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Supporting Information for

First observation of the Earth's permanent free oscillations on Ocean Bottom Seismometers

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Introduction

The text S1 explains how the broadband ocean bottom seismometer setup (hard- and software) may cause the glitch in the RHUM-RUM dataset and in datasets where similar seismometers are used. We suggest some changes for future expeditions. In the text S2 we outline the methodology of using autocorrelation to retrieve the hums eigenmodes in the RHUM-RUM data. The figures S1 and S2 accompany the text S2.

Text S1.

The glitch explained

Our broadband OBS data contain several nearly-periodic impulsive electronic signals, or glitches. Their shapes and periodicities vary slightly between stations, and occasionally also vary in a single station. The largest glitch occurs every hour and is triggered by a software-controlled, hourly check of the mass positions. The same glitch is present in datasets from previous deployments such as: the 2006–2007 PLUME data set around Hawaï [Laske et al., 2009]; and the SISMANTILLES and OBSANTILLES projects in the Lesser Antilles subduction zone in early 2007 [Hirn et al., 2010; Bécel et al., 2011]. There is a published mention of the hourly glitch [Bécel et al., 2011], but no glitch-removal procedure was yet published. Moreover, after preprocessing we find smaller glitches with periods of 2.6 hours and 24 hours, most likely caused by writing operations on the hard disk. The hourly glitch interferes with a free-mode analysis because it has harmonics every 0.276 mHz in the free-mode band, close to approximately every third mode.

It has been known for some time that addressing the serial interface of the T240 seismometer causes a small transient signal in the seismic signal. The resulting glitch signal is much stronger in our OBS data than on a land station due to a ground loop in the cable connecting the seismometer sphere to the central unit. This cable has only six wires: ground, power, serial communication, and three single-ended seismic signal wires. Communication signals and varying power consumption cause currents through the ground wire, and since the wire and the connectors have a resistance, they also cause a voltage drop along the wire. The digitizer sits in the central unit and responds to the differential signal between the seismometer output and the near end of the ground wire, which includes the voltage drop. Any current-consuming operation such as activating the serial interface or re-centering the mass is then reflected in the seismic data. Besides the electric effect in the cable, any operation that changes the power consumption of the seismometer will also change its temperature and may therefore produce a slow transient in the seismic signals. We think that this explains the long tail of the hourly glitch. Though the hourly glitch can be avoided by reprogramming the leveling check to occur at longer intervals, a long period glitch would still remain.

In order to reduce the effect of the glitch, we propose to eliminate the ground loop in a future experiment. This requires changing the hardware by using separate ground wires for the analog seismometer channels and for the power supply. The number of wires in the cable can remain the same when the digital communication signal is superimposed to the supply voltage with a modulator-demodulator (modem) technology. A small glitch might remain present as the mass check remains to be done by a serial link inside the seismometer.

Noise reduction on the OBS: pre-processing and linear regression

In order to reduce processing time for this study concerned with long-period seismograms, we start by resampling the data of the vertical, pressure and two horizontal channels from 62.5 to 0.625 Hz. Figure 1 (a) in the main text shows the resampled data of the vertical component of station RR28 in blue. The following steps were applied to monthly data segments. We subtract the mean of each channel, and filter the data between 2 and 30 mHz using a Butterworth lowpass filter (corner frequency of 30 mHz) and a Butterworth high pass filter (corner frequency of 2 mHz). After preprocessing the nearly hourly glitch becomes visible.

After the hourly glitch removal, long period glitches are still present in the data, but are hidden in the noise. We perform a linear regression to remove noise recordings from pressure and tilt on the vertical channel. Zürn and Widmer [1995] successfully used a linear regression factor to remove barometric pressure effect on the vertical recorded acceleration.

Let us consider the vertical seismic acceleration, hereafter called A, and the derivative of the pressure, hereafter called P. We use 5 channels: P, time-shifted P, the horizontal channels and the Hilbert transform of P. We try to find 5 regression factors for a simultaneous least-squares problem between the 5 channels and A. These channels are chosen empirically as to best reduce the noise level. Nevertheless they were inspired by previous studies [Crawford et al., 1998; Zürn and Wielandt, 2007; and Zürn et al., 2007].

We combine P with P shifted in time by 32 seconds (empirically estimated for very low frequencies) to estimate the derivative of P. Pressure variations induce ground displacement. The forcing on the acceleration channel therefore corresponds to the derivative of P [Crawford et al., 1998; Zürn and Wielandt, 2007].

The tilt of the 3 components of the seismometer is related to the gradient of the pressure. For the horizontal channels, Zürn et al [2007] estimated the gradient of the pressure by the Hilbert transform of the pressure; and used it to correct tilt noise on the horizontal components. Unless the seismometer is perfectly levelled, its vertical component will be sensitive to horizontal acceleration. Part of the horizontal signal, which consists mainly of tilt noise at long periods, is then translated to the vertical component. We consider therefore 2 regression factors, between the horizontal channels and the vertical channel, represent tilt noise. We found that including the Hilbert transform of P improves the noise reduction on the vertical channel. Therefore we added the Hilbert transform of P to obtain a 5^{th} regression factor with respect to the vertical channel in acceleration.

We found that the glitch removal was most efficient on raw data. Therefore, we remove the instrumental response after the entire glitch removal procedure.

Text S2.

The autocorrelation of the hum

We calculate the autocorrelation for a time window of 2 days, using 50 % overlap. For each window we use a maximum lag of 11.11 hours, including the first and second circuit -between

2.67 to 3.24 and 5.33 to 6.49 hours respectively- assuming Rayleigh waves with an average velocity of 3.77 km/s in a homogeneous half-space). We zero the autocorrelation outside the following windows: between 6 minutes before and 6 minutes after zero lag; between 2.67 and 3.24 hours before zero lag and after zero lag; between 5.33 and 6.49 hours before zero lag and after zero lag. Data in the latter pair of windows are multiplied by one half. The effect of nulling is shown in figure B1: first we use the entire autocorrelation to compute the PSD (a); second we window the autocorrelation around zero lag, the first and the second orbit before computing the PSD (b); and final (c) similar to (b) except for multiplying the second orbit on the autocorrelation by a factor of 0.5 before computing the PSD. The reason for applying a damping factor to the second orbit is that this signal is more attenuated and dispersed and therefore has a smaller signal-to noise ratio.

In the windowed autocorrelogram (c), when we zoom in on the R1 wavetrain, we occasionally still see a small peak (not visible in Figure S1) at a lag of three times the hourly glitch periodicity (about 3*3621 seconds). This small peak has the same shape as the central peak of the autocorrelation around zero lag. We remove it as follows: 1) we take the autocorrelogram around zero lag and multiply it by an empirical factor of 0.039. 2) we shift it by 3 times the periodicity of the hourly glitch (about 3*3621 seconds). 3) We subtract (2) from the autocorrelogram shown in (c). By this we make sure that this glitch has been removed in the final PSD (figure S1,c).

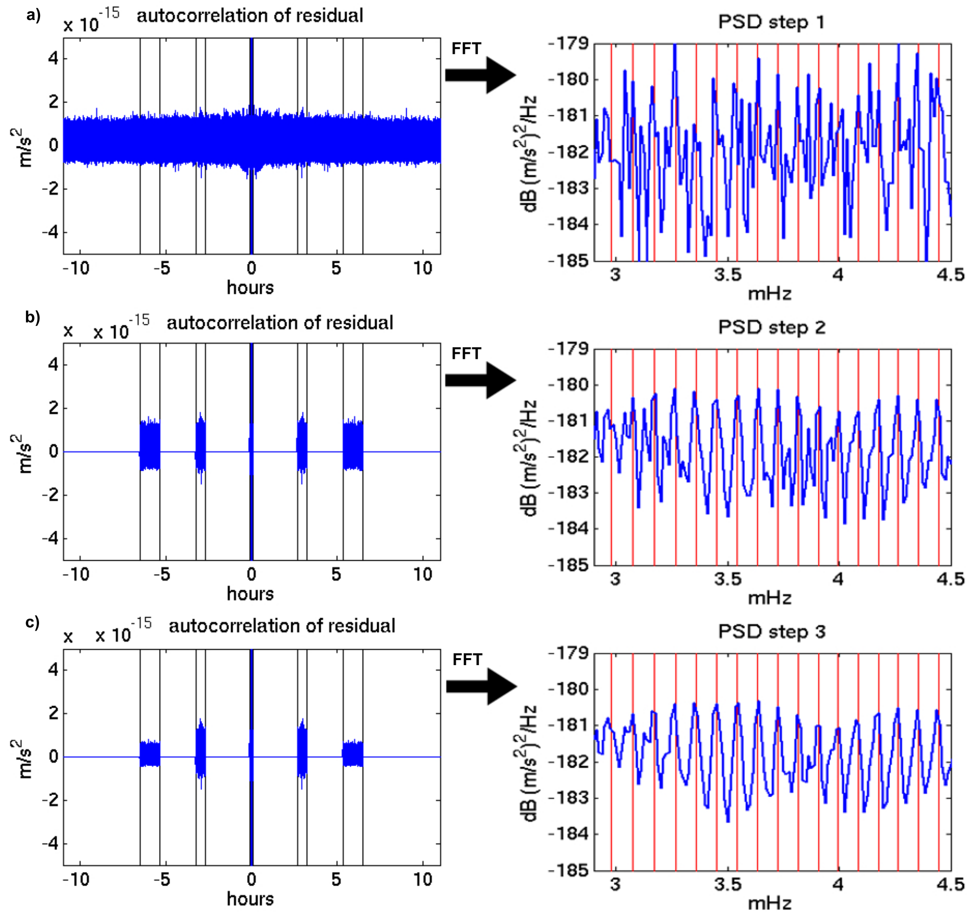

Figure S1. The effect of nulling, example of station RR28. In (a) we show the autocorrelation of the month December 2012 from day 13.5 to 31, with a lag of 11 hours on the left; and its Fourier transform on the right. The first and second orbit around the earth are highlighted by the black vertical lines. Some of the spectral peaks of the power spectral density in blue coincide with the eigenfrequencies of the PREM in red, but there is also some noise in between the peaks. In (b) we null the autocorrelation outside of the zero lag, first and second tour. We see that the noise decreases but the peaks remain. In (c) we reduce the contribution of the second orbit assuming it to be more noisy by dividing the autocorrelation in its window by 2. We now see a further decrease in noise, and clear peaks coinciding with the PREM.

In figure S2 we show the base noise level, calculated as a continuous curve connecting the troughs between the spheroidal normal modes by linear interpolation in cyan for RR34, in magenta for RR28 and black for TAM. We subtract the base noise level for each station in acceleration from the spectra, and show the result as the dB of acceleration in figure 3 of the main text.

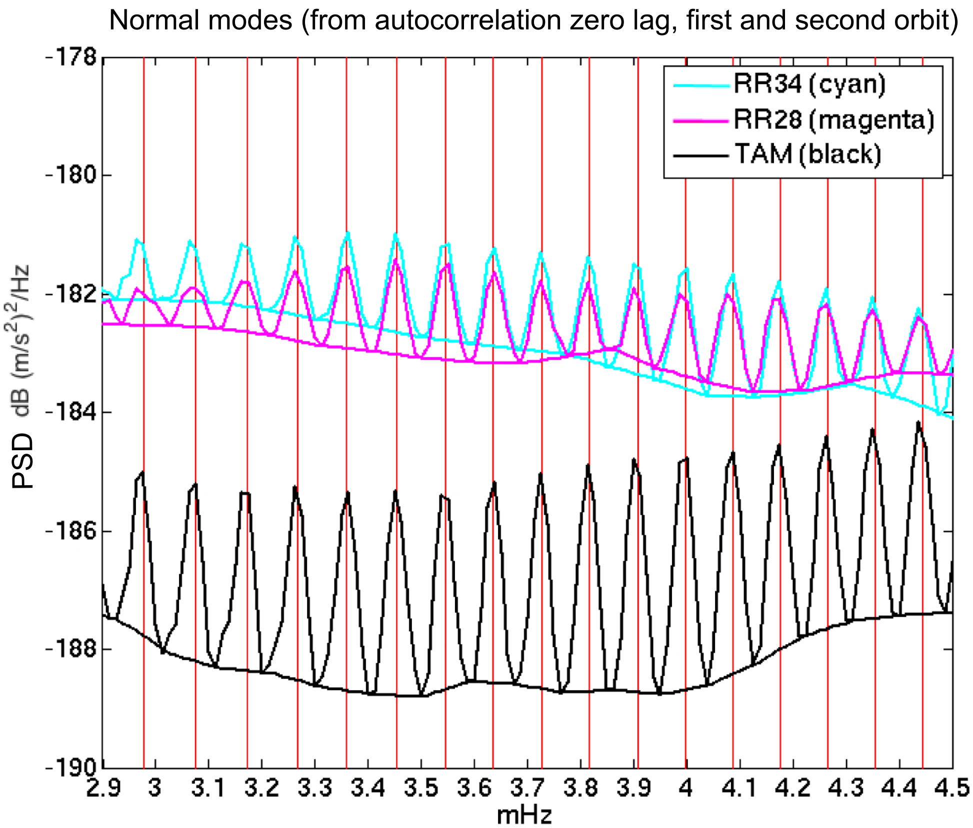

Figure S2. The Fourier transform of the autocorrelation average from dataset per station. We calculate the base noise level that we subtract from the station. The subtraction is done on the absolute values of the Fourier transform of the autocorrelation. The logarithmic values are only used for representation. The results after subtraction are shown in figure 3 in the main text.

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