure 1. Plot of the real part of the stacked cross-spectral density as a function of station separation distance at a fixed frequency of 3.71 mHz. The Legendre function with angular order of 29 is superposed as a reference.

of horizontal nodes) and the summation is taken over the angular orders up to 200.

3. Results and Discussion

[5] We determine the coefficients $\alpha_l(f)$ by minimizing the squared difference between data Φ_d and model Φ_m. In Figure 2 we plot the value of $\alpha_l(f)$ so obtained as a function of angular order l and frequency f, yielding the wavenumber-frequency spectrum of ground noise. The spectrum exhibits a distinct dispersion curve of the fundamental Rayleigh waves over a frequency range from 2 to 20 mHz (from 15 to 200 in angular order). Note that the power spectral density (PSD) of the ground noise averaged over stations is represented as

$$\Phi_m(0, f) = \sum_l \alpha_l(f), \qquad (2)$$

but that such PSD representation is unable to resolve spectral peaks of the fundamental spheroidal modes at frequencies higher than 7 mHz. We have been able to identify the signal by decomposing ground noise into the wavenumber-frequency domain. Figure 2 also exhibits a curve corresponding to the first overtone branch from 2 to 4 mHz (from A to B). It is in general difficult to detect weaker signal at higher frequencies or along other overtone branches in part because of a spatial alias of the energy along the fundamental dispersion branch and in part because of a limited improvement of the S/N ratio by stacking in the presence of asphericity of the Earth structure which makes the cross-spectra path-dependent.

[6] We can calculate the PSD of the fundamental Rayleigh waves by restricting the summation of $\alpha_l(f)$ in equation (2) to an appropriate range of l. The range of l we chose corresponds to ±2% of the theoretical phase velocity of the fundamental Rayleigh waves for the Earth model PREM [*Dziewonski and Anderson*, 1981]. Figure 3 shows the PSDs of the fundamental Rayleigh waves so obtained, which are compared to the New Low Noise Model (NLNM) [*Peterson*, 1993]. In the model of NLNM the PSD increases rapidly with decreasing frequency below 2 mHz due most probably to the Newtonian attraction of air mass fluctuation [*Zürn and Widmer*, 1995]. Above 20 mHz, on the other hand, the PSD increases rapidly with increasing frequency due probably to the wave breaking of ocean swell known as

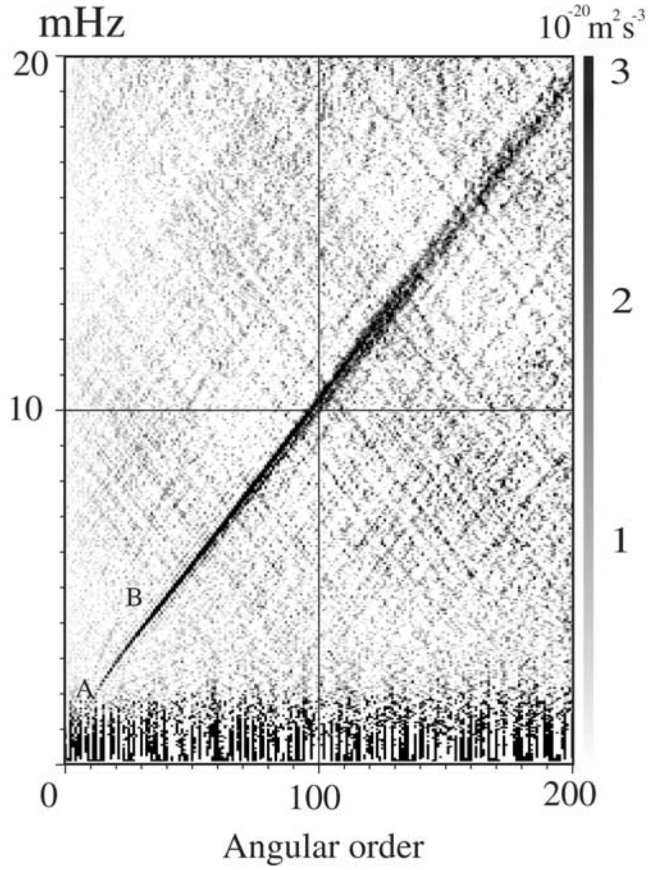

Figure 2. Wavenumber-frequency spectral representation of the ground noise. The wavenumber is given by the angular order l, which corresponds to the wavelength $2\pi R/(l + 1/2)$, where R is the radius of the Earth. This illustration shows strong energy concentration along the fundamental mode branch up to angular order 200 and weak energy concentration along the first overtone branch (from points A to B). Stripes along the fundamental dispersion branch and those in mirror symmetry are due to spatial alias of the energy of fundamental Rayleigh waves.

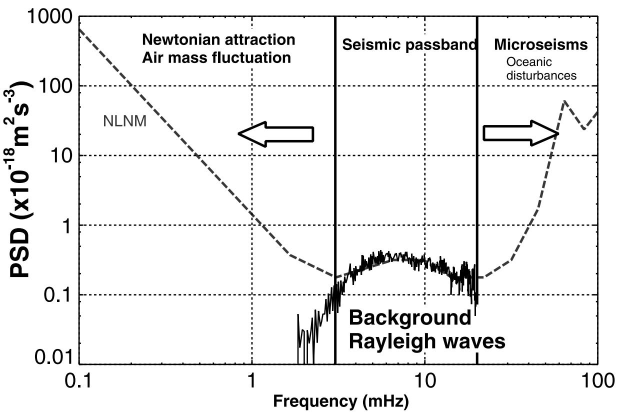

Figure 3. Comparison of the PSDs of the background fundamental Rayleigh waves (solid line) to those of the ground noise (broken line) in the New Low Noise Model (NLNM) [*Peterson*, 1993]. They coincide with each other in the almost entire seismic passband from 2 to 20 mHz. The model PSD increases rapidly with decreasing frequency below 3 mHz because of the gravitational effect of air mass fluctuation [*Zürn and Widmer*, 1995], and with increasing frequency above 20 mHz because of the microseisms effect [*Hasselman*, 1963].

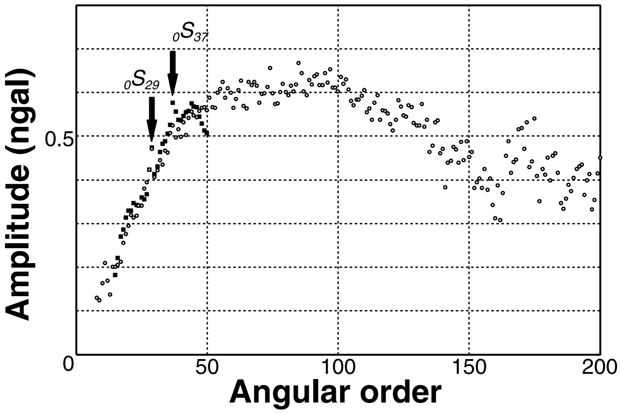

Figure 4. Rms amplitudes of the fundamental spheroidal modes (fundamental Rayleigh waves). Open circles show the modal amplitudes obtained in the present study. Closed squares in the lower frequency range indicate the modal amplitudes obtained through the normal mode approach [*Nishida et al.*, 2000]. The modes denoted as $_0S_{29}$ and $_0S_{37}$ are theoretically expected to be coupled with acoustic free oscillations in the atmosphere.

microseisms [*Hasselman*, 1963]. The band in between represents the seismic passband where a local extremum occurs near 8 mHz. The existence of this local extremum is known but its cause has been poorly understood [*Peterson*, 1993]. The PSDs of the fundamental Rayleigh waves we detected coincide remarkably well with the PSDs of the NLNM over almost the entire passband from 3 to 20 mHz, including the local extremum near 8 mHz, indicating that the transparency in the passband is limited by the Rayleigh waves.

[7] The excitation of these Rayleigh waves must be global and random, otherwise our wavenumber-frequency approach would not work efficiently. The global and random nature of the excitation sources has been studied extensively for the background free oscillations in a limited frequency range below 7 mHz [*Nishida and Kobayashi*, 1999]. It can be shown from the amplitude comparison that these background free oscillations are of the same phenomena as the Rayleigh waves we detected. We calculate the rms amplitude of the spheroidal mode with an angular order l from the wavenumber-frequency spectrum shown in Figure 2 by summing the coefficients $\alpha_l(f)$ with successively different f over an appropriate frequency band. The frequency band we choose corresponds again to ±2% of the theoretical phase velocity of the fundamental Rayleigh waves for PREM [*Dziewonski and Anderson*, 1981]. The sum is then multiplied by the frequency interval and then a square root is taken to obtain the modal rms amplitude. Figure 4 shows a comparison of the modal amplitudes so obtained (open circles) with those obtained in the normal mode approach (closed squares). The two measurements overlap in an angular-order range below 50 (frequency range from 2 to 5 mHz), where the measured values agree remarkably well with each other. This agreement indicates that the Rayleigh waves we detected are of the same phenomenon as the background free oscillations investigated in detail in the previous studies. In Figure 4, two types of measurements consistently show the excess amplitude at angular order 29 due most probably to acoustic resonance between the solid Earth and the atmosphere [*Nishida et al.*, 2000]. Comparison of the frequency of these excess amplitudes with those associated with the 1991 Pinatubo eruption [*Kanamori and Mori*, 1992; *Widmer and Zürn*, 1992] suggests that the excitation sources of the background Rayleigh waves lie in a thin layer just above the Earth's surface. The observed amplitudes of the overtones are by an order of magnitude smaller than those of the fundamental modes, supporting the idea that they are generated near the Earth's surface [*Fukao et al.*, 2001].

[8] The spectral amplitude of the ground noise below 7 or 8 mHz can be explained quantitatively by an atmospheric excitation theory [*Fukao et al.*, 2001]. In this theory the spectral amplitude of air pressure fluctuation follows a power-law decay in a consistent manner with the observations, and its coherence length decreases slowly with increasing frequency to a value of 600 m at 8 mHz. A straightforward extrapolation of this theory beyond 8 mHz predicts further increase of modal amplitude with increasing frequency, while the observed modal amplitude decreases with increasing frequency above 8 mHz so that it begins to deviate from the theory near 8 mHz. We suggest two possible mechanisms for this deviation. The first mechanism invokes a change of physical processes of atmospheric disturbances at about 8 mHz, accompanying changes of the frequency dependences of the rms amplitude and coherence length of air pressure fluctuations. The second possible mechanism is to consider the role of oceans. We suggest that oceans might act as a buffer to transmit atmospheric disturbances to the ocean bottom at frequencies above 8 mHz, in part because oceanic disturbances may spread away horizontally more rapidly than atmospheric disturbances and in part because the transmission to the ocean bottom of oceanic disturbances may be limited by the skin depth effect.

[9] Our approach of calculating the wavenumber-frequency spectrum with the assumption of stationary stochastic waves has enabled us to detect background Rayleigh waves along the fundamental dispersion branch in the entire seismic passband from 2 to 20 mHz. Their modal amplitude has a local extremum near 8 mHz, where some change in the statistical properties of the random excitation sources is suggested.

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