University of Bath

Alternative formats
If you require this document in an alternative format, please contact:
openaccess@bath.ac.uk

Spectral probability density as a tool for ambient noise analysis

Nathan D. Merchant[a)]
Department of Physics, University of Bath, Bath, BA2 7AY, United Kingdom
n.d.merchant@bath.ac.uk

Tim R. Barton, Paul M. Thompson, and Enrico Pirotta
University of Aberdeen, Lighthouse Field Station, Cromarty, Ross-shire, IV11 8YL,
United Kingdom
t.r.barton@abdn.ac.uk, lighthouse@abdn.ac.uk, enrico.pirotta@abdn.ac.uk

D. Tom Dakin and John Dorocicz
Ocean Networks Canada, University of Victoria, Victoria,
British Columbia V8W 2Y2, Canada
tdakin@uvic.ca, jdorocic@uvic.ca

Abstract: This paper presents the empirical probability density of the power spectral density as a tool to assess the field performance of passive acoustic monitoring systems and the statistical distribution of underwater noise levels across the frequency spectrum. Using example datasets, it is shown that this method can reveal limitations such as persistent tonal components and insufficient dynamic range, which may be undetected by conventional techniques. The method is then combined with spectral averages and percentiles, which illustrates how the underlying noise level distributions influence these metrics. This combined approach is proposed as a standard, integrative presentation of ambient noise spectra.
© 2013 Acoustical Society of America

1. Introduction

Passive acoustic monitoring (PAM) of underwater ambient noise is the primary investigative tool in the growing research areas of acoustic habitat characterization and anthropogenic noise monitoring. Conventional methods of presenting ambient acoustic data include the power spectral density (PSD; e.g., Merchant *et al.*[1]) to show temporal variation, and two-dimensional spectral averages (e.g., Wysocki *et al.*[2]) or percentiles (e.g., Curtis *et al.*[3]) to summarize frequency content. However, these standard techniques cannot reveal multimodality or outlying data, and may conceal contamination by system noise and inadequate dynamic range in the recording system.

An alternative to two-dimensional spectra has been developed for baseline monitoring and system diagnostics of seismic sensor networks, which presents the empirical probability densities of frequency bands computed from the PSD.[4] A less developed version of this method was previously presented in an underwater acoustics context by Parks *et al.*[5] The technique[4] presents the full range of observations in the form of normalized histograms, revealing modal behavior, outliers, and limiting features such as persistent tonal components and the system noise floor. Here, we adapt the method to include finer frequency resolution, maintaining the 1-Hz intervals of the PSD.

[a)]Author to whom correspondence should be addressed.

This more statistical approach requires large sample sizes, which are becoming the norm as advances in PAM technology make long-term deployments and large datasets feasible. Many emerging applications of long-term acoustic monitoring could benefit from this analysis, such as *in situ* performance assessment of cabled PAM observatories (e.g., NEPTUNE Canada,[6] VENUS,[7] and the LIDO network[8]), long-term noise monitoring for statutory regulation (e.g., the European Marine Strategy Framework Directive[9]), and, more generally, data analysis and system diagnostics of autonomous and shipside PAM devices.

We combine the method, hereafter termed spectral probability density (SPD), with conventional percentiles and spectral averages, demonstrating the utility of this integrative approach through example datasets from an autonomous PAM device and a cabled undersea observatory. We propose that the SPD be considered alongside established analysis techniques for the assessment of ambient noise data.

2. Data acquisition and analysis

Data were recorded in two locations: The Moray Firth, Scotland, UK, and the Strait of Georgia, British Columbia, Canada. The Moray Firth data consisted of two deployments of a Wildlife Acoustics SM2M Ultrasonic autonomous PAM device in The Sutors ($57° 41.1402'$ N, $3° 59.8914'$ W), first between June 13 and July 7, 2012, and then (with an upgraded circuit board) from September 7–27, 2012. Data were calibrated according to the manufacturer's specifications, which agreed with a separate pistonphone calibration to within ± 1 dB over the frequency range 25 to 315 Hz. Recordings were made on a duty cycle of 1 min every 10 min, sampling at 384 kHz/16 bits.

The Strait of Georgia data were acquired from the VENUS network, a cabled seafloor observatory operated by Ocean Networks Canada, using an Ocean Sonics icListen-LF smart hydrophone (0.1 to 1600 Hz). The system calibration and data acquisition were as described in previous work,[1] but the data covered a longer period, from December 14, 2011 to August 1, 2012. A total of 57 957 five-min recordings, sampled at 4 kHz and 24 bits and totaling 191 GB, were downloaded from the VENUS server. Due to anomalous metadata or file length, 268 files were discarded. Further data were absent due to downtime during administrative tasks and intermittent redactions made to protect sensitive information. The overall time series coverage was 85%.

The SPD is calculated from the PSD as normalized histograms of the decibel levels in each frequency bin. To calculate the PSD, the complete dataset of S samples of the instantaneous pressure $p(t)$ is divided into M segments, each containing N samples. The data segments are multiplied by a window function w, such that the mth non-overlapping segment is given by

$$p^{(m)}[n] = \frac{w[n]}{\alpha} p[n + mN],$$ (1)

where $0 \leq n \leq N - 1$ and $0 \leq m \leq M - 1$,[10] and α is the coherent gain factor of the window function.[11] The discrete Fourier transform (DFT) of the mth segment is then given by

$$P^{(m)}(f) = \sum_{n=0}^{N-1} p^{(m)}[n] \exp\left(\frac{-j2\pi fn}{N}\right).$$ (2)

For real signals, the DFT is symmetrical around the Nyquist frequency, $F_s/2$, and the single-sided pressure amplitude spectrum is

$$P_{ss}^{(m)}(f') = \frac{\sqrt{2}}{N} \cdot P^{(m)}(f'),$$ (3)

where $1 \leq f' \leq N/2$. The PSD of the mth data segment is then

$$\mathrm{PSD}^{(m)}(f') = \frac{1}{B}|P_{ss}^{(m)}(f')|^2, \tag{4}$$

where B is the noise power bandwidth of the window function, which normalizes the frequency bin values to those obtained with a bin width of $1\,\mathrm{Hz}$ and a rectangular (Dirichlet) window

$$B = \frac{1}{N}\sum_{n=0}^{N-1}\left(\frac{w[n]}{\alpha}\right)^2. \tag{5}$$

The PSD periodogram is then an $N/2$ by M matrix comprising the PSDs of each of the M data segments

$$\mathrm{PSD}(f', m) = 10\log_{10}\left(\mathrm{PSD}^{(m)}(f')\right). \tag{6}$$

The SPD of frequency bin f' is given by the empirical probability density

$$\mathrm{SPD}(f') = \frac{1}{Mh}H(\mathrm{PSD}(f', m), h), \tag{7}$$

where $H(\mathrm{PSD}(f', m), h)$ denotes the histogram of M values of the PSD at frequency f' with a histogram bin width of h dB re $1\,\mu\mathrm{Pa}^2\,\mathrm{Hz}^{-1}$. The histograms are then combined to form a matrix across all frequencies.

In the analyses presented in this paper, a Hann window ($\alpha = 0.5$, $B = 1.5$) of duration 1 s was used, and the temporal resolution of the periodograms was down sampled to 60 s using the standard Welch method.[12] The histogram bin width, h, was 0.1 dB re $1\,\mu\mathrm{Pa}^2\,\mathrm{Hz}^{-1}$.

3. System and data diagnostics

The SPD can show whether the dynamic range of the recording system is appropriate to field conditions: In Figs. 1(a) and 1(b) the primary mode (maximal probability density) converges with the lowest recorded noise levels at $\sim$10 kHz, and the noise floor appears artificially flat, remaining at $\sim$47 dB re $1\,\mu\mathrm{Pa}^2\,\mathrm{Hz}^{-1}$ above $\sim$1.5 kHz. This indicates that the data are constrained by the sensitivity of the instrument, and that additional gain or other system modifications would be needed to measure low noise levels in this frequency range. According to the canonical ambient noise curves produced by Wenz,[13] such a noise floor prevents measurement of the lowest sea states above $\sim$1.5 kHz. Conversely, Fig. 1(c) demonstrates that the VENUS data were not limited by the dynamic range of the instrument.

If ambient noise spectra are to be presented in 1/3 octave bands, any anomalous spikes in the narrowband spectrum should be characterized as these will dominate their respective 1/3 octave bands. Such tonal components are evident in Fig. 1(a) (as a series of harmonic spikes above 1 kHz, believed to be system self-noise) and Fig. 1(c) (at 74 Hz, believed to be system noise from an adjacent instrument[1]). While tonals may appear in percentile plots (overlain on the SPD in Fig. 1) and the PSD, the SPD can show whether they are persistent throughout the deployment, as in Fig. 1(c) where this was clear from the lack of data points below the tonal spike at 74 Hz. By contrast, the tonal components between 0.1 and 1 kHz in Fig. 1(b) originated from persistent but variable low-level industrial noise, possibly from an oil rig or the nearby shipyard. The reduction in tonal system noise between the Moray Firth deployments [Figs. 1(a) and 1(b)] was due to an upgraded circuit board.

The dynamic ranges of PSD plots are often chosen to highlight specific spectral features, which may result in masking of low-level tonal components if the floor of
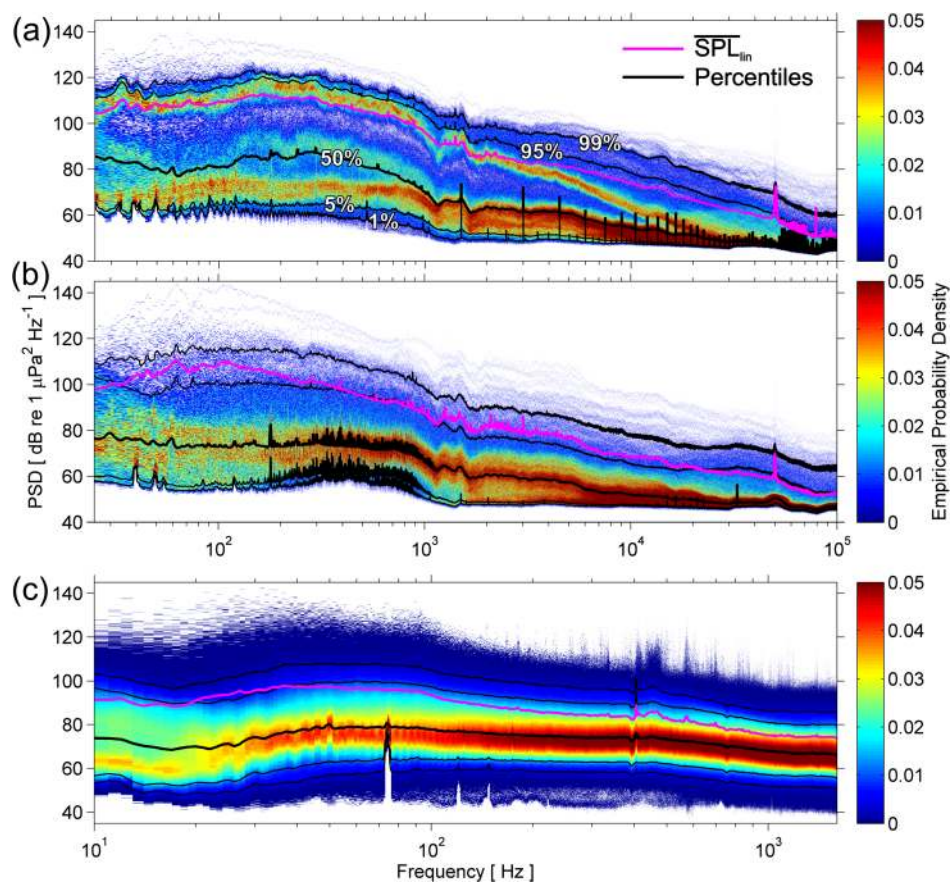
Fig. 1. (Color online) Spectral probability densities of Moray Firth deployments over the range 25 Hz to 100 kHz: (a) June 13 to July 7, 2012; (b) September 7–27, 2012. (c) VENUS deployment over range 10 to 1600 Hz from December 14, 2011 to August 1, 2012. Note the different frequency range in (c).

the color scale is too high. The PSDs in Fig. 2, for example, exclude data below 70 dB re $1 \mu Pa^2 Hz^{-1}$, which Fig. 1 shows is a substantial proportion. Potential masking of persistent low-amplitude tonals is precluded by performing an SPD analysis, since the full dynamic range is presented. Combining this with spectral percentiles (as in Fig. 1) ensures that high-frequency tonal spikes, which may be too narrow to be evident on SPD or PSD plots, are not overlooked.

4. Ambient noise characterization

As well as evaluating data quality, the SPD can also help to characterize ambient noise levels. For example, the first Moray Firth deployment featured a one-week period of consistently high noise levels as an oil rig was towed into the area by two vessels operating with dynamic positioning [see Fig. 2(a) from June 16 onwards]. The received vessel noise was concentrated below 1 kHz, and exhibited a tide-dependent Lloyd's mirror effect. In the SPD [Fig. 1(a)], this sustained period of vessel noise appears as a secondary modal ridge ~40 dB greater than the primary mode in the range 0.1 to 1 kHz. In contrast, this underlying bimodality is concealed by the linear mean, $\overline{SPL}_{lin}$, and percentiles, which could be misleading if used as the sole method of analysis.

While it is often necessary to condense data into average noise levels (e.g., for comparison with other studies or to record temporal trends), different averaging
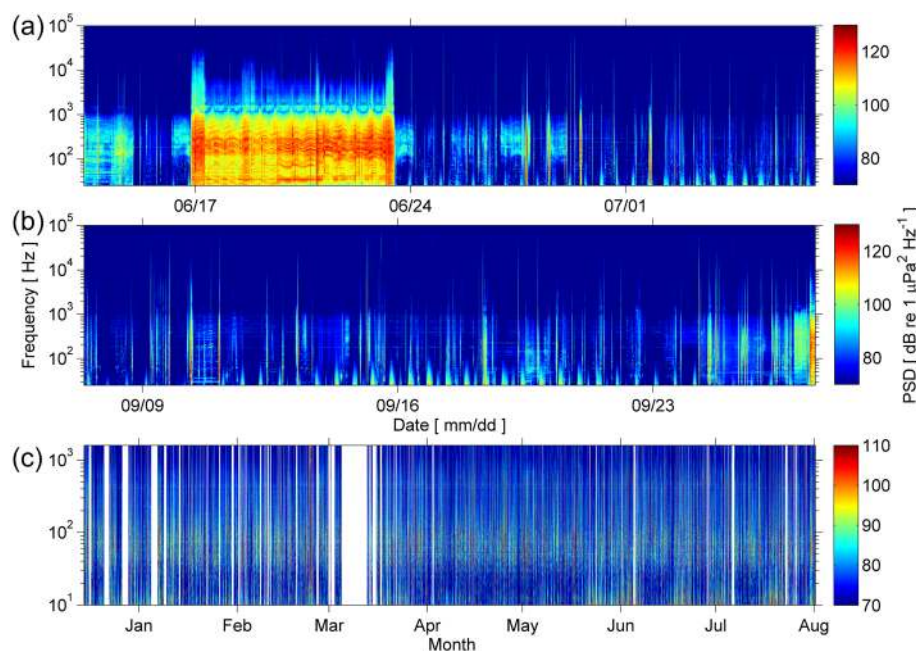
Fig. 2. (Color online) Power spectral densities of Moray Firth deployments over the range 25 Hz to 100 kHz: (a) June 13 to July 7, 2012; (b) September 7–27, 2012. (c) VENUS deployment over range 10 to 1600 Hz from December 14, 2011 to August 1, 2012.

metrics can produce widely differing average levels, which may result in misinterpretation of noise data.[1] One way to assess the behavior of averages is to present them in the context of the distributions they represent. This can be performed across the frequency spectrum using the SPD: Fig. 1 shows that the shape of $\overline{\text{SPL}}_{\text{lin}}$ broadly follows the profile of the maximal recorded levels, while the median more closely reflects the mode, as shown by the maximal probability density.

A further application is the characterization of outliers and their influence on noise level metrics. In Fig. 1, $\overline{\text{SPL}}_{\text{lin}}$ is consistently below the 95th percentile except where maximal outliers are particularly deviant. Both Moray Firth deployments [Figs. 1(a) and 1(b)] featured tonal outliers at 50 kHz caused by ship-borne depth sounders operating at this frequency. The broadband outliers in Fig. 1(b) were due to a rig being towed past the deployment site on September 27, evident in Fig. 2(b), and those in Fig. 1(c) were particularly loud vessel passages, including the sustained presence of a VENUS maintenance vessel for several hours[1] visible on February 23–24 in Fig. 2(c). This illustrates how loud events influence $\overline{\text{SPL}}_{\text{lin}}$, and suggests that the relationship between $\overline{\text{SPL}}_{\text{lin}}$ and the 95th percentile could be used as an indicator of outlier influence.

5. Conclusion

With an expanding range of PAM systems on the market and increased exploitation of ambient noise monitoring for various research applications, there is a growing need to be able to assess whether an instrument's dynamic range and gain settings are appropriate to field conditions, and whether data are suitable for their intended purpose. We have demonstrated that the SPD can fulfill this role, complementing the calibration of PAM systems by assessing performance in the field.

We have also shown that the SPD contextualizes conventional spectral averages and percentiles by revealing the underlying noise level distribution. This can alert investigators to the influence of outliers and the presence of phenomena such as

multimodality which are not shown by conventional techniques. Combining conventional methods with the SPD in this way enables a more complete understanding of ambient noise data, and should, we believe, be considered as a standard analysis technique for ambient noise monitoring.

Acknowledgments

References and links

[1] N. D. Merchant, P. Blondel, D. T. Dakin, and J. Dorocicz, "Averaging underwater noise levels for environmental assessment of shipping," J. Acoust. Soc. Am. **132**(4), EL343–EL349 (2012).

[2] L. E. Wysocki, S. Amoser, and F. Ladich, "Diversity in ambient noise in European freshwater habitats: Noise levels, spectral profiles, and impact on fishes," J. Acoust. Soc. Am. **121**(5), 2559–2566 (2007).

[3] K. R. Curtis, B. M. Howe, and J. A. Mercer, "Low-frequency ambient sound in the North Pacific: Long time series observations," J. Acoust. Soc. Am. **106**(6), 3189–3200 (1999).

[4] D. E. McNamara and R. P. Buland, "Ambient noise levels in the continental United States," Bull. Seismol. Soc. Am. **94**(4), 1517–1527 (2004).

[5] S. E. Parks, I. Urazghildiiev, and C. W. Clark, "Variability in ambient noise levels and call parameters of North Atlantic right whales in three habitat areas," J. Acoust. Soc. Am. **125**(2), 1230–1239 (2009).

[6] NEPTUNE Canada, http://www.neptune.uvic.ca/ (Last viewed January 11, 2013).

[7] VENUS, http://venus.uvic.ca/ (Last viewed January 11, 2013).

[8] M. André, M. van der Schaar, S. Zaugg, L. Houégnigan, A. M. Sánchez, and J. V. Castell, "Listening to the deep: Live monitoring of ocean noise and cetacean acoustic signals," Mar. Pollution Bull. **63**(1–4), 18–26 (2011).

[9] A. J. Van der Graaf, M. A. Ainslie, M. André, K. Brensing, J. Dalen, R. P. A. Dekeling, S. Robinson, M. L. Tasker, F. Thomsen, and S. Werner, "European Marine Strategy Framework Directive-Good Environmental Status (MSFD GES)," Report of the Technical Subgroup on Underwater Noise and Other Forms of Energy (2012).

[10] S. Marple, *Digital Spectral Analysis with Applications* (Prentice Hall, Englewood Cliffs, NJ, 1987).

[11] M. Cerna and A. F. Harvey, "The fundamentals of FFT-based signal analysis and measurements," Application Note 041, National Instruments (2000).

[12] P. Welch, "The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms," IEEE Trans. Audio Electroacoust. **15**(2), 70–73 (1967).

[13] G. M. Wenz, "Acoustic ambient noise in the ocean: Spectra and sources," J. Acoust. Soc. Am. **34**(12), 1936–1956 (1962).