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Some problems of analyzing bio-sonar echolocation signals generated by echolocating animals living in the water and in the air

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In this paper we present some similarities and differences of bio-sonar echolocation signals in water and in the air. The echolocation cues of marine mammals and bats are frequency and amplitude modulated signals. The main problems to describe such signals are envelope detecting and Time-Frequency decomposition. On this poster some DSP algorithms, which may be used to analyze this type of signals, are presented. Basic linear STFT calculation, nonlinear Wigner-Ville'a spectrogram and some Time-Scale representation of signal using wavelets are the compared methods of estimation of the frequency modulation function. We present also analysis of capability of acoustic identification of species bats.

1 Introduction to bat sounds

Echolocation signals of various species of bats differ on numerous grounds. Some differences are based on parameters associated with amplitude and time-frequency parameters. If signal envelope is known it is possible to reconstruct the signal by means of amplitude modulation. The problem of determining frequency modulation function is very complex due to Gabor-Heisenberg uncertainty principle. Study results of a comparison of the estimation quality of bats' echolocation signal parameters are presented in the following paper. Finding a suitable method of digital processing of signals my have a significant influence on the development of biosonar employing 3D space imaging techniques described in papers [11] and allow more effective recognition of bat's individual features on the basis of the sounds they make [2],[3].

2 Material and methods of biosonar signal processing

2.1 Signals

Echolocation signals of bats native to Lower Silesia region of Poland (Noctula Noctula, Myotis Daubentoni, Plecotus auritus species) recorded with the use of Avisoft UltraSoundGate system were used as study material. On the grounds of the research presented in paper [12] synthesis of echolocation signals with a given FM modulation was performed. All the signals were presented in digital form. 250 kHz sampling frequency and 16 bit resolution were used. In order to compare bat signals propagated in the air analysis was also performed of Physeter catodon sperm whale's signal emitted in water. In this case the sampling frequency was 12 kHz

2.2 Signal processing

From among various methods of digital signal processing the following algorithms were selected and compared:

- STFT – Short Time Fourier Transform,
- WV – Wigner – Ville distribution,
- PWV – Pseudo Wigner – Ville distribution,
- SPWV – Smoothed Pseudo Wigner – Ville distribution,
- SPAW – Smoothed Pseudo Affine Wigner – Ville distribution,
- DFLA – D – Flandrin distribution.

Presented below are the relations and properties of the above mentioned transforms:

STFT [4]:

$$F_x(t,v;h) = \int_{-\infty}^{+\infty} x(u)\cdot h^*(u-t)\cdot e^{-j2\pi vu}du \qquad (1)$$

where: x – analysed signal, t – time, v – frequency, h(t) – window of analysis concentrated around t=0, v=0. This transform perfectly represents harmonic signals with constant frequency (in the window of analysis).

WV [13]:

$$W_x(t,v) = \int_{-\infty}^{+\infty} x\left(t+\frac{\tau}{2}\right)\cdot x^*\left(t-\frac{\tau}{2}\right)\cdot e^{-j2\pi v\tau}d\tau \qquad (2)$$

Cohen's class transform abased on distribution of energy in spectrum. It perfectly represents signals with linear frequency modulation. In case of other signals interferences appear, which makes spectrogram analysis difficult.

PWV [13],[4]:

$$PW_x(t,v) = \int_{-\infty}^{+\infty} h(\tau)\cdot x\left(t+\frac{\tau}{2}\right)\cdot x^*\left(t-\frac{\tau}{2}\right)\cdot e^{-j2\pi v\tau}d\tau \qquad (3)$$

in case of this type of distribution, undesirable spectrum elements are minimized by means of window h(τ).

SPWV [13][4]:

$$SPW_x(t,v) = \int_{-\infty}^{+\infty} h(\tau)\int_{-\infty}^{+\infty} g(s-t)\cdot x\left(s+\frac{\tau}{2}\right)\cdot x^*\left(s-\frac{\tau}{2}\right)ds\cdot e^{-j2\pi v\tau}d\tau \qquad (4)$$

improved version of PWV distribution, in which smoothing occurs in the time domain (window g(t)) and frequency domain (window h(τ)).

SPAW [10]:

$$P_x^k(t,v) = \int_{-\infty}^{+\infty} \frac{\mu_k(u)}{\sqrt{\lambda_k(u)\lambda_k(-u)}} T_x(t,\lambda_k(u)v;\psi)T_x^*(t,\lambda_k(-u)v;\psi)du \qquad (5)$$

where T_x is a wavelet transformation given by equation (6),

$$\psi(t) = \left(\pi t_0^4\right)^{-\frac{1}{4}} \exp\left[-\frac{1}{2}\left(\frac{t}{t_0}\right)^2 + j2\pi v_0 t\right] \qquad (6)$$

and λ_k is a Morlet wavelet given by formula (7)

$$\lambda_k(u,k) = \left(\frac{k\left(e^{-u}-1\right)}{e^{-ku}-1}\right)^{\frac{1}{k-1}} \qquad (7)$$

when k = 2 affine smoothed pseudo Wigner – Ville distribution is obtained.

DFLA [10],[4]:

$$D_x(t,v) = v\int_{-\infty}^{+\infty}\left(1-\left(\frac{\chi}{4}\right)^2\right)\cdot R(x,v,\chi)\cdot e^{-j2\pi\chi v\tau}d\chi \quad (8)$$

where R(x,v,χ) is given by equation (9)

$$R(x,v,\chi) = x\left(v\cdot\left(1-\left(\frac{\chi}{4}\right)^2\right)\right)\cdot x^*\left(v\cdot\left(1-\left(\frac{\chi}{4}\right)^2\right)\right) \quad (9)$$

this distribution perfectly represents hyperbolic frequency modulation, type:

$$\frac{1}{\sqrt{v}} \quad (10)$$

2.3 Methods of analysis

The obtained and generated signals were used as test signals for comparison of algorithm presented in subsection 2.2. Envelope analysis and suitable time-frequency (time-scale) transformation was made. A toolbox for MatLab® suite called TFTB (Time Frequency ToolBox) version 0.2 and documentation was used during the study [4],[5].

3 Results of analysis

3.1 Enveloppe detection

For the purpose of signal envelope discrimination, an artificial signal was used. It was frequency modulated by means of hyperbolic function and amplitude modulated by means of Gaussian function (11):

$$y(t) = e^{-\pi\left(\frac{t-t_0}{T}\right)^2} \quad (11)$$

The results were presented in Fig. 1. In order to compare algorithm effectiveness an analysis was also performed of envelope discrimination for actual signals i.e. echolocation signal of a bat of species Plecotus auritus and a sperm whale of Physeter catodon species. The results of all those analyses were presented as suitable graphs in Fig. 2 and Fig. 3.

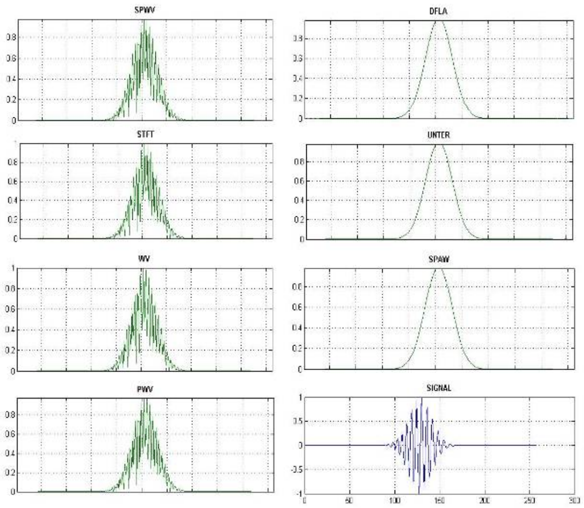

Fig. 1. Envelope detection of an artificial signal.

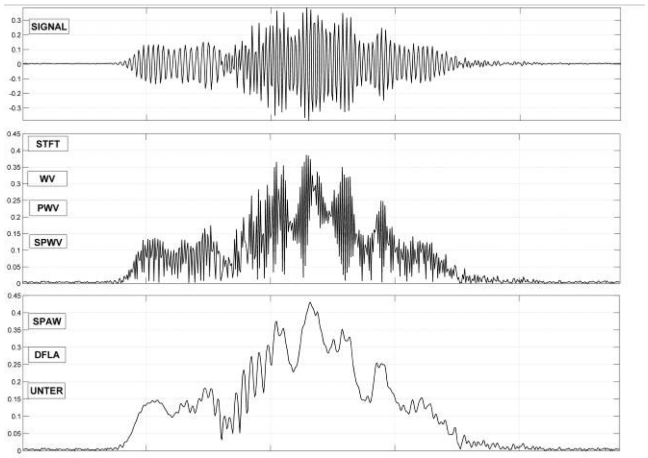

Fig. 2. Envelope detection of an actual Plecotus auritus bat signal.

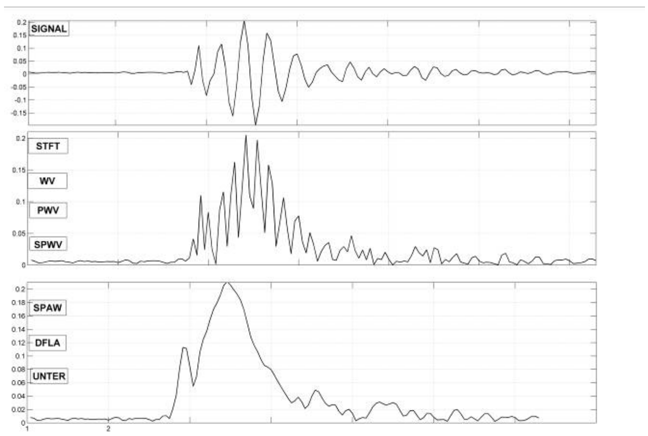

Fig. 3. Envelope detection of an actual Physeter catodon sperm whale signal.

3.2 Time frequency analysis

Similarly to section 3.1, the study was performed for a group of time-frequency decompositions using synthesized signals and actual sounds made by bats and a selected marine mammal. In accordance with information provided in papers [2],[12] the echolocation signals of bats studied here are frequency modulated signals, for which the modulation function is a linear or hyperbolic one. It was, therefore, decided to select time-frequency decomposition of deterministic signals by means of methods described in subsection 2.2 as research method. It was also suggested to examine root mean squared error (RMS) which is given by equation (14). Linear modulated signal LFM (12) and power modulated signal PFM were used as test signals (13).

$$LFM(t) = e^{i2\pi\left(f_0 + \frac{k}{2}t\right)t} \tag{12}$$

$$PFM(t) = e^{i2\pi\left(f_0 t + \frac{c}{1-k}|t|^{1-k}\right)} \tag{13}$$

The results were presented in Fig. 4 and Fig. 5 in graphical form.

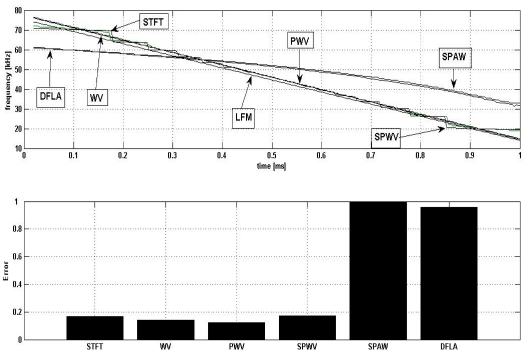

Fig. 4. Linear function approximation.

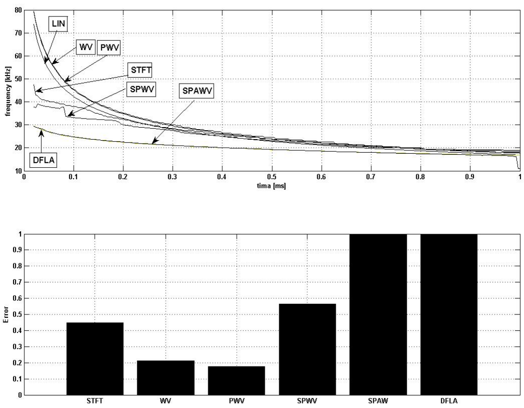

Fig. 5. Power function approximation.

Approximation error was specified on the basis of equation (14):

$$RMS_{Err} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\widehat{fm} - fm\right)^2} \tag{14}$$

where fm indicates LFM or HFM function, and $\widehat{fm}$ is its approximation using a selected algorithm.

In Table 1 below analysis results were shown of the signals of Myotis Daubentoni bat, which were obtained using linear function approximation resulting from estimation of frequency modulation function. Such treatment is justified because frequency modulation for this species is close to linear (15):

$$f(t) = A \cdot t + B \tag{15}$$

Since the studied signal is a nonstationary one, parameters A and B estimation error was not given.

	A [kHz/ms]	B [kHz]
STFT	-8.16	64
WV	-7.21	56.7
PWV	-5.27	41.2
SPWV	-8.06	63.3
SPWA	-3.53	56.9
DFLA	-4.53	63.2

Table 1. Estimation of frequency modulation function parameters (15) for Myotis Daubentoni bat.

Fig. 6 below shows Winger-Ville distribution, on the grounds of which parameters A and B were determined.

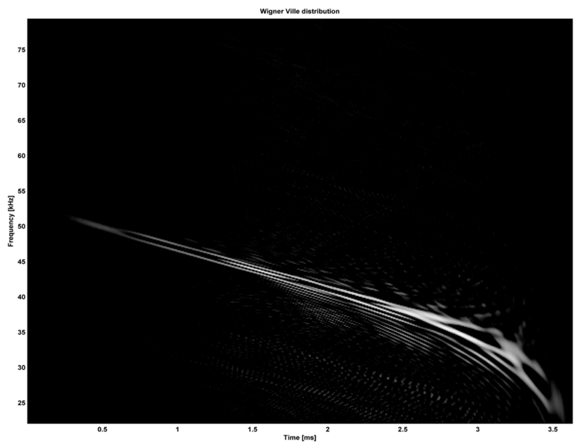

Fig. 6. Wigner-Ville distribution of echolocation signal of Myotis Daubentoni bat, which was recorded with a time-expansion recorder. Sampling frequency was 44.1 kHz, which for this type of recording is within frequency band up to 220.5 kHz.

For Nyctaulus Noctula species of bat an analysis of signal with determination of exponential modulated function was performed (16)

$$f(t) = C \cdot e^{-kt} \tag{16}$$

Table 2 below shows the results of estimation of frequency modulation function parameters on the basis of echolocation signal of a Nyctaulus Noctula species of bat.

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	k [1/s]	C [kHz]
STFT	0.0605	58.5
WV	0.0966	47.4
PWV	0.0448	50.9
SPWV	0.0607	57.9
SPWA	0.0795	51.9
DFLA	0.0964	43.3

Table 2. Estimation of frequency modulation function coefficients (16) for Nyctaulus Noctula.

The image of echolocation call in the form of Smoothed Pseudo Wigner-Ville distribution was shown in Fig. 7.

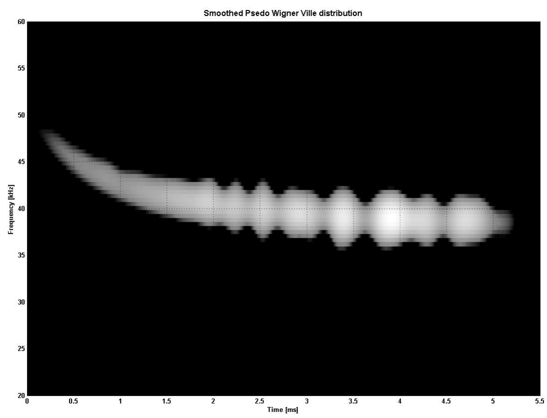

Fig. 7. Smoothed Pseudo Wigner-Ville distribution of echolocation call of Noctaulus Noctula.

The figure below also shows time-frequency transformation for a sperm whale.

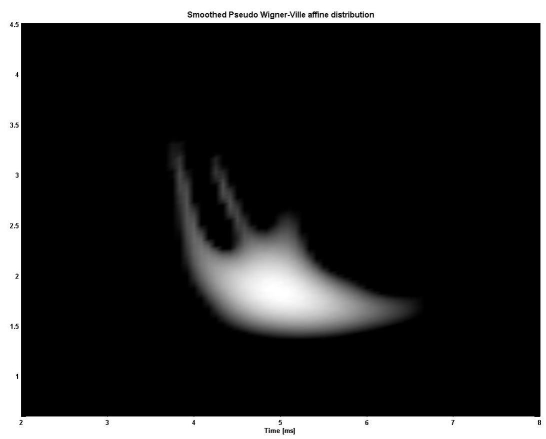

Fig. 8. Time-frequency decomposition of a Physeter catodon sperm whale signal.

4 Conclusions

On the grounds of the performed studies and the obtained results the matter of processing bio-echolocation signals can be regarded as a problem which is complicated in the area analysis method selection and calculation complexity. It is important to note that among the analysed methods of methods of digital echolocation signal processing it is not possible to name a single method, which would allow perfect description of a studied signal. In section 3.1 analysis of the envelope of echolocation signals was the region of interest. On the basis of Fig. 1 it is possible to conclude that the best envelope approximation is obtained using transformations based on wavelets theory. It can also be proven that the other algorithms approximate envelope on the basis of the absolute value of the studied signal. In accordance with the presented wavelet transformations it can be admitted that envelope is a representation of a signal on the lowest level of scale factor. It is especially important to notice the structure of envelope of echolocation signals for both bats and sperm whales, which cannot be described by means of a simple mathematical model. Since, as was described in section 1, time-frequency type of signal representation is most information rich, the main focus in this study was on this type of transformation. Comparative analysis for the algorithms mentioned in section 2.2 suggests that both linear frequency modulation signal and power modulation signal is best represented by Pseudo Wigner – Ville transformation (in the sense of mean squared error). It must also be stressed that in case of all types of transforms signal windowing was done on an arbitrary basis with the use of Hamming window. In the second part of section 3.2 analysis of the capabilities of mathematical description of frequency modulation function of actual echolocation signals of various bat species was performed. Assuming a given modulation type in advance allows estimation of modulation function using time-frequency representations. Table 1 shows the results of this kind of modelling for Myotis Daubentoni signal. Analysis of the obtained results and consideration of the results of LFM signal analysis leads to a conclusion that the most faithful representations are achieved with the use of classical STFT methods and Cohen's class distributions (WV, PWV, SPWV). It can also be noted that there are distinct interferences near 3 [ms] (see Fig. 6). It is associated with departure from the linearity of modulation for actual signal. Spectrum smoothing is aimed at minimization of this type of unwanted effects which make analysis of this type of distribution more difficult. It can be observed for SPWV distribution of Noctaulus Noctula bat signal (shown in Fig. 7). For the sake of comparison of the parameters of bio-echolocation signals propagated in various media time-frequency decomposition of Physeter catodon sperm whale signal was shown in Fig. 8. It can be observed that signals emitted in water by marine mammals have frequencies that are lower then air propagated signals by a decade. It is associated with wave length and attenuation values for different frequency bands in these two media. Calculation complexity of the presented algorithms, especially in case of wavelet transformations, should also be emphasized. Although it was not a part of the study, it can easily be shown that the time of calculations performed on a PC class computer is much longer in case of SPAW and DFLA transformations than in case of other distributions. Analysis of the possibility of processing of the presented signals on a platform based on DSP CPU, which is dedicated to this kind of applications, is an interesting idea both from practical and research point of view. Wider knowledge of echolocation calls and analysis of bat's localisation mechanisms can result in development of air operating navigation devices, the functioning of which can be based on bio-echolocation mechanisms. The attempts to mathematically model bats' signals by means of advanced methods of digital signal processing can also contribute to the development of non-invasive, automatic recognition and classification of individual features (species, gender, age) of bats.

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