FLUCTUATION DRIVERS AND VARIABILITY OF VERY LOW FREQUENCY LONG TERM OCEAN AMBIENT NOISE

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Abstract: *Long term ocean acoustic noise data from widely separated measurement sites, spanning periods of up to 15 years, have been made available for analysis by the Comprehensive Test Ban Treaty Organization (CTBTO). Raw noise data, sampled at a rate of 250 Hz, were Fourier Transformed in 10-sec segments to provide noise spectra with a resolution of 0.1 Hz over long periods of time. Low-frequency spectrum level time series data were examined for two purposes: (1) to identify long term statistical trends that might signal changes in climate, and (2) to identify natural or man-induced processes that drive observed fluctuations in noise spectral level. Noise levels in the 1 – 5 Hz part of the spectrum are thought to be relatively free of noise from shipping and marine life. As such, noise fluctuations in this band tend to be driven by natural processes, such as weather, natural seismic activity and sun and moon positions. The statistical behavior of noise at these low frequencies has unique properties, which may provide the opportunity to confidently isolate specific noise forcing functions, allowing interpretation of the time change of oceanic sea noise.*

Keywords: *ambient noise, noise fluctuations*

1. INTRODUCTION

Long term ocean acoustic noise data from three widely separated measurement sites, spanning periods of up to 15 years, have been made available for analysis by the Comprehensive Test Ban Treaty Organization (CTBTO). Analysis results presented here pertain to the site near Wake Island in the Western Pacific Ocean. Raw noise data, sampled at a rate of 250 Hz, were Fourier Transformed in 10-sec segments to provide noise spectra with a resolution of 0.1 Hz over long periods of time. Low-frequency spectrum level time series data were examined for two purposes: (1) to identify long term statistical trends that might signal changes in climate, and (2) to identify natural or man-induced processes that drive observed fluctuations in noise spectral level.

Noise levels in the band from 1 to 5 Hz, which are the focus of the present paper, are thought to be relatively free of noise from shipping and marine life. As such, noise fluctuations in this band tend to be driven by natural processes, such as weather, natural seismic activity and sun and moon positions. The statistical behavior of noise at these low frequencies has unique properties, which may provide the opportunity to confidently isolate specific noise forcing functions, allowing interpretation of the time change of oceanic sea noise.

2. TIME SERIES FOR 1-HZ SPECTRUM LEVEL

Figure 1 presents a roughly 10-year-long time series for the 1-Hz ambient noise spectrum level near Wake Island in dB re 1μPa^2/Hz. There are obvious issues with the data, mainly the time gaps where data could not be extracted from the hard drive using existing software and the spikes seen in year 2013 and later. The statistics presented within the figure are based only on the actual data. It is expected that the issue with the gaps will be resolved later, but for the temporal statistics discussed later, the missing values were replaced by the overall mean noise level. Several data values showed NaN (not-a-number). These were replaced by the average spectral level in order to do the subsequent analysis.

Possibly the two most obvious features of the black band representing the data are its height – standard deviation of 6.84 dB – and its general steadiness over the 10-year span. The dashed line is a linear regression curve computed to show growth or decline of noise level. The result is an increase of about 1 dB/decade. Regression trends were computed also for individual years, and significant rates of increase or decrease were found, but these all even out over the full ten- year period. A lesson to note here is that one should not look for meaningful long-term trends in single year data.

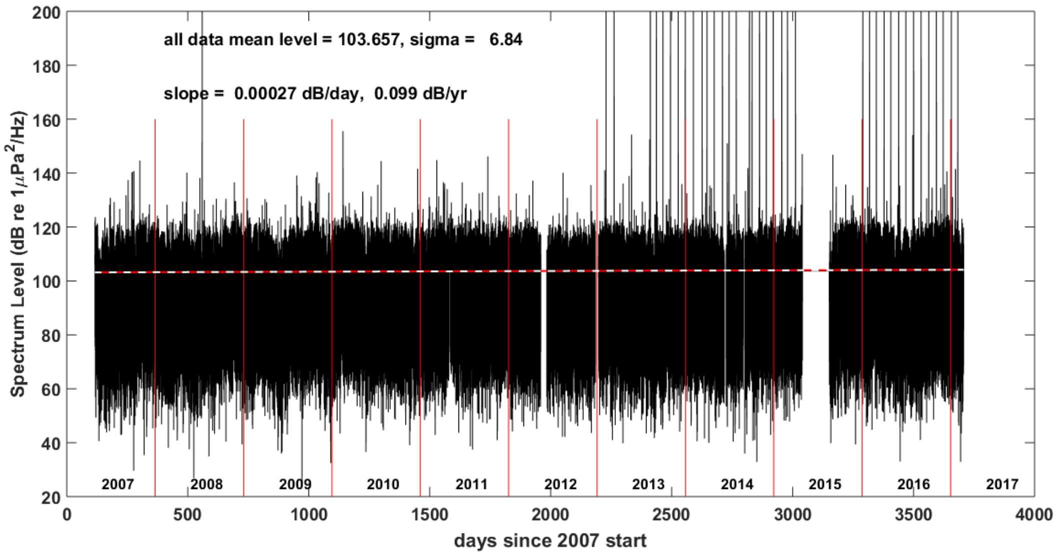

Figure 1. Time series of spectrum level for 1-Hz tonal.

3. ANALYSIS OF TIME SERIES FLUCUATIONS

The fluctuations in the noise spectrum level, as plotted in Figure 1, are investigated through the computation and display of three analysis products; (1) power spectral density of the time series, (2) the logarithmic spectrum, or distribution of variance, and (3) the coherence of the time series as a function of time shift. The power spectral density for the 1-Hz level time data in Figure 1, computed by taking the Discrete Fourier Transform of the time series, is presented in log-log format in Figure 2. Note here that the unit of frequency used in describing the fluctuations is a cycle per hour (cph).

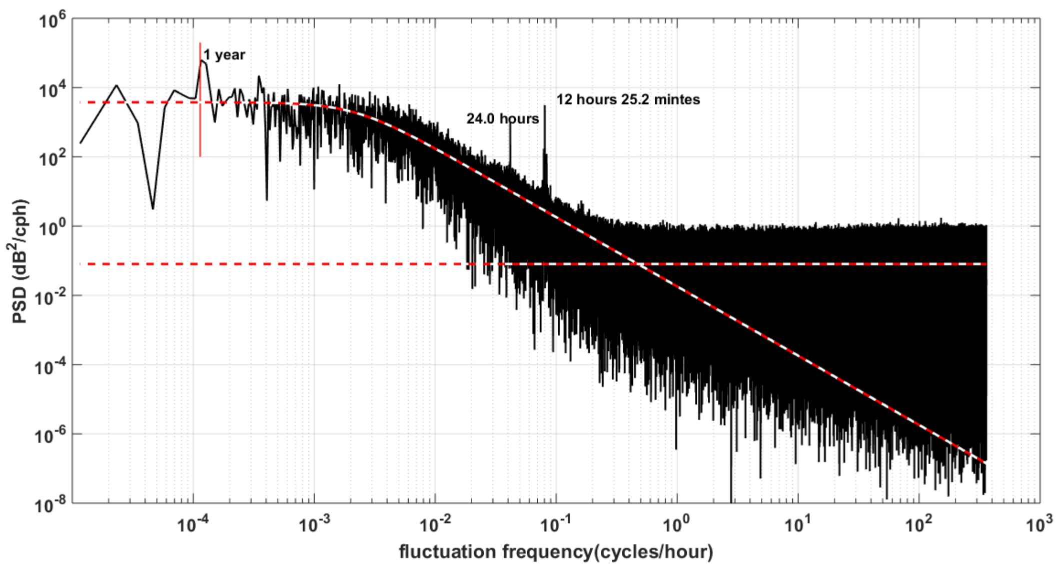

Figure 2. Power spectral density of fluctuation in 1-Hz noise level.

Two general processes are indicated in this figure. The first process, shown on the left side of the figure, is indicated by the generally flat region at low frequencies up to about 0.004 cycles per hour (cph), followed by a decay rate of about $1/f^2$ or -2 on the log-log plot. The presence of a flat section followed by a slope of -2 is characteristic of a first-order stochastic Markov process. The theoretical expression for the spectral density Φ of a first-order process is [1]

$$\Phi = 2V\tau / (1 + (2\pi f\tau)^2) \quad (1)$$

where τ is the coherence time of the process and V is its variance. The coherence time is estimated from the coherence function in Figure 4 and, for this case, is estimated to be 72.7 hours, or about 3 days, and the variance associated with this process, from Figure 3, is 13.03. The upper dashed line in Figure 2 has a slope of -2, corresponding to $1/f^2$ and provides confirmation that the fluctuations come from a first-order stochastic process.

A second process is indicated by the flat region at fluctuation frequencies above about 0.2 cph. The flat section to the right of about 0.2 cph suggests the presence of a second stochastic process that does not begin a downward slope until fluctuation frequencies above the upper frequency limit in this analysis, which is 360 cph. The power spectral density in this second flat region is given by

$$\Phi = V / f_{max} , \quad 2)$$

where V in this case is the variance associated with this second process, which is 29.17. The resulting spectral density is 0.0806 dB^2/cph and is indicated by the horizontal dashed line in Figure 2..

The second set of features consists of the three spectral lines indicated in the figure. These correspond, as labeled, to periods of 12 hours 25 minutes (the tidal cycle), 24 hours, and one year.

Figure 3 provides an alternate way to view the spectrum of the fluctuations. In this presentation the spectrum is presented in proportional bins – tenth decade – instead of in uniform frequency bins. In addition the information is presented in terms of period along the abscissa, rather than frequency. Each bar represents the variance contribution in a one-tenth-decade bin, and the total variance is the sum of the contributions from all bins. These results are based on the data in Figure 1. The quantity presented here is known by some as the logarithmic spectral density.

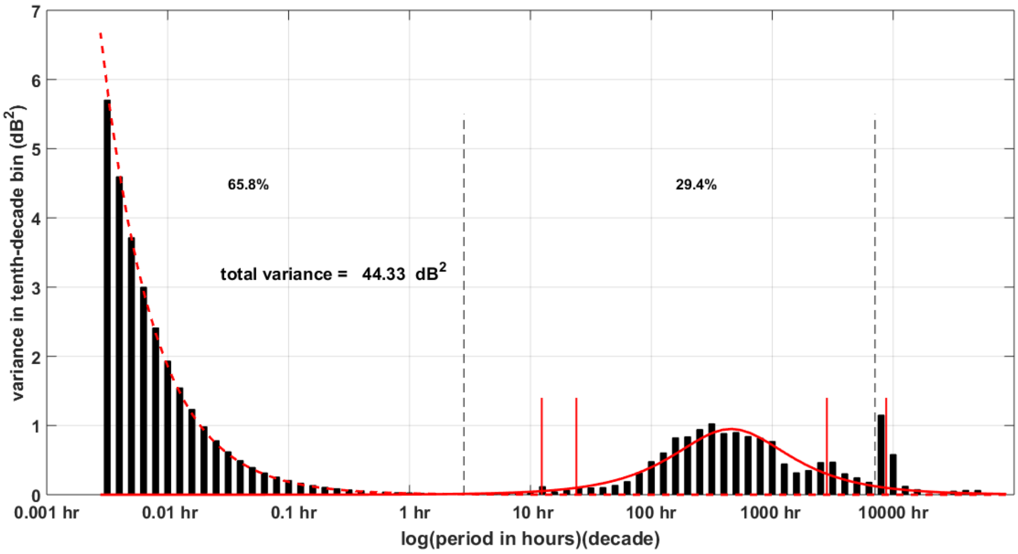

Figure 3. Distribution of fluctuation variance for 1-Hz tonal over 10 years.

What is notable here is the near total absence of variability for fluctuation periods in the range ½ to 20 hours, thus separating the character of the variability into three contributing sections: first is the very short term process that extends in the figure to periods up to about 3 cph and accounts for approximately 66% of the total variance (found by adding the variance contributions in the left hand section), second is the appearance of one or possibly two partly overlapping stochastic processes apparent from about 3 to 8000 cph and which together account approximately for an additional 30% of the variance, and lastly an annual variation that is interpreted as a cyclical process driven by the annual solar cycle and not as a stochastic process. The primary peak in the middle section occurs at 316 hours or about 13 days, and the secondary peak at about 118 days.

The two theoretical curves for the logarithmic spectral density are given by

$$\text{Logarithmic spectral density} = \text{power spectral density} * \text{frequency} * 2.3, \quad (3)$$

where the power spectral density is given by either of Equations 1 or 2, and the factor 2.3 enters because the data are presented using logarithms to base 10 rather than natural logarithms.

Figure 4 shows the coherence function for the 1-Hz time series in Figure 1 for time shifts from zero to 150 hours. The coherence function is normalized to unity for zero time shift. This figure, again, indicates the presence of at least two temporal fluctuation processes. First is the delta-function-like behaviour at time shift near zero. The coherence drops from unity almost immediately to a value of about 0.35, indicating a coherence time less than the time step size of 5 s. Following this drop the coherence drops roughly exponentially, consistent with a first-order process. A straight-line regression curve was fitted to the natural log of the coherence function against time, and the slope of this line was then used to provide an estimate of the coherence time of about 72.7 hours. The coherence time commonly is taken as the time for the coherence function to drop below 1/e of its initial value. The two dashed lines in Figure 4 are the 1/e lines for each of the two processes.

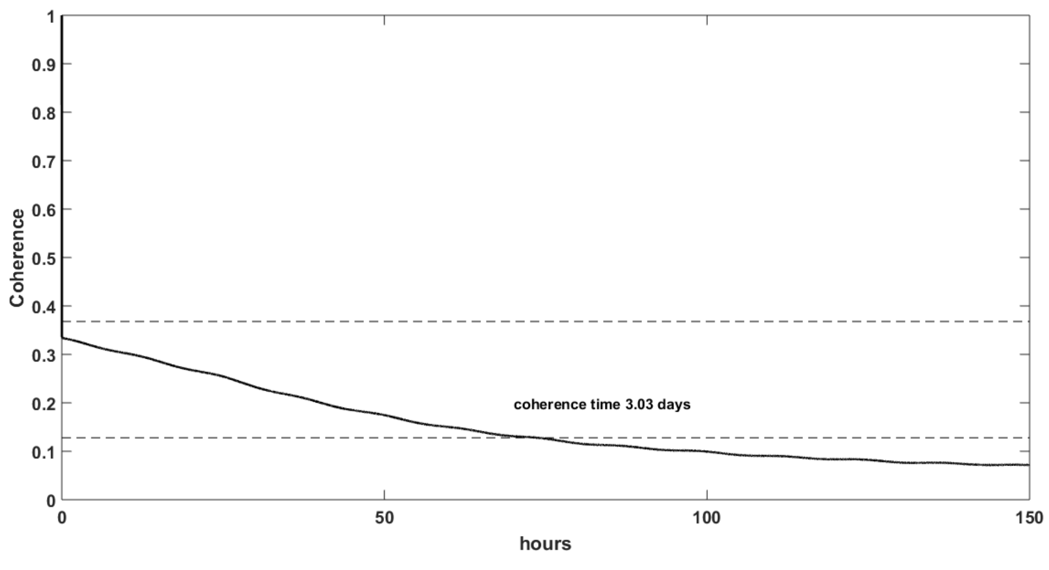

Figure 4. Coherence function for fluctuations of 1-Hz tonal.

In summary, fluctuations in the 1-Hz signal appear to be related primarily to three, possibly four principal causes: short-period fluctuations at the left of Figure 3 are likely caused by phase interference, a mid-range stochastic process centred about 13 days or 2 weeks and likely related to wind speeds, a weaker longer-period stochastic process of unknown cause centred around about 4 months, and finally an annual variation. Bradley and Nichols [2] report strong correlation between wind speeds near Wake Is. and the 1-Hz noise level.

Results at 3 and 5 Hz are, in a general sense, like those at 1 Hz but with some substantial differences in how the variance is distributed over fluctuation period. The distributions of variance are shown in Figure 5 for these three frequencies. One notices especially the growth at 3 and 5 Hz of substantial variability at periods of around 10 to 20 minutes, and the relative lack of variability in the 2-week time frame. The goal now is to unravel the extent to which the variability is caused primarily by changes in the strength or number of sound sources or changes in propagation losses.

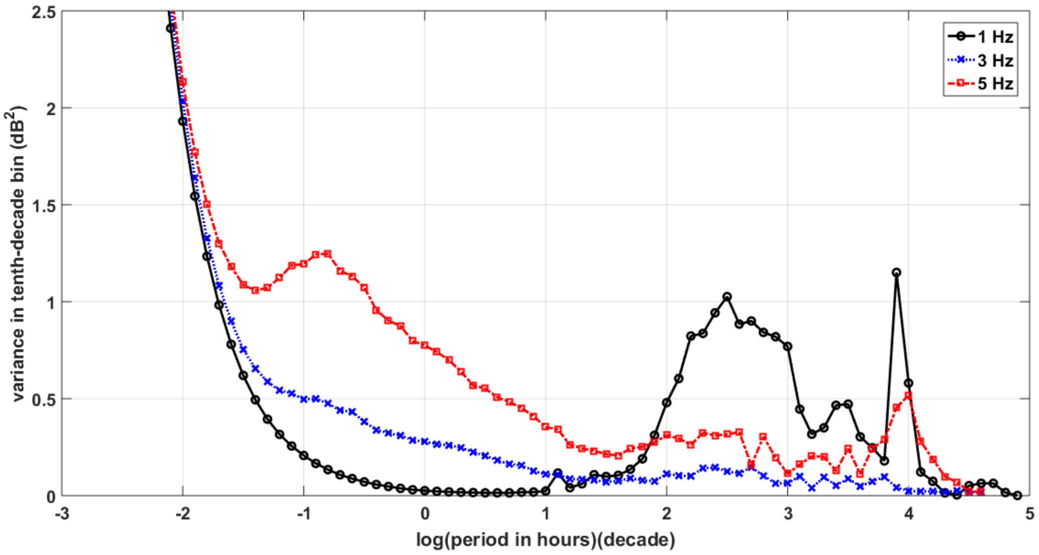

Figure 5. Comparison of fluctuation variance for tonals of three frequencies.

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