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Earth's continuous oscillations observed on seismically quiet days

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Abstract. Analysis of IDA gravimeter data between 1983 and 1994 and GEOSCOPE data between 1988 and 1994 show that fundamental modes of the Earth, for frequencies between 2 and 7 mHz, are excited even on seismically quiet days. Amplitudes of acceleration are slightly less than one $ngal(10^{-9}gal)$. Examination of a sequence of shorter time interval records suggests that the Earth is oscillating continuously. Currently, both atmospheric excitation and tectonic motions are possible cause(s) of these oscillations.

Introduction

Nawa et al. [1997] recently reported that the Earth may be oscillating continuously irrespective of earthquake occurrence. Their data covered the period from 1993 to 1995 and showed continuous fundamental mode peaks that did not correlate with occurrence of large earthquakes. While their superconducting gravimeter data was high quality, one of the shortcomings was its short time interval of only a few years. The main aim of this paper is to examine this phenomenon by IDA gravimeter data and GEOSCOPE data which provide longer observation records.

The particular questions we wish to examine are (1) whether there is evidence for continuous oscillations and (2) whether there is evidence for seasonal and annual variations in the data. The first question has priority in our investigation and is affirmatively answered in this paper. The second question is examined because it may provide some perspective as to the cause of these oscillations. The observed oscillations can be caused by either (i) tectonic effects or (ii) atmospheric effects. Cumulative effects of small earthquakes (smaller than $5 \times 10^{16} N \cdot m$) and silent earthquakes (*Beroza and Jordan,* [1991]) are possible examples for tectonic effects, although the former is very unlikely. Atmospheric effects (mainly wind effects) can also generate acceleration on the order of a nanogal (*Tanimoto,* [1997]; *Fukao et al.*, [1997]) through atmosphere-solid earth couplings. In order to understand further details on this coupling, however, much more elaborate study is required than this short letter. This paper will mainly concentrate on establishing the existence of continuous oscillations.

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This distinction between tectonic effects and atmospheric effects may have far-reaching consequences, because it may lead to a new avenue for future planetary observation; if the observed continuous oscillations are caused by atmospheric effects, one can reasonably expect that similar fundamental mode excitation is occurring in inner (Earth-like) planets (*Kobayashi and Nishida*, preprint). It then implies that fundamental mode oscillations of such planets may be detected by installing broadband instruments; the key is that quakes are not required to excite such oscillations. On the other hand, if the observation is shown to be caused by small earthquakes or silent earthquakes, it must be concluded that tectonic motion is required to excite such oscillations; possibilities of detecting fundamental modes are greatly reduced in tectonically quiet planets. Therefore, it is important to distinguish whether such motions are caused by atmospheric effects or tectonic effects.

Data Analysis

Our analysis proceeds in the following way; we first apply the Hanning window to data for a time-series length (T) of 24 hours and transform the data to the Fourier spectral domain. Mathematically, our operation is described by

$$U(\omega) = \frac{4}{T} \int_0^T w(t)u(t)e^{-i\omega t}dt \qquad (1)$$

where $w(t)$ is the Hanning window, $u(t)$ is the time series and ω is the angular frequency. The coefficient $4/T$ exists so that, if $u(t)$ has a sinusoidal form of $A\cos(\omega t)$ or $A\sin(\omega t)$, spectral amplitudes become equal to $A = |U(\omega)|$ for the frequency range of interest. We then remove instrument response effects from $U(\omega)$ by division and convert it to acceleration. This is hereafter referred to as $F(\omega)$.

In order to examine existence of continuous oscillations, it is necessary to minimize effects from earthquakes as much as possible. We have adopted the following criteria to do this; (1) remove all data if earthquakes were reported in the Harvard moment tensor catalogue in the same day, which basically removes data from the days that had earthquakes with moment $5\times10^{16}(N\cdot m)$ or larger; (2) remove data for 5 days after earthquakes with moment larger than $5 \times 10^{19}(N \cdot m)$ (about magnitude 7); (3) remove data for 3 days after earthquakes with moment between 10^{18} and 5×10^{19}

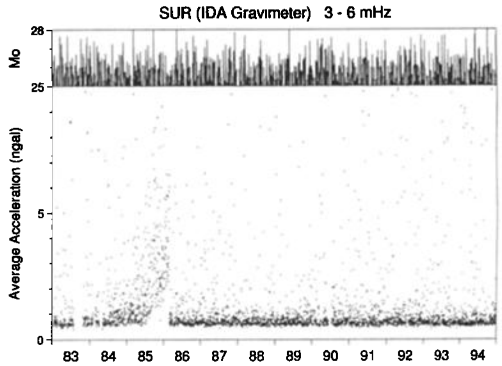

Figure 1. Average acceleration between 3 and 6 mHz for an IDA gravimeter station, SUR. All data are plotted, including large earthquakes. Moments from the Harvard moment tensor catalogue are shown at top.

($N \cdot m$); (4) examine data visually to check existence of small earthquakes or surface wave trains and remove data if such wave trains existed. Visual examination is critical since most available catalogues (PDE, ISC and Harvard moment tensor catalogue) are not perfect even for their intended threshhold (e.g. *Shearer*, [1994]; *Ihmle and Jordan*, [1996]; *Rouland et al.*, [1992]).

Data with glitches were avoided, although tides were not removed from data, since they do not affect spectral analysis in the frequency range of our interest (above 1 mHz). An example of spectral amplitude at an IDA station (SUR, South Africa) is given in Fig. 1. Concentration of points near 0.5 (*ngal*) indicates that the detection limit of IDA gravimeter data is about this value. We will basically examine data near this detection limit.

Removal of many data by the above criteria for SUR led to seismograms in Fig. 2a. For the period between

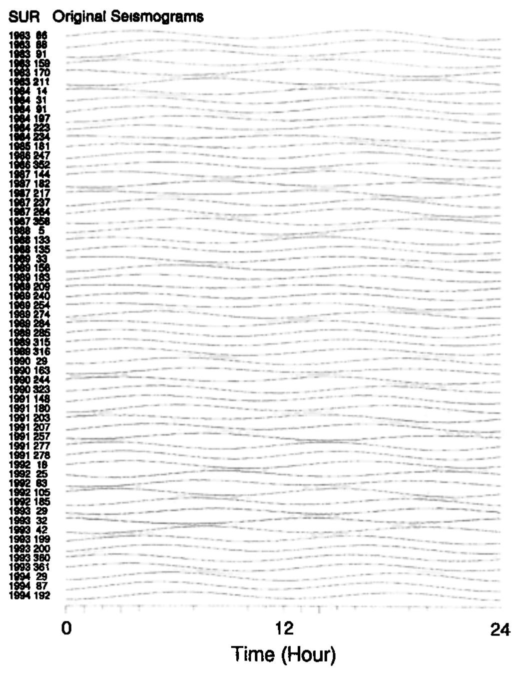

Figure 2a. Selected seismically quiet days for SUR. There are 61 days for period between 1983 and 1994.

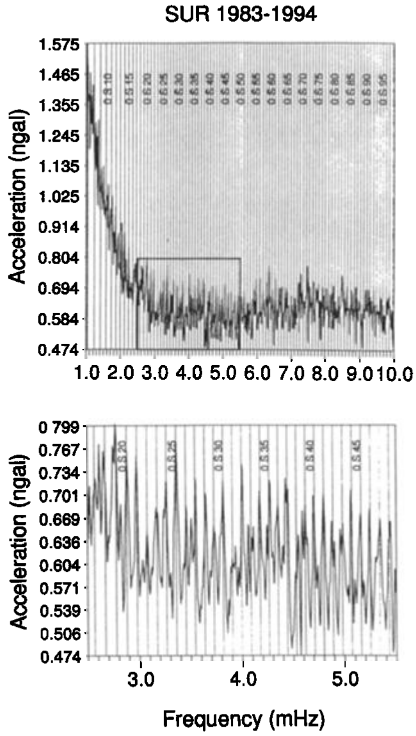

Figure 2b. Averaged spectra from 61 seismically quiet days at SUR for frequencies between 1 mHz and 10 mHz (top) and an enlarged figure between 2.5 mHz and 5.5 mHz (bottom).

1983 and 1994, we identified 61 days that satisfy our criteria for seismically quiet days. Similar analyses for ESK (Scotland) and PFO (Southern California) yielded 48 and 42 days respectively.

Fig. 2b shows the stacked (averaged) spectral amplitude at SUR from 61 selected days. The top figure shows spectra for frequency between 1 and 10 mHz and the bottom figure shows an enlarged figure between 2.5 and 5.5 mHz. A box outlined in the top figure indicates the enlarged portion. Vertical lines indicate fundamental mode frequencies of an Earth model PREM (Dziewonski and Anderson, 1981). The top figure shows the well-known trend for seismic noise (e.g. Peterson, 1993) with a flat portion above 3 mHz and rapidly increasing portion below 3 mHz. While correlation of spectral peaks with fundamental mode frequencies are hard to identify in the top figure, the enlarged (bottom) figure shows that many peaks between 2.5 and 5.5 mHz match fundamental mode frequencies. In fact, this match occurs over a slightly wider frequency range, approximately between 2 and 7 mHz, and becomes ambiguous outside this frequency range. Similar features are found for ESK and for PFO.

There are, however, some peaks that exist between adjacent fundamental mode peaks in Fig. 2b. They do not match overtone frequencies nor toroidal mode peaks. They also vary from one station to another, and suggest that they are due to some noise at each station.

There are also some fundamental mode peaks that seem to be split, but this feature also changes for each station. Some splittings are clearly too large to be explained by the Earth's three-dimensional structure effect. Stack of all three stations (Fig. 2c) tends to sup-

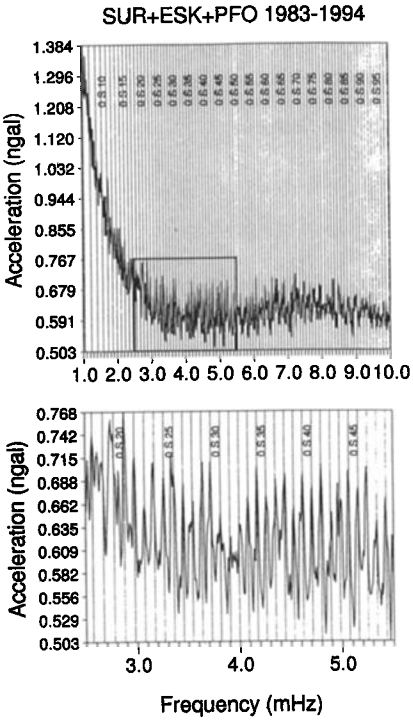

Figure 2c. Averaged spectra from three stations, SUR, ESK and PFO, for frequencies between 1 mHz and 10 mHz (top) and an enlarged figure between 2.5 mHz and 5.5 mHz (bottom). The number of quiet days are 48 and 42 for ESK and PFO, respectively.

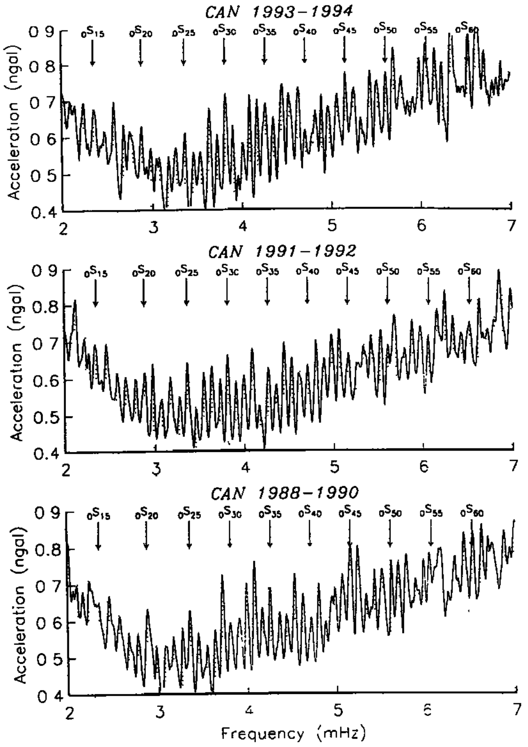

Figure 4. Spectral amplitudes from a GEOSCOPE station, CAN (1988-1994). Results from three short intervals, 1993-1994, 1991-1992, 1988-1990 are plotted from top to bottom. These fundamental modes seem to be excited continuously.

press such peaks and thus seems to support the view that they are caused by noise.

We do not understand why some peaks are not as well excited as other modes. For example, mode ${}_0S_{31}$ has low amplitude in comparison to other modes. It is not likely that the three-dimensional structure effect can single out this particular mode nor earthquakes can create this feature easily. Also GEOSCOPE station CAN in Fig. 4 does not show such a feature. It may be possible if the source is not earthquake, but we should postpone such a speculation to a later discussion.

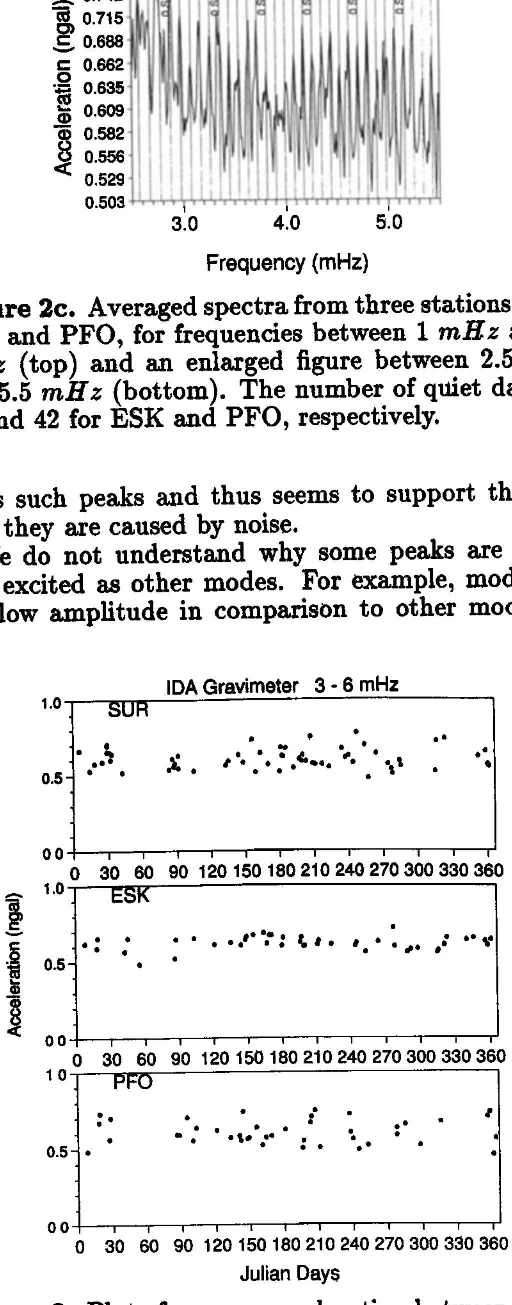

Figure 3. Plot of average acceleration between 3 mHz and 6 mHz against the Julian days. If seasonal variations existed, they should show up in this plot. However, there is no hint of seasonal variations.

Fig. 3 displays average acceleration between 3 mHz and 6 mHz, computed by

$$A2 = \frac{1}{f_2 - f_1} \int_{f_1}^{f_2} |F(f)| df, \qquad (2)$$

where $f_1 = 3mHz$ and $f_2 = 6mHz$. The horizontal axis is the Julian day and the vertical axis is average acceleration. The data between 1983 and 1994 were folded onto the Julian day of each datum; any significant seasonal variations should emerge in this type of plot. Seasonal variations are important criterion to constrain the cause of continuous oscillations, because if seasonal variation existed, it would be more natural to accept the atmospheric origin of these oscillations. Fig. 3 shows, however, that there is virtually no evidence of seasonal dependence in excited amplitudes.

As a check for the temporal behavior, we examine GEOSCOPE data (1988-1994). IDA data do not provide good S/N for short time intervals as in Fig. 4. We divide the period into three 2-3 year intervals, 1988-1990, 1991-1992, and 1993-1994, and examine spectral amplitudes in each period in a similar manner to the above analysis. Fig. 4 shows the results for CAN. The top figure shows the spectral amplitude for 1993-1994, the middle for 1991-1992, and the bottom for 1988-1990. Peaks at fundamental mode frequencies are recognized in all plots for frequencies between 2 and 7 mHz. Amplitudes of excitation are about the same level throughout the six years, indicating that excitation is not due to a particular transient phenomenon.

Discussion

Our main question is the cause of these oscillations. These oscillations can be caused by tectonic motions such as cumulative effects of small earthquakes (less than moment $5 \times 10^{16} N \cdot m$ or about magnitude 5), silent earthquakes (*Beroza and Jordan* [1991]) or atmospheric excitations (e.g. *Tanimoto*, [1997]). While we do not know the answer yet, our data provide some clues to this question.

First of all, it should be noted that frequency dependence of spectral amplitude is different from that of earthquakes; amplitude of excitation (in acceleration) shows that it is almost flat above 3.5 mHz and has an increasing trend below 3.5 mHz. Flatness of spectra above 3.5 mHz tends to suggest that this is not caused by earthquakes, because the frequency range (2-7 mHz) is much below the corner frequencies of large earthquakes; in such a frequency range, displacement, rather than acceleration, should be flat in this frequency range. This argument, however, may be challenged, considering the fact that the frequency range of these modes is narrow and scattering effects can decrease amplitudes at higher frequencies (pointed out by a reviewer, P. Ihmle). This is an important point but may not apply here, because stacking analyses of data with earthquakes tend to show increasing amplitude with frequency, which is not seen in Fig. 2b or Fig. 2c. Such analyses do not necessarily show well-resolved fundamental mode peaks, perhaps because of scattering effects, but do show higher amplitude for higher frequency.

In addition, the increasing trend of amplitudes below 3.5 mHz may be important; note that some peaks seem to become higher for lower frequency modes. Some modes appear to rise above the (rising) background noise level for frequencies below 3 mHz. While this needs further observational verification, it is interesting because it cannot be explained by earthquakes; on the other hand, this trend can be easily explained by atmospheric excitation if atmospheric motion has turbulence which is approximated by the Kolmogorov scaling law (*Tanimoto*, [1997]).

Cumulative effects of small earthquakes is not likely to be the cause because of the following reason; statistical analysis of the IDA and GEOSCOPE data indicates that average acceleration due to magnitude 5 event (the cut-off level) is close to the detection limit, 0.5 $ngal$, or even smaller for the frequency range of our interest (2-7 mHz). Rate of occurrence of earthquakes is such that there are, on the average, ten times more events for a decrease of magnitude by one (Gutenberg and Richter's law); on the other hand, amplitude in the frequency band 2-7 mHz is proportional to moment, thus decreases by thirty (1/30) for a decrease of magnitude by one. If each small event contributes randomly, combined effect is $\sqrt{10} \times 1/30 \approx 1/10$ from events at magnitude one below the cutoff. Cumulative effect from all events below the cutoff is then $0.5 \times (1/10 + 1/10^2 + \cdots) = 0.06(ngal)$. Clearly, this is much too small to be observed. If all events contribute constructively, then it becomes $0.5 \times (1/3 + 1/3^2 + \cdots) = 0.25(ngal)$. This estimate is the maximum and becomes closer to the detection limit (especially for GEOSCOPE data), but it is still smaller than the observed signal. Real cumulative effect from small events is likely to be smaller than this estimate. Therefore, cumulative effect of small events is not likely to be the cause of excitation.

Consequently, there remain two possible causes, silent (slow) earthquakes and atmospheric effects for the observed oscillations. However, resolution of this problem is left for the future.

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