PASSIVE ACOUSTIC DETECTION AND OBSERVATIONS OF WIND-WAVE BREAKING PROCESSES

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This study is a preliminary work aiming to obtain statistics of wind waves on the base of the ambient sea noise parameters. In experiment conducted on the Baltic Sea, passive acoustic methods were exploited in order to detect and parameterize breaking evens. A four hydrophones array was used to record ambient sea noise for five days. Data collected during this experiment allowed us to track moving acoustic sources, to estimate their speed, duration and number in a unit of time. All these parameters were determined using generalized the cross correlation method. Some examples of obtained cross correlation time series with brief description of encountered difficulties in analysis are presented. Variation in number, duration and speed of breaking events in time are compared with averaged noise level and significant wave height. This last parameter, describing in a unified way the wave field, constitutes the essence of further investigations. Distributions of obtained values are shown and further improvement of a method is shortly introduced.

INTRODUCTION

It is commonly accepted that breaking wind waves are the dominant source of ambient sound in the sea. During whitecapping, the air is pushed under the sea surface and newly formed, mechanically excited gas bubbles generate sound. Field experiments have shown that frequency of that noise is in the range 40–20000 kHz [1]. Acoustical and optical measurements demonstrated that the pressure pulses associated with single bubble formation, their coalescence and breaking, produce sound between 500 and 5000 Hz [2]. In order to recognize, locate and track such sound sources related to the breaking wave process, passive acoustic methods can be exploited. As Loewen and Melville [3] stated, detection of breaking event enables estimation of wave energy loss through measurements of the amount of radiated acoustic energy in this process.

Nowadays, breaking waves are observed using different measuring techniques as – tracking of sea spikes with radar [4], video tracking of whitecap evolution [5, 6] or infrared remote sensing of breaking waves [7].

Alternatively, sometimes more effective various passive and active acoustic methods can be employed [8]. Each of enumerated methods has limitations concerning the space and time scales of the observations. In particular, due to the problem of the ambient sea noise presence, the passive acoustic tracking of breaking events is difficult to perform especially in case of small-scale breakings [8].

The other factors, which should be taken into consideration, are a dynamic range of the sensors, their durability against of stormy weather or chemical corrosion. The peculiar construction and relatively deep underwater deployment of hydrophones prevent them from the corrosion and destructive power of breaking waves.

1. EXPERIMENT AND INSTRUMENT DESCRIPTION

Acoustical observations of breaking wind waves have taken place in the southern part of Gulf of Gdansk, Fig. 1, in November 2009. The sea depth in the area was around 20 m. The point was chosen due to parallel continuous measurements of the wave field by a *Datawell Waverider*, moored in the proximity of the acoustical observations.

Fig. 1. Location of the experiment conducted in November 2009 (*www.d-maps.com)*

Noise measurements were performed using an Autonomic Hydroacoustic System (AHS) schematically shown in Fig. 2. Base of the AHS is a steel container of 1m height and with 0.4 m diameter, which embodies electronic components with amplifiers, controlling computer, AD converters and a power supplying battery set. Outside the container four omnidirectional hydrophones were mounted at the end of four forming a cross arms. Each of 2 m length arm was attached to the container and oriented parallel to the sea surface. Opposite hydrophones were at the distance of 4.4 m. The hydrophones were placed at the depth of 10 m beneath the sea surface. Reson TC 4032-5 hydrophones equipped with integral low-noise 10 dB preamplifiers were used as sensors. Additional amplification of the returning signal was possible. Hydrophone's sensitivity is equal -170 dB re 1 V/µPa at 1m and is linear in the frequency range 0.1–15 kHz. General purpose of the AHS is wider, but in the experiment under consideration, only passive acoustical unit was used. The waverider buoy measuring at the same time wave parameters was launched at the distance of one nautical mile from the AHS.

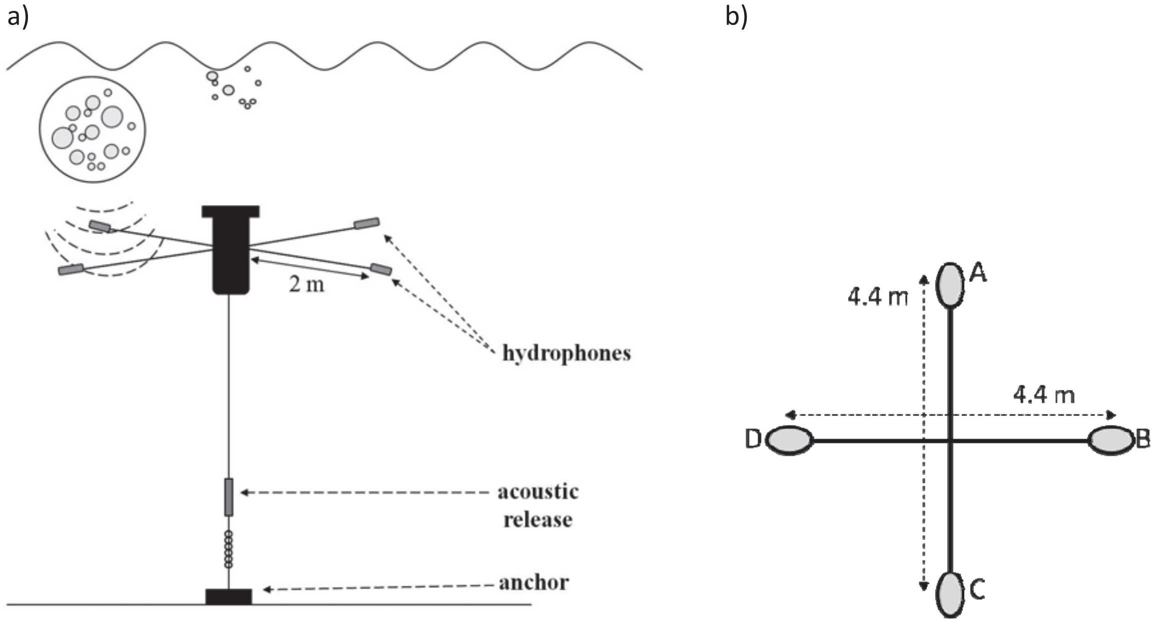

Fig. 2. a) Scheme of the Autonomic Hydroacoustic System mounted during experiment on the Baltic Sea; b) top view of the arms of the AHS with hydrophones fixed at the end of the arms

2. DATA COLLECTING AND POSTPROCESSING

Measurements of underwater noise were conducted for about 5 days. Every 150 s all hydrophones were simultaneously recording 90 s underwater noise sequences. Thus the individual measuring cycle lasted 4 minutes. Overall time of measurement was about 118 hours. In the DSP controlling system, signals from hydrophones were sampled at 50 kHz frequency and digitized at 12-bit resolution. Amplification was executed by four independent preamplifiers. Filtering in low- or high pass band was also possible. Preprocessed data were saved on the separate compact flash cards.

In postprocessing acoustic signals were filtered in 200–5000 Hz frequency band. Subsequently, cross-correlation functions for acoustic signals from opposite hydrophones were calculated. The aim and details of this last procedure is described in Section 3.

3. CORRELATION TIME SERIES AND THEIR INTERPRETATION

The sound coming from an acoustic source arrives at each hydrophone at a time determined by the source and hydrophone positions. Information on the hydrophones position and time difference of arrival of sound between each of hydrophone allows us to locate the sound source. For that reason, signals registered at opposite hydrophones were cross-correlated.

Time delay estimation was accomplished by using the general cross correlation method for signals at two hydrophones and determining position of the peak in the correlation. Before the correlation, signals were filtered in the range 200–5000 Hz, to obtain higher S/N ratio and to improve the estimator performance. This is an equivalent of a window function in the general cross correlation method. A whole post processing was performed in *Matlab* environment where unbiased estimate of cross correlation function was implemented in a form (1):

$$
\begin{aligned}
R_{xy,unbiased}(\tau) &= \frac{1}{T-|\tau|}R_{xy}(\tau) \\
R_{xy}(\tau) &= \begin{cases} \sum_{t=0}^{T-\tau-1} x_{t+\tau}y_t^* & \tau \geq 0 \\ R_{xy}^*(-\tau) & \tau < 0 \end{cases}
\end{aligned}
\tag{1}
$$

where $x_{t+\tau}$ and y_t are samples of signal, τ – is a time delay, T – length of a vectors $x_{t+\tau}$ and y_t related to observation time. To identify event of wave breaking, the observation time T should be appropriately chosen so that the source position does not change considerably during this time. For this reason, we have chosen 1024 as a length of each correlated dataset, which corresponds to 0.02 s of a noise record. Subsequently, the envelope of each cross correlation function was determined. As a result of 90 s dataset postprocessing, we have obtained two correlation matrices. Example of such result is shown in Fig. 3.

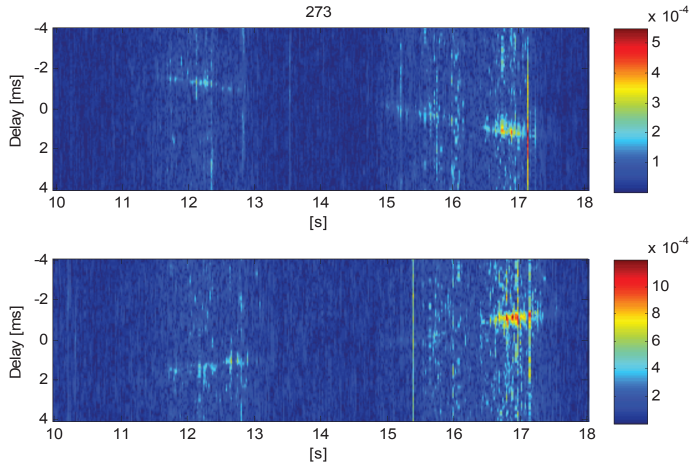

Fig. 3. Correlation of the noise time series obtained for two pairs of hydrophones.
Color denotes value of the unbiased cross correlation function

Maximum values of cross correlation functions are arranged in simply noticeable streaks. These smudges correspond to the passage of acoustic sources motion. Using equations proposed by Ding and Farmer [8]:

$$
\begin{aligned}
x_s &= \frac{c\tau_{AC}}{2}\left[\left(1-\frac{c^2\tau_{BD}^2}{d^2}\right)\frac{d^2-c^2\tau_{AC}^2+c^2\tau_{BD}^2}{\Delta^2}+\frac{4z_s^2}{\Delta^2}\right]^{1/2} \\
y_s &= \frac{c\tau_{BD}}{2}\left[\left(1-\frac{c^2\tau_{AC}^2}{d^2}\right)\frac{d^2-c^2\tau_{BD}^2+c^2\tau_{AC}^2}{\Delta^2}+\frac{4z_s^2}{\Delta^2}\right]^{1/2}
\end{aligned}
\tag{2}
$$

where c – sound speed, τ_{AC}, τ_{BD} – time delay between two opposite hydrophones, d – spacing between opposite hydrophones and $\Delta^2 = d^2 - c^2\tau_{AC}^2 - c^2\tau_{BD}^2$, and assuming that the sound source is located on the sea surface $z_s = 0$ and the position of the AHS is fixed, we can calculate position x_s, y_s of the source of sound. Depending on the direction of the vector of the source motion, smudges on the correlation matrix image exhibit in a different way. Examples of numerical modeling of the correlation matrices, reflecting the various point source propagation directions are shown in Fig. 4.

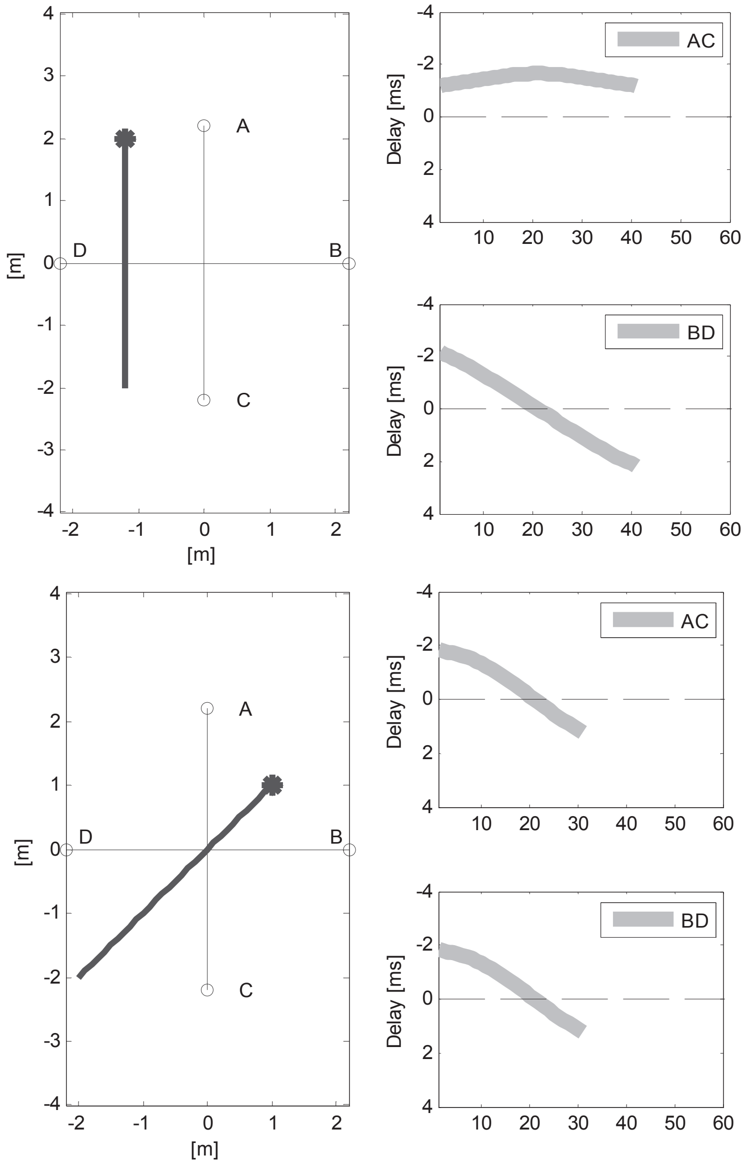

Fig.4. Each image presents a case of wave arriving from different directions. Black line denotes wave path and the star points wave direction. Hydrophones are depicted as empty circles and described by letters, the view is from above the sea surface. Smaller plots show theoretical correlation time series related to specific source direction case, where gray lines are related to peaks in correlation time series

During analysis of correlation time series obtained from experimental data, we have assumed that single peaks take form of straight lines. The reason of this assumption is a lack of good, automatic procedure of finding significant peaks in correlation time series. Even if streaks were clearly noticeable in ‘eye-analysis’, due to many maximum values in the single time series, it caused difficulties in applying automatic procedures to find proper maximum. Frequently it led to indication of a false time delay, which may cause an error in determining source position and velocity.

Another frequently encountered difficulty was blurring of the streak in one or both correlation time series. It this case it was only achievable to count such sources and determine duration of a breaking event but information about their velocity was impossible to specify. This effect was mentioned earlier [9] and was described as finite source dimension effect. In our examination we have considered only these events which we could not only detect but also parameterize.

4. ESTIMATED PARAMETERS OF ACOUSTIC EVENTS

Continuous measurements of underwater ambient noise resulted in obtaining information about wave statistics – number, duration and direction of propagation of water waves in the area close to the AHS location. Radius of the area from which we have been capable of detecting acoustic events was around 20–30 m.

The result of analyzing single 90 s dataset is schematically presented in Fig. 5. Several acoustic events have been identified jointly with determining their velocity, duration and direction of propagation. This last parameter was estimated in relation to the hydrophones position on the AHS, as the compass was not working properly. Therefore, we cannot give cardinal directions of the waves propagation. For this particular example, mean velocity of propagation was 5 m/s and mean direction 41°. A closer look at the duration of registered events, which was less than 1 s, gives a suggestion that only the most acoustically active part of wave breaking was identified. Another possible reason may be the influence of a background noise, masking acoustic events. As a result the number and duration of breaking waves can be underestimated. To improve further measurements and acoustic events recognition and parameterization, higher amplification of input signals should be applied.

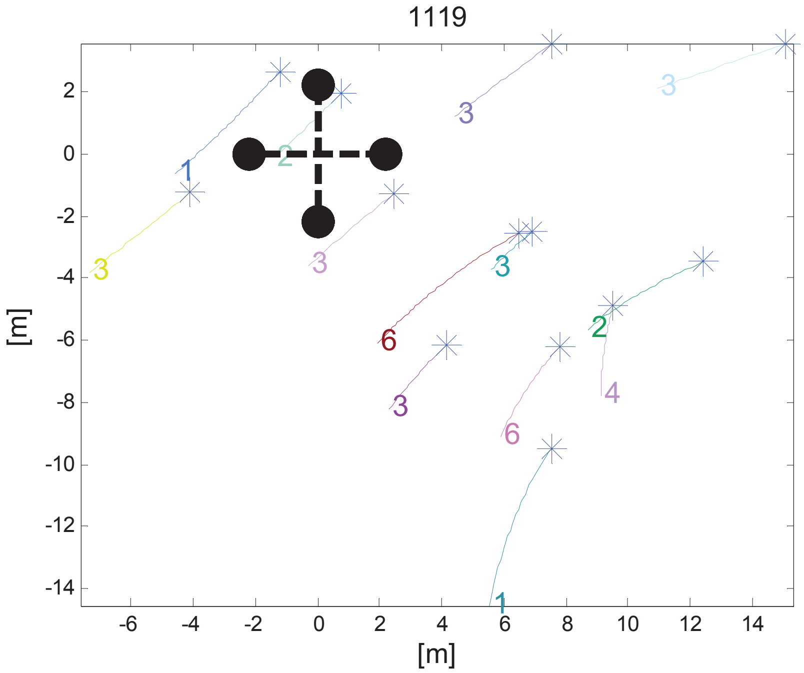

Fig. 5. Schematic presentation of the results of acoustic events recognition and tracking. It is a top view of the sea surface, where black circles indicate hydrophones position. Curves denote source trajectories and stars point the direction of motion. Numbers correspond to the order of appearance of individual events

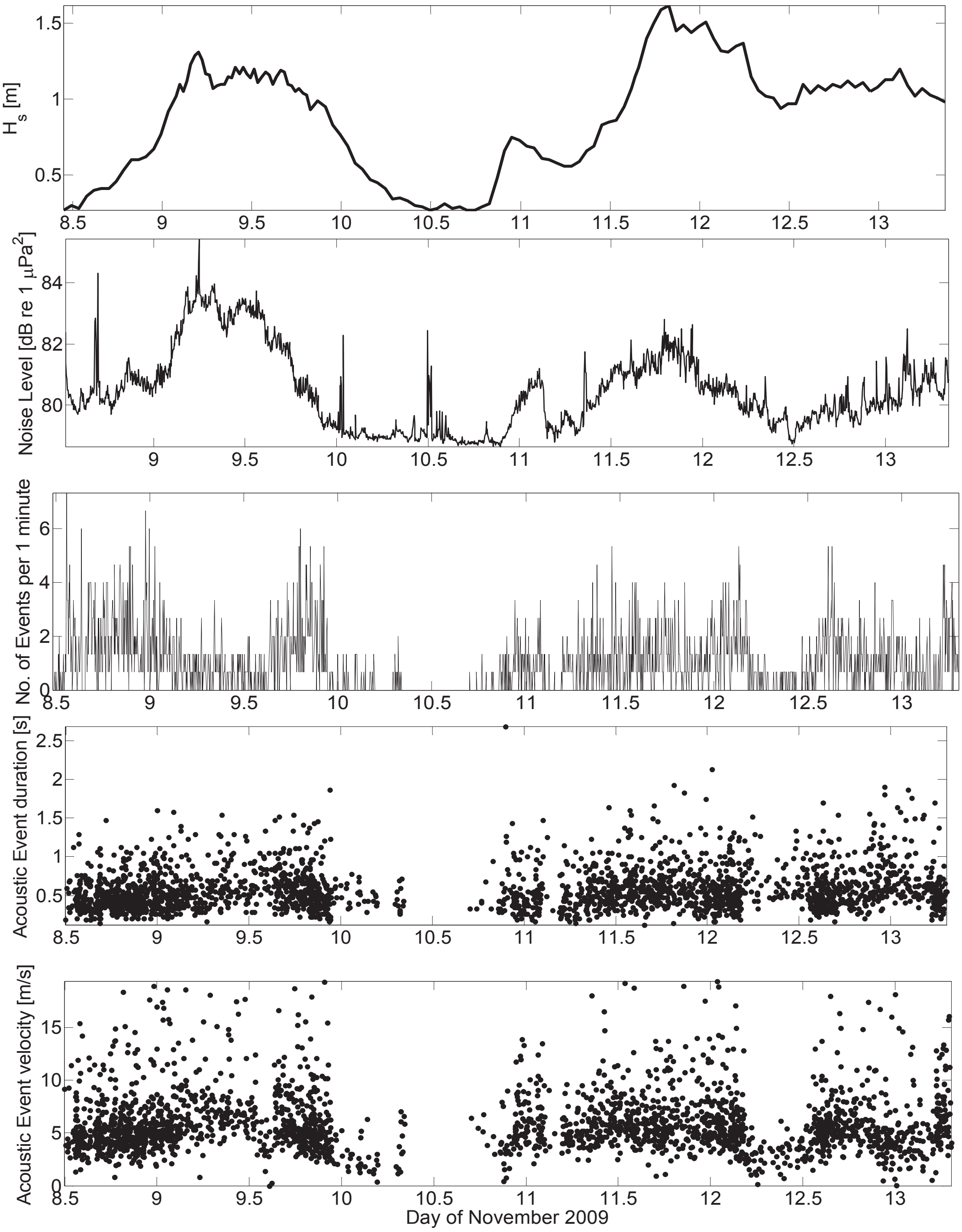

Fig. 6. Time series of a) significant wave height, b) noise level at single hydrophone averaged in 90 s, c) number of detected and tracked acoustic events, d) acoustic event duration and e) event velocity

As it was mentioned earlier, our acoustical experiment was conducted in a vicinity of the *Datawell Waverider* buoy of the Institute of Hydroengineering, PAS. These measurements provided us with various directional and scalar wave parameters. Since the investigation of relationship of acoustical measurements and wave parameters is not the intention of this work, we show only time series of significant wave height just to introduce the forthcoming course of our analysis. Fig. 6 a) presents time series of significant wave height registered by the *Waverider* buoy and 6 b) shows corresponding noise level averaged in the time interval of 90 s, measured by a single hydrophone. Values of H_s might not correlate very well with noise under breaking waves but when we filter out the swell components from the sea surface elevation time series, the correlation would improve [10]. That would be one of the following steps in further data analysis. Fig. 6 c) represents the number of acoustically tracked surface events. Growth of the H_s is accompanied by increase in number of acoustic events, however only to the certain point. While the significant wave height and mean noise level is relatively high, there is a significant decrease in the number of recognized events. This might be associated with the masking effect of the increasing background noise. Especially small breakers may be not detectable due to the high level of this noise or they can merge giving no significant images, as was suggested by Ding and Farmer [9]. Event duration and velocity appear to change in accordance to the noise level as well as significant wave height.

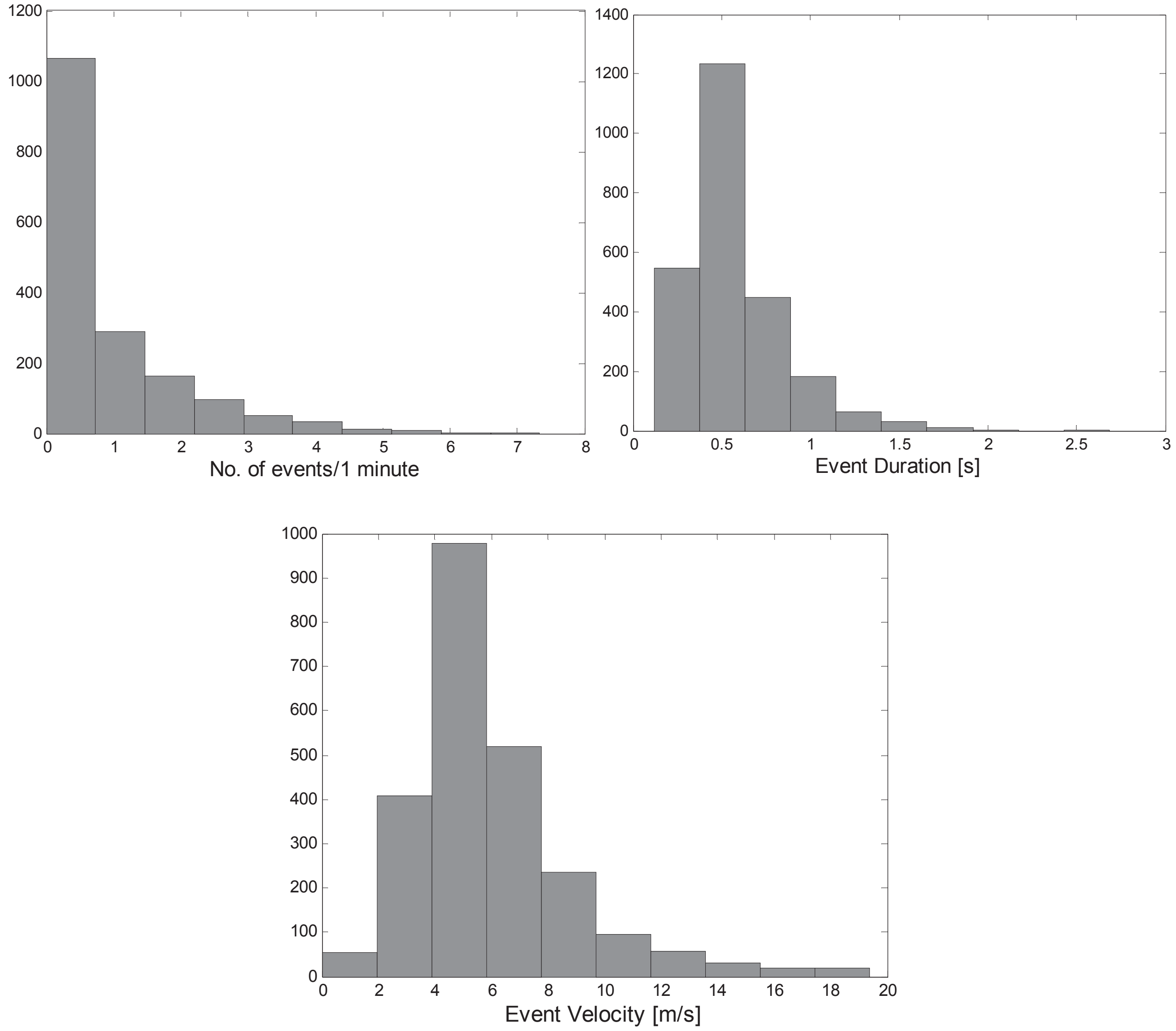

Fig. 7. Histograms of number, duration and velocity of recognized acoustic events, respectively

Histograms of parameters of tracked acoustic events are shown in Fig. 7. In the most cases not more than 2–3 acoustic events per 1 minute were parameterized. Frequently the reason of this was blurred or absent streak in the correlation time series. Thus even if we have observed a pattern connected with the passage of acoustic source, we could not estimate its velocity and therefore the event was not counted. Time of observation of interesting events was not longer than 2.5 s what is comparable to previous similar experiment of Ding and Farmer (1994). The event velocity values ranged from 1 to tens of meters per second (the highest values are not shown on the histogram, assumed to be an error in correlation streaks marking) but mean event velocity was around 5 m/s.

5. SUMMARY

However, the passive acoustic methods are not a quite a new tool in estimating breaking wave statistics, they still need theoretical and technical advance to achieve technology **maturity** and understanding properly the process of breaking.

Our experiment has shown the possibilities of passive acoustics in tracking and parameterization of breaking waves, which are considered to be the primary source of underwater noise. It has been proved that even by simple, preliminary acoustic data analysis, the number of events and their features such as duration, direction and motion can be estimated. At this stage, we have assumed that breaking wave is a point source of the sound, located at the sea surface what can be a certain cause of errors. In enhancement of our approach, we have to deal with this issue as well as with changing position of the AHS.

It should be pointed out that to obtain results that are more reliable, the improvement of adopted approach should be done. However, results of first attempt to the issue seem to be promising. Also comparing acoustic parameters of breaking events with proper wave characteristics would provide very valuable information essential in estimation of wave energy dissipation.

ACKNOWLEDGMENTS

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REFERENCES

[1] Farmer D. M., Vagle S., On the determination of breaking wave distributions using ambient sound, J. Geophys. Res. 93, (1988), 3591–3600.

[2] Deane G. B., Sound generation and air entrainment by breaking waves in the surf zone, J. Acoust. Soc. Am. 102(5), (1997), 2671–2689.

[3] Loewen M. R., Melville K., Microwave backscatter and acoustic radiation from breaking waves, J. Fluid. Mech., 224, 601–623.

[4] Phillips O. M., Posner F. L., Hansen J. P., High range resolution radar measurements of the speed distribution of breaking events in wind-generated ocean waves: surface impulse and wave energy dissipation rates, J. Phys. Ocean., 31, (2001), 450–460.

[5] Melville W. K., Matusov P., Distribution of breaking waves at the ocean surface, Nature, 417, (2002), 58–63.

[6] Hwang P. A., Sletten M. A., Energy dissipation of wind-generated waves and whitecap coverage, J. Geophys. Res., 113, 2008.

[7] Jessup A. T., Zappa C. J., Loewen M. R., Hesany V., Infrared remote sensing of breaking waves, Nature, 385, 52–55.

[8] Ding L., Farmer D. M., A signal-processing scheme for passive acoustical mapping of breaking surface waves, J. Atm. Ocean. Tech., 9, (1992), 484–494.

[9] Ding L., Farmer D. M., Observations of breaking surface wave statistics, J. Phys. Ocean., 24, (1994), 1368–1387.

[10] Felizardo F. C., Melville W. K., Correlations between ambient noise and the ocean surface wave field, J. Phys. Ocean., 25, (1995), 513–532.