

Quantifying Physical Processes in the Marine Environment using Underwater Sound

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Abstract: *Many physical processes in the marine environment generate underwater sound. These sounds are often recognizable by their spectral or temporal characteristics. By training an underwater recorder to first classify the sound source, quantifiable measurements of the physical processes can be made in real time, and reported as interpreted data, rather than just sound levels. An objective acoustic classification procedure is presented. Examples from different marine environments including deep ocean, coastal waters, under sea ice cover, in a tidewater glacier bay, and from a submarine groundwater spring are presented. These measured sounds are interpreted as, for example, wind speed, precipitation, sea ice type, flow rate, etc... These examples demonstrate that remote acoustic monitoring of the ocean environment will produce quantitative measurements of physical processes that will be continuous, in near real time, and from times and locations where it is difficult or impossible to make such measurements by more conventional methods.*

Keywords: *ambient sound, acoustic classification, wind speed, rainfall rate, ice coverage, passive acoustic monitoring*

1. INTRODUCTION

Monitoring underwater sound in the marine environment has become a new international mandate [1]. In addition to the direct measurements of sound levels, the interpretation of the sound can be used to identify the sources of the sound, and to quantify the processes producing it. Sound in the ocean is generated by physical processes such as wind, rainfall, sea ice, seismic activity, biological activities such as marine mammal vocalizations, fish and crustacean sounds, and anthropogenic activities including shipping, construction, sonars, fishing, mineral exploration, etc... All of these different sounds have spectral and temporal characteristics that allow them to be identified. This classification process needs to be automated so that information derived from passive acoustic monitoring can be efficiently transmitted to users, many of whom are not interested in the original sound signals, but in the quantification of the processes producing the sound.

Figure 1 shows a typical time series of ambient sound in the marine environment. Different processes producing sound have different time scales, and so the time record can be thought of as a series of acoustic events imbedded in a background sound field. In the frequency range from a few hundred Hertz to tens of kilohertz, most of the biological and anthropogenic sounds have very short time scales, or order seconds, whereas geophysical processes producing sound such as wind, rain and sea ice have time scales of minutes to hours. This paper focuses on the geophysical sound sources, and treating them as the product of background ambient sound signals. From this background ambient sound, sound budgets for different marine environments and locations can be produced [2,3].

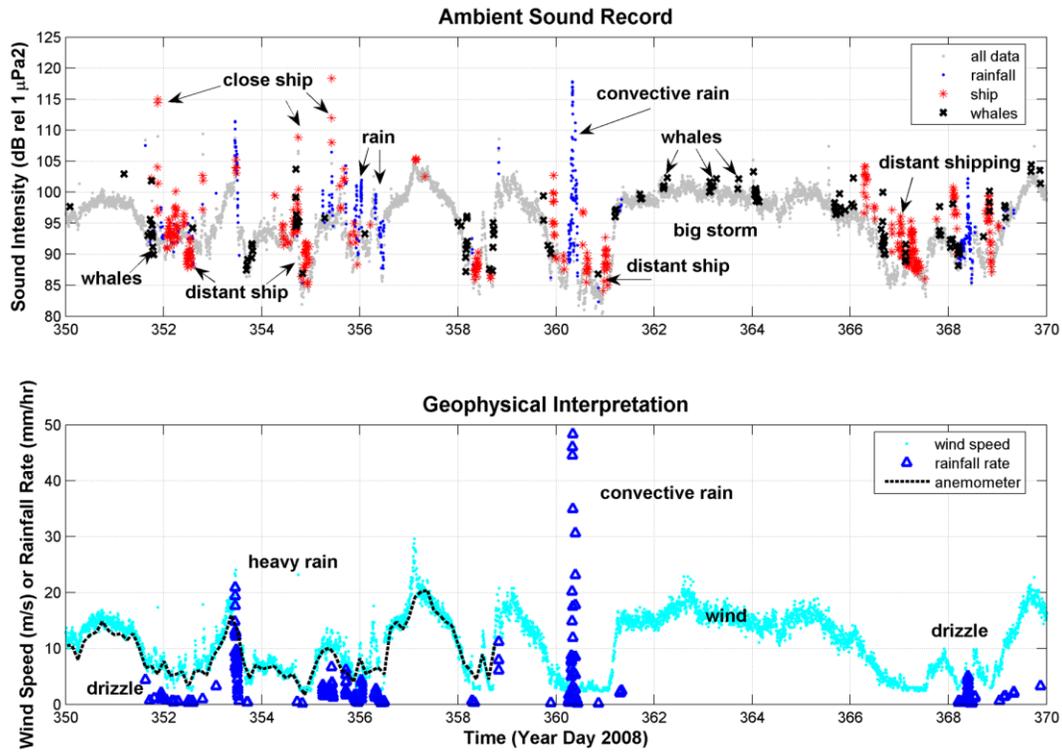


Fig. 1: A 20-day ambient sound record (a) from Athos in the northern Aegean Sea. A slowly varying background sound is punctuated by shorter duration acoustic events such as rain storms, ship passages, whale vocalizations, etc... The geophysical interpretation of the sound record (b) is the desired product for many users. Classification includes the detection and removal of noises, such as ships, and then the subsequent quantification of the physical processes producing the sound. Note that the surface anemometer on this mooring failed on Day 358, but the acoustical wind speed measurement continued throughout the duration of the deployment.

2. RECORDING EQUIPMENT

Passive acoustic monitoring (PAM) instruments are becoming technically accomplished. High bandwidth and high sampling rates are now possible for longer and longer periods of deployment. With this capacity, lots of data – even of the order of terabytes – are available for analysis. Unfortunately, the reality of so much data is the challenge of processing it in a timely

manner, or transmitting it to shore from remote locations. In fact, for many applications it is really the interpretation of the acoustic data as geophysical quantities, biological activities or human activities that is of greater interest than the original acoustic record. Furthermore, if one is interested in the background acoustic signal, then a low-duty cycle recorder, sub-sampling the environment is a more practical recorder to deploy.

The data reported here are from a low duty cycle (~ 1%), high bandwidth (50 kHz), low-noise recorder known as a Passive Aquatic Listener (PAL). These instruments are designed for low-term deployment (over 1 year is possible) as autonomous instruments on surface or sub-surface ocean moorings, both deep water and coastal, either with other instruments on the same mooring or as dedicated acoustic moorings [4,5]. The PAL electronics has also been deployed on autonomous drifters [6]. The data recorded are not the temporal time series (at 100,000 Hz), but rather spectral components of the sound samples, producing a time series of spectral components with a time step determined by the duty cycle, i.e., one sample every few minutes.

3. CLASSIFICATION ANALYSIS

3.1 Open water

A critical component of the quantitative use of the ambient sound field to describe the marine environment is the identification of the sound source. This analysis depends on the assumption that different sound sources have unique spectral characteristics that allow identification through multivariate analysis of spectral parameters, such as sound levels at various frequencies and spectral slopes in various frequency bands. This process is illustrated in Fig. 2. Different combinations of spectral parameters have been plotted with respect to one another for a 20-day period at the Athos PAL mooring (Fig. 1). Several categories of sound sources are identified in their generic position on each subplot. Two or three categories of precipitation are recognized (drizzle, heavier rain and very heavy convective rain), and two or three categories of ship noise (close ships, distance ships and distance ships during very calm sea conditions). Wind generated locus is highlighted and can be thought of as a continuous locus of data spanning a range of wind speeds from 3-15 m/s. The combination of 8 kHz and 20 kHz (B) is most useful for separating wind source from precipitation, but shipping signal are often ambiguous with the wind/rain source. In contrast, the shipping signal is better detected using 2 kHz and 20 kHz (A), although heavy rain and loud close ships are still ambiguous. Comparing the spectral slope from 2 – 8 kHz with the sound level at 8 kHz (C) allows heavy rain and close ships sources to be identified. Using the slope between 8 – 15 kHz (D) easily identifies drizzle sound sources. Additional temporal characteristics can also be considered, and are useful for identifying very short calls, clicks or banging, allowing these “noises” to be detected, identified and removed, or quantified for other users for whom these noises are their signal.

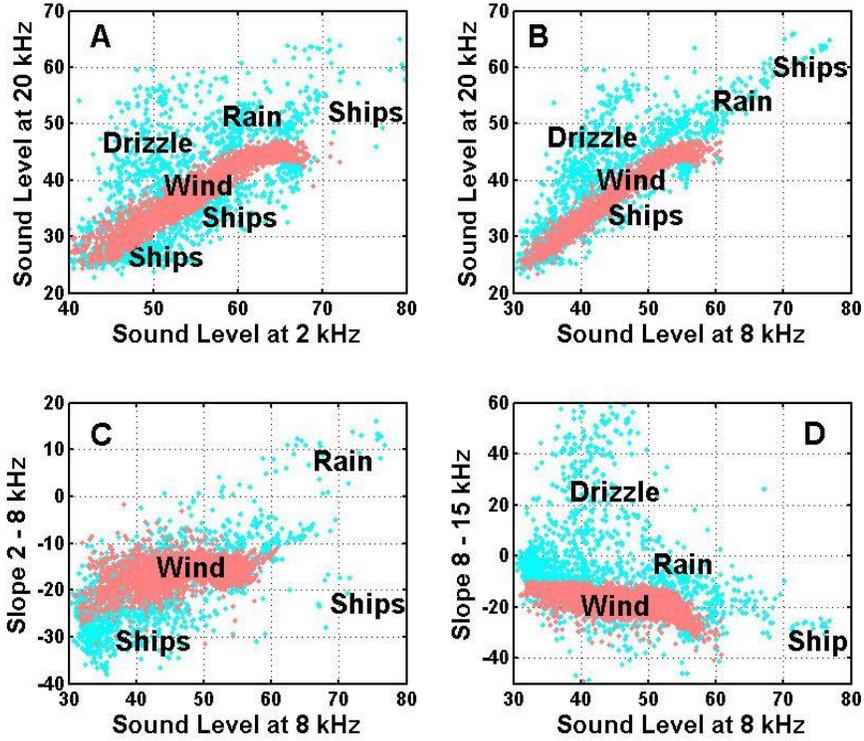


Fig. 2: Scatter plots of acoustic parameters using (A) 2 Hz vs 20 kHz; (B) 8 kHz vs 20 kHz; (C) 8 kHz vs 2-8 slope; (D) 8 kHz vs 8-15 slope. Data acquired from the Athos mooring PAL for Days 350-370 of 2008, with the wind sound source data highlighted in red. The units are dB relative $1 \mu\text{Pa}^2\text{Hz}^{-1}$ for sound level and dB/decade for spectral slope.

From these diagrams, multivariate classification tests can be established (see Appendix). Once the sound sources categories are safely identified, quantitative algorithms can be applied (Fig. 1b). Algorithms for wind speed and rainfall rate are given by:

1) Wind speed algorithm:

$$U = a_0\text{SPL}8^3 + a_1\text{SPL}8^2 + a_2\text{SPL}8 + a_3 \quad (1)$$

where U is wind speed (m/s), $\text{SPL}8$ is the sound level at 8 kHz (dB relative to $1 \mu\text{Pa}^2\text{Hz}^{-1}$) and the coefficients are [.0005; -0.0310; .4904; 2.0871], respectively.

2) Rainfall rate algorithm:

$$\log_{10}(R) = b_0\text{SPL}_5 + b_1 \quad (2)$$

where R is rainfall rate (mm/hr), SPL_5 is the sound level at 5 kHz (dB relative to $1 \mu\text{Pa}^2\text{Hz}^{-1}$) and the coefficients are [.0325; -1.4416], respectively (from [7]).

3.2 Sea Ice

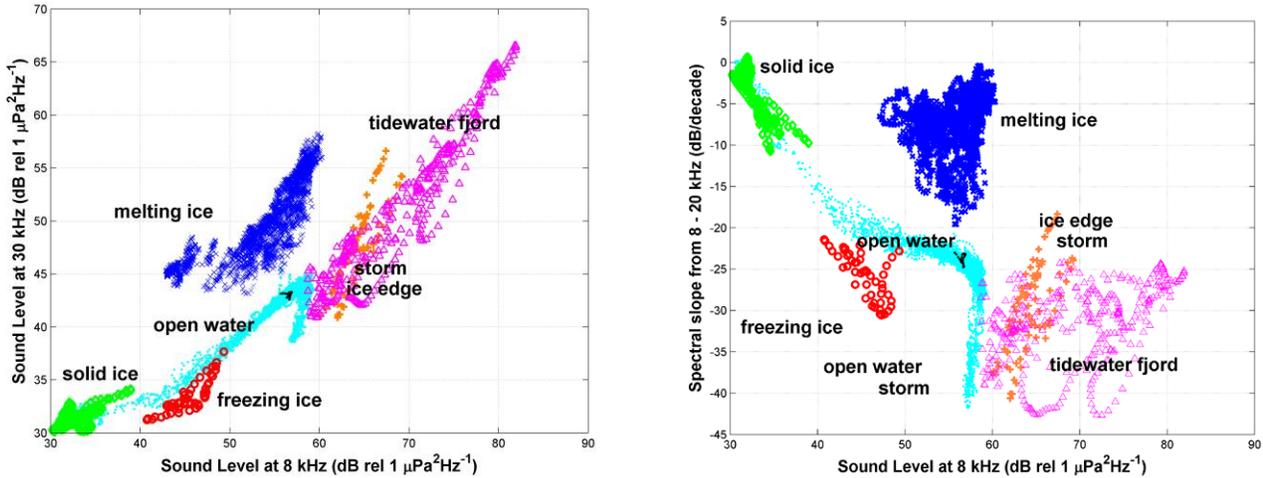


Fig 3: Sea ice classification diagrams for data from the Bering Sea. Different ice conditions (melting, solid, freezing, storm at ice edge, open water) were present during the ice season and have different spectral characteristics. The cluster of black dots in the “open water” category are from a brief time period (a few hours) in the middle of the ice season when open water was known to be present at the mooring site [8]. The “open water” category is from before the onset of sea ice at the mooring location. Data from Icy Bay, Alaska, an ice covered tidewater fjord, show different spectral features, distinguishing its soundscape from the Bering Sea ice soundscape .

Sea ice is another major source of underwater sound in ice covered seas. Physical processes associated with sea ice and sound generation include the screeching sound of ice floes rubbing together as the ice freezes, the banging of ice floes in storms, the fizzing of ice as it melts, and the relative quiet (at frequencies over 20 kHz) of solid ice coverage. In addition to these physical sounds, marine seals and whales contribute a colorful sound chorus, at least in the Bering Sea where the data from Fig. 3 were collected. Fig. 3 shows that these physical processes have very distinctive spectral characteristics and these features can be used to identify the surface ice conditions (from below the ocean surface). This, in turn, suggests that it is possible to listen for open water, which could then be used to allow sub-surface instrumentation to surface safely. In Fig. 3, the acoustic detection of open water in the middle of the sea ice season is shown by the cluster of black points in the middle of the “open water” data cluster. The ice pack was known to have retreated to the north at this time [8].

3.3 Tidewater glacial bay

Monitoring glacial activity, especially the discharge of fresh water into the ocean from tidewater glaciers (ones that flow directly into the ocean), is very difficult. The temporal record of ambient sound generated by glacial processes is being explored in Icy Bay, Alaska. The spectral characteristics of the sound recorded at Icy Bay near the Yhatse Glacier are shown in Fig. 3. The remarkable comment is that the sound levels are very high, and variable, and clearly different than sea ice acoustic spectra. The interpretation of this signal is uncertain [9].

3.4 Submarine freshwater spring

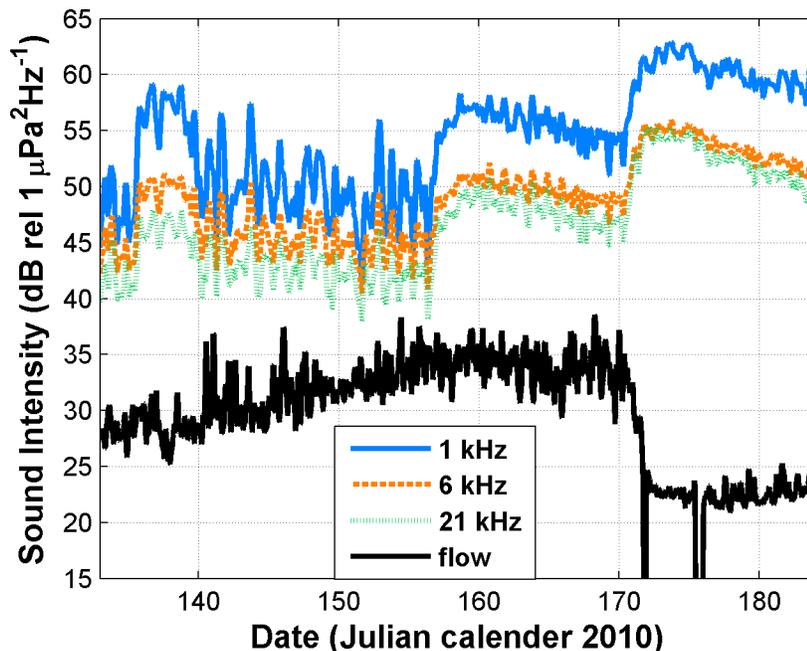


Fig 4: Ambient sound from a marine freshwater spring in Stoupa, Greece. Sound levels are shown together with flow rate (cm/s) at the head of a submarine fresh water spring near Stoupa, Greece [10].

Another example of using ambient sound to monitor physical processes in the marine environment is shown in Fig. 4. Fresh water springs discharge into the coastal marine environment near Stoupa, Messinia, Greece. The acoustic signal shows that the sound levels change as the flow rate changes, but not in a predictable way. As the flow rate decreases on Day 170, the sound levels increase! [10]

4. CONCLUSIONS

The background ambient sound in the marine environment contains quantifiable information about the physical processes producing the sound. By first classifying the sound source, geophysical summaries of these processes can be produced (Fig. 1). This will allow real-

time reporting of geophysical data from remote, and potentially difficult, locations using passive monitoring of ambient sound as a primary measurement technology. An algorithm for the acoustic classification of typical open water sound sources is presented, and quantitative algorithms for wind speed and rainfall rate are given. Classification diagrams for ice coverage are also presented and show the potential for ice type classification. Other examples include sounds from a tidewater glacier fjord (Icy Bay, Alaska) and from a submarine freshwater spring near Stoupa, Messinia, Greece.

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APPENDIX: An automated classification algorithm for sound sources in open water

Shipping categories:

Close ship passage if: $SPL_8 > 60$ dB and $SLOPE_{2-8} < -18$ dB/decade

Distant shipping if: $(SPL_{20} < 0.93 * SPL_2 - 16.5 \& SPL_2 < 63)$ or $(SPL_{20} < -0.2448 * SPL_2^2 + 31.9 * SPL_2 - 996 \& 63 \text{ dB} < SPL_2 < 68 \text{ dB}) \& SLOPE_{2-8 \text{ kHz}} < -18$ dB/decade

Distant shipping if: $(SPL_2 > 65 \text{ dB} \& SPL_2 < 80 \text{ dB} \& SPL_{20} > -0.09 * SPL_2^3 + 12.18 * SPL_2 - 363 \& SPL_{20} < SPL_2 - 17)$ & $SLOPE_{2-8 \text{ kHz}} < -18$ dB/decade

Biological categories:

Whale echo location clicking if : $SPL_{30} > SPL_{20} \& SPL_{30} > 38$ dB

Rainfall categories:

Medium rain (stratiform) if: $SPL_{20} > SPL_5 * .75 + 5 \& SPL_5 \leq 70$ dB

Heavy rain (convective) if: $SPL_8 > 60$ dB & $SLOPE_{2-8 \text{ kHz}} > -18$ dB/dec & $SPL_{20} > 45$ dB

Drizzle if: $SPL_8 < 50$ dB & $SLOPE_{8-15} > -5$ dB/decade & $SPL_{20} > 35$ dB & $SPL_{20} > SPL_8 * .9$ dB

Rain with high winds if: $(SPL_{20} > -0.1144 * SPL_8^2 + 12.728 * SPL_8 - 307)$ & $(SPL_{20} < -0.1 * SPL_8^2 + 11.5 * SPL_8 - 281)$ & $51 \text{ dB} < SPL_8 < 64 \text{ dB} \& SLOPE_{2-8 \text{ kHz}} > -18$ dB/decade

Wind categories:

Wind if: $SPL_2 < 65$ dB & $SPL_{20} < 0.73 * SPL_2 + 1.3$ & $SPL_{20} > 0.93 * SPL_2 - 16.5$

High winds (with unresolved shipping noise) if: $SPL_2 > 63$ dB & $(SPL_{20} > -0.2448 * SPL_2^2 + 31.9 * SPL_2 - 996 \& SPL_2 < 68 \text{ dB}) \& (SPL_{20} < -0.09 * SPL_2^2 + 12.18 * SPL_2 - 363)$

A hierarchy of classifications is applied. First the shipping and biological categories are determined. These samples are removed, and then the rainfall categories are selected. Finally, the remaining samples are tested for wind.