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Recognition and Tracking of Targets with Periodic Sound Sources by Passive Acoustic Beamforming

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ABSTRACT

The sound signatures of many vessels, ground vehicles and aircrafts exhibit strong periodic components. In the spectral domain their power is concentrated in narrow bands. These lines can be easily detected in the spectral background noise. This knowledge is used to improve the performance of a small acoustic array for the recognition and tracking of sound sources by assuming that one spectral peak from one spatial bearing is generated by one sound source.

In the frequency domain, the strongest narrow lines relative to the broadband spectral noise are detected. For every detected spectral peak the bearing of the sound source is estimated by the robust conventional beamforming (phase shift and sum beamformer). A small steering window describes the precision of the bearing estimation. The target steering pattern is the accumulation of the periodic components of one acoustic source for one direction. The certainty of target recognition is given by a confidence measure between 0 and 1. The increase in the certainty of the signal detection and the decrease in the uncertainty of the bearing estimation result in an improved target discrimination. The ideas of the signal processing method will be presented. The effectiveness will be demonstrated by examples of tracking ground vehicles using a small acoustic array.

1.0 INTRODUCTION

Passive acoustic arrays are used to observe the surrounding area. The intention is to recognize approaching objects on the basis of the received sound signatures. To achieve a good directivity the dimensions of the antenna should be large compared to the wavelength of the acoustic signals. In underwater acoustics long towed arrays are applied for the detection and the location of ship noise. In airborne sound small microphone antennas are used to detect and to track the bearings of ground vehicles and aircrafts.

The emitted sound of many vessels, ground vehicles and aircrafts (apart from jets) exhibit both periodic narrowband components and random broadband noise. The periodic components are exceptionally loud in the low frequency range from 20 Hz to 200 Hz. The measured sound signature of a ground vehicle passing the microphones is shown in Fig. 1. The upper diagram contains the received acoustic level $RL(t)$ for three octave bandpass filters as a function of time t. The narrow peak (at 80 s) is caused by a detonation. For the time interval, which is marked in yellow, the power spectral density $PSD(f)$ as a function of frequency f is shown in the lower diagram. It is estimated by averaging the short time spectra. In the spectral domain the

Paper presented at the RTO SET Symposium on "Capabilities of Acoustics in Air-Ground and Maritime Reconnaissance, Target Classification and Identification", held in Lerici, Italy, 26-28 April 2004, and published in RTO-MP-SET-079.

power of the periodic components is concentrated in narrow bands. Because these lines are very strong they can be easily detected in the spectral broadband noise.

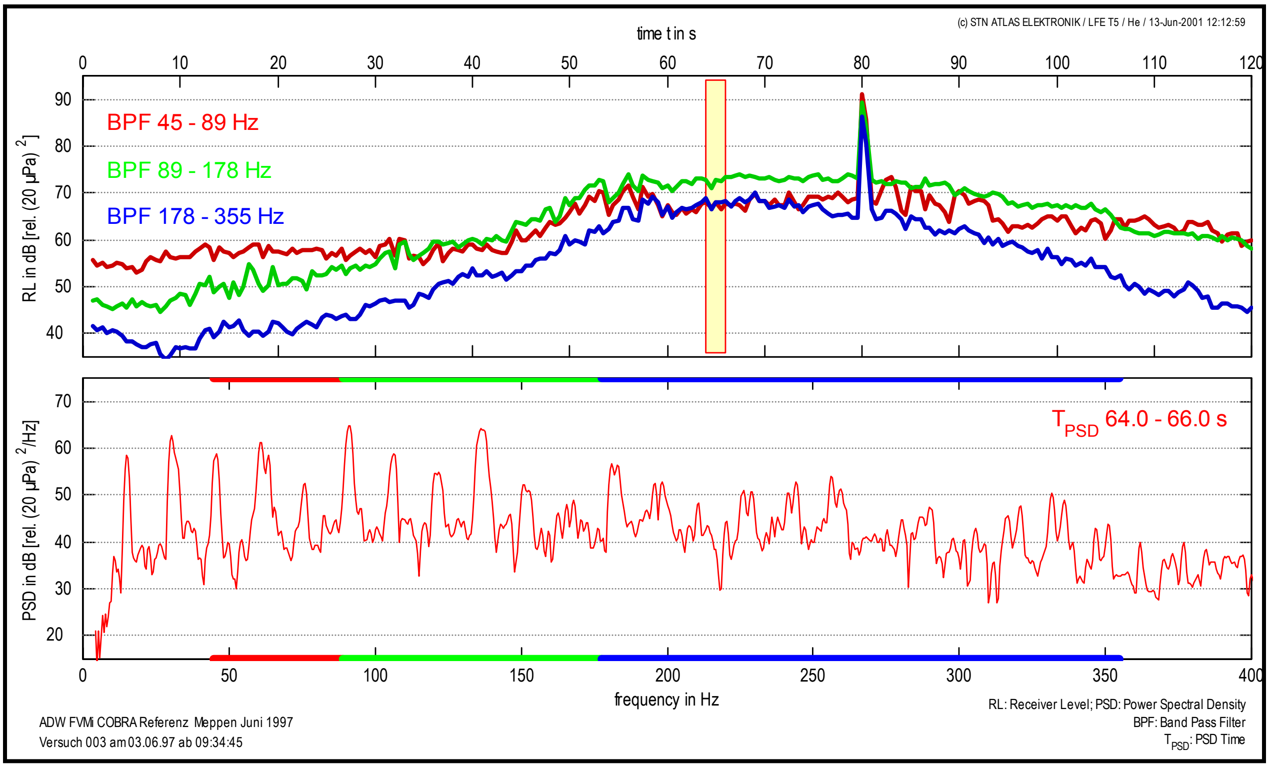

Figure 1: Acoustic signatures of a ground vehicle

An acoustic antenna is made of an array of several microphones, which receive the sound emitted by the sources and transmitted by the airborne sound channel. For many applications it is not possible to choose an antenna with dimensions large compared to the wavelength. In the air an acoustic wave of 100 Hz exhibits a wavelength of about 3.40 m. A small two-dimensional acoustic array is shown in Fig. 2. Six microphones are placed on a circle with a diameter of 1 m and the seventh microphone is placed in the centre. This antenna is used for all examples in this paper.

The received signals from the array of sensors are processed to estimate the bearing φ to the sound source. One well-known method is conventional beamforming. Assuming far field conditions the received signal can be modelled as a plane wave relative to the array. The beamforming can take place in the time domain by a time-delay-and-sum beamformer or in the frequency domain by a phase-shift-and-sum beamformer [Nielsen 1991]. The beam pattern in Fig. 2 is calculated by conventional beamforming. The beam power $RL(\varphi,f)$ is normalized relative to the power $RL_0(f)$ in the centre of the circular array.

Conventional beamforming is a rugged method in order to safe detection of the acoustic sources. For low-frequency sound the bearing estimation is imprecise especially if several sources are observed. For the antenna in Fig. 2 the 3 dB width of the main beam is 162 ° at 100 Hz and 76 ° at 200 Hz. High-resolution methods are used to improve the precision of the bearing estimation and to discriminate different sources [Nielsen 1991] [Childers 1978] [Bienvenu 1981]. Additional assumptions (concerning the sound sources, the sound channel or the background sound) permit to optimize the process of beamforming. The efficiency of the optimization is severely limited if an assumption is violated. Therefore often high-resolution beamforming is controlled by conventional beamforming.

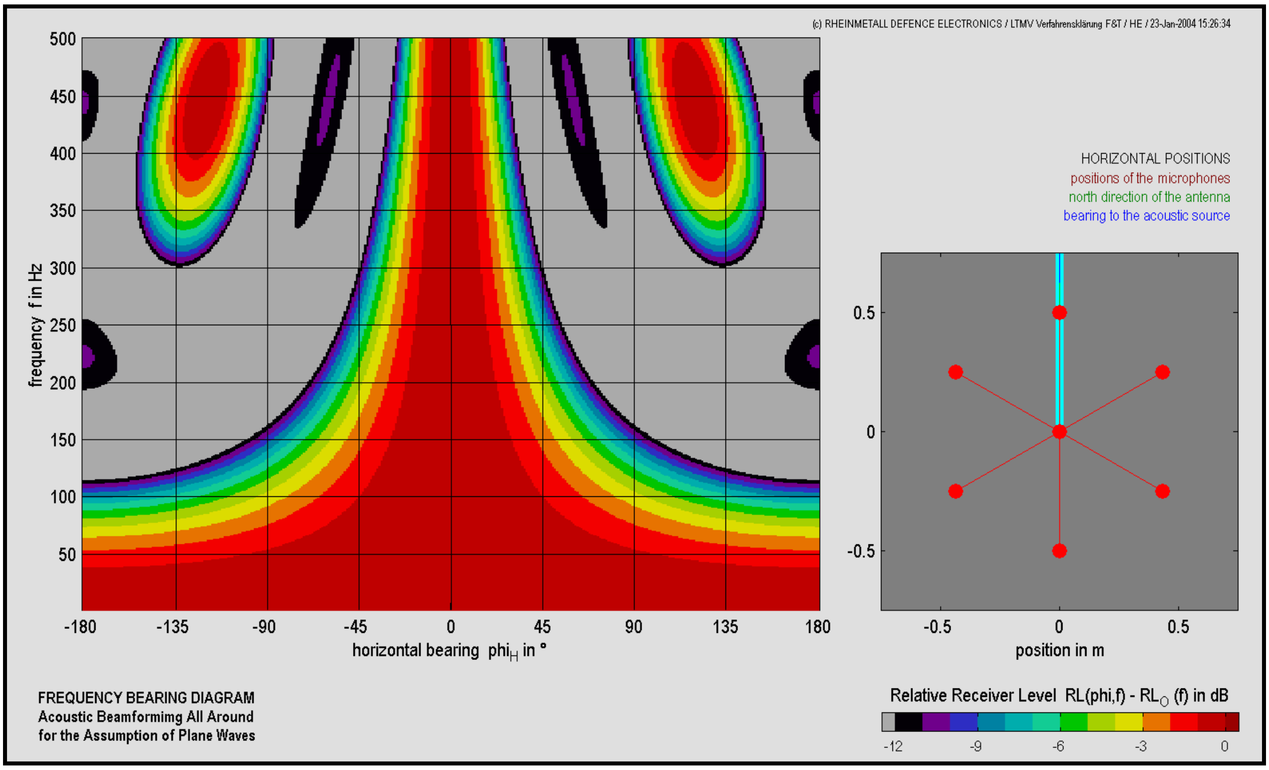

Figure 2: Normalized beam power pattern of a circular array

The beamforming technique presented in this paper is based on the rugged method of conventional beamforming. The performance of a small acoustic array for the recognition and tracking of targets is improved by using the knowledge that the desired targets emit sound with periodic narrowband components. The following assumptions are made:

- The power of the periodic components is concentrated in narrow frequency bands.
- The broadband noise varies slowly in the spectral domain.
- The received signal can be modelled as a plane wave relative to the array.
- One spectral peak from one spatial bearing is generated by one sound source.

In each step of signal processing those portions of the received signal are extracted, which exhibit the highest signal to noise ratios. Only these selected portions are used in the next step of processing to determine the parameters for the recognition and tracking of targets. An optimisation method, which may fail if an assumption is violated, is not applied. The idea is to use rugged receivers for detecting the largest signal portions and to apply maximum-likelihood estimators [Whalen 1971] for calculating the source directions without assuming a priori knowledge of the signal parameters.

The paper is organized as follows. In section 2, the selection of the strongest spectral lines in coloured noise using a normalized power spectral density is described. The extraction of narrow narrowband beams by angle weighting is introduced in section 3. The selection of the strongest targets by detecting the periodic sound sources in the accumulated narrow narrowband beam pattern is described in section 4. In theses sections the concepts are explained by simple simulations and demonstrated by authentic signatures from ground vehicles measured by a small acoustic array. Finally in section 5 the results are summarized.

2.0 SELECTION OF THE STRONGEST SPECTRAL LINES

The emitted sound of many vessels, ground vehicles and aircrafts exhibits both periodic narrowband components and random broadband noise. At the receiving microphone array additional environmental sound is measured. This background noise consists of both narrowband (as industrial noise) and broadband (as wind noise) portions. The periodic components are used for beamforming because of their high signal to noise ratio.

A single narrowband signal with unknown amplitude, unknown frequency and unknown phase is easily detected in the power spectral density [Whalen 1971], if the spectral distribution of the broadband noise is known. Unfortunately the broadband noise varies in time and in frequency. Fig. 3 demonstrates the situation by means of simulated data for one microphone. The power spectral density $PSD_{rr}(f)$ of a synthetic received signal $r(t)$ is calculated by averaging a few short time spectra. The spectrum consists of several narrowband peaks in coloured broadband noise.

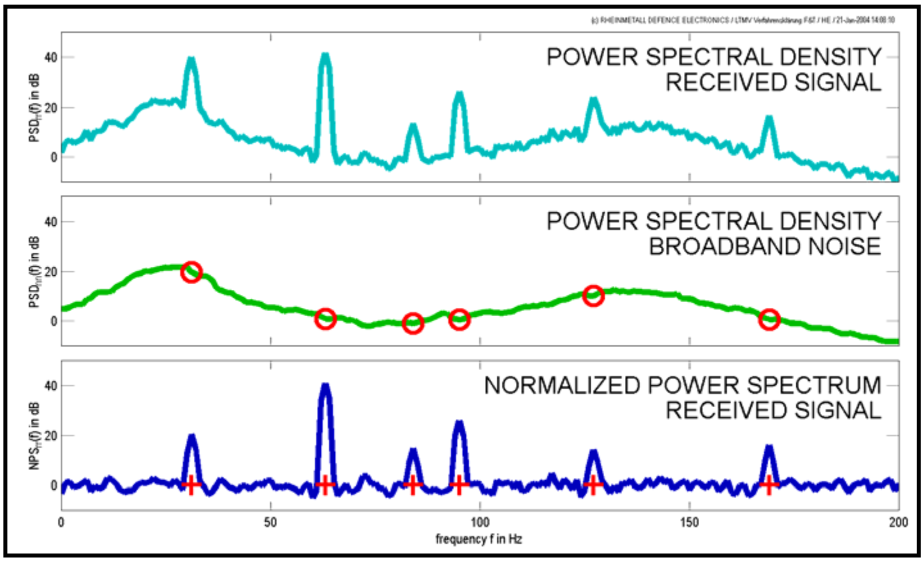

Figure 3: Detection of narrowband signals by spectral normalisation

A reliable estimation of the spectral broadband noise is necessary to detect the spectral lines automatically. There are a couple of well-known techniques [Hermströwer 1976] [Struzinski 1984] to solve this problem. Here the broadband spectrum is estimated in an iterative procedure by median filtering the broadband spectrum [Blommer 1995] and eliminating the spectral peaks subsequently. The broadband noise power spectral density $PSD_{nn}(f)$ is a smoothed version of the broadband noise portion in the spectrum $PSD_{rr}(f)$, see Fig. 3.1.

The ratio of the primary spectrum $PSD_{rr}(f)$ to the noise spectrum $PSD_{nn}(f)$ is called the normalised power spectrum $NPS_{rr}(f)$. This process of whitening produces a broadband noise spectrum, which exhibits an expected value of 1 (respectively 0 dB, see Fig. 3.1) for all frequencies. The spectral peaks are easily detected by comparing the normalised power spectrum to a threshold, which is constant for all frequencies. The acoustic signature of a wheeled vehicle on a cross-country drive is represented in the right diagram of Fig. 4 by a time-frequency-spectrogram using the normalized short time power spectra. The curves in the left diagram show the total power and the broadband power as a function of time. Although the signature significantly varies in time and frequency there are no problems to detect the line pattern caused by the propulsion system of the vehicle.

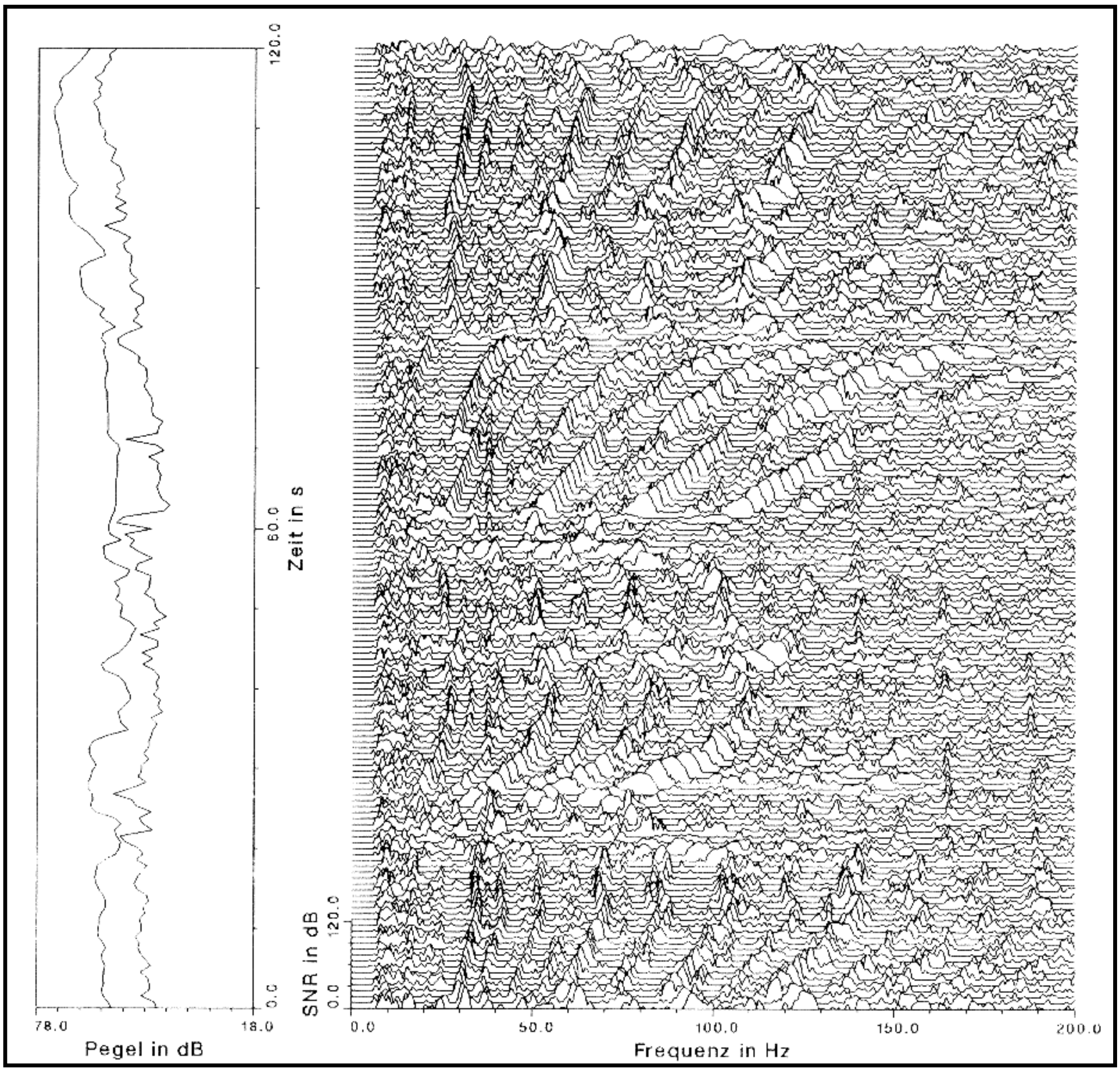

Figure 4: Normalized LOFAR spectrogram
Acoustic signature of a ground vehicle (distance from 420 m to 75 m)

The strongest spectral peaks are selected. In Fig. 3 these lines are marked by red crosses. The detection threshold should be very low to register even weak sources. A maximum number H of spectral lines are extracted. The complex spectral lines $CFS_m(f_h)$ for the m-th sensor are normalised by the broadband noise power spectral density $PSD_{nn}(f_h)$ at the central sensor:

$$L_m(f_h) = CFS_m(f_h) \,/\, PSD_{nn}(f_h) \text{ for } h = 1 - H \text{ and } m = 1 - M$$

Only the normalized complex spectral lines $L_m(f_h)$ at the H frequencies of the M sensors are needed for beamforming. These lines represent the desired periodic narrowband components of the signatures received by the array sensors. All other signal portions are eliminated. The beamformer uses only those spectral lines that exhibit the highest signal to noise ratios to achieve a good directivity. Due to the fact that the signatures are analyzed in the low frequency range, the beamformer is called LOFAR Lines Beamformer (LOFAR: Low Frequency Analyzing and Ranging).

3.0 SELECTION OF THE STRONGEST DIRECTIONS

The selected LOFAR lines are used for conventional beamforing [Nielsen 1991]. For every extracted frequency f_h the narrowband beam pattern $NBP_h(\varphi)$ for all bearings around, -180 ° < φ= ≤ +180 °, are determined. $P_h(\varphi)$ is the power of the h-th spectral line in the direction φ calculated on the basis of the phase-shifted and summed lines $L_m(f_h)$ of the M sensors. In Fig. 5 the six beam pattern of the six LOFAR lines extracted in Fig. 3 are shown. The width of the main beam is wide for low narrowband signal frequencies and small for higher frequencies.

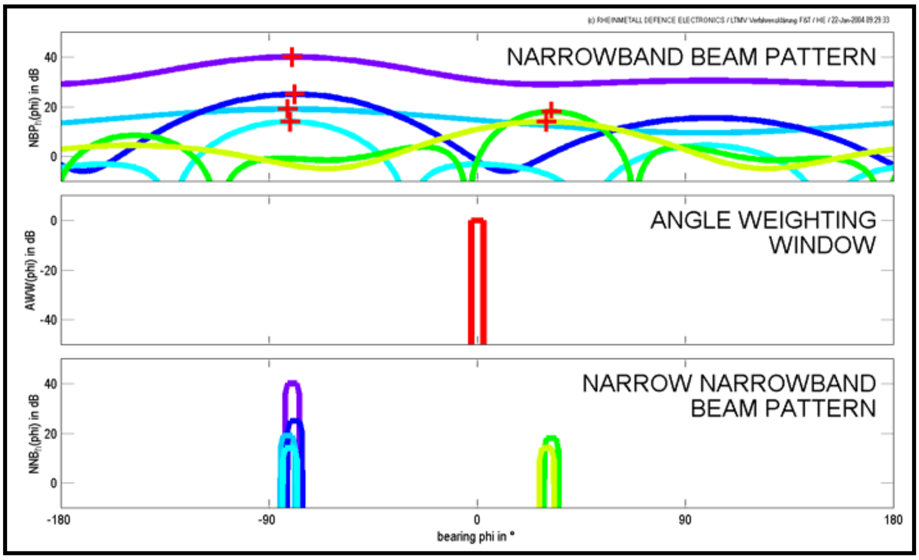

Figure 5: Extraction of narrow narrowband beams by angle weighting

If the assumption is true, that one spectral peak from one spatial bearing is generated by one sound source, the desired bearing for the line of frequency f_h is the angle φ_h in the maximum of the beam pattern $NBP_h(\varphi)$. In Fig. 5 red crosses mark these bearings. For four lines the strongest direction are near –80 ° and for two lines they are near +30 °. In Fig. 6 the measured frequency bearing diagram for a short time signal of 1 s is shown. $NPS(\varphi,f)$ is the normalized beam power of the acoustic array as a function of bearing φ and frequency f. Here white circles mark the strongest direction $NBP_h(\varphi_h)$ of the selected LOFAR lines. Two acoustic sources are identifiable. Two ground vehicles passing the microphone array generated these signatures.

The precision of the bearing measurements depends on several factors like the source movements, the sound channel, the signal to noise ratio and the parameters of signal processing. An angle weighting window $AWW(\varphi)$ is established to describe the accuracy of the measurements, see Fig. 5. The window width depends on the narrowband beam pattern of the LOFAR line. The width increases, if the signal frequency f_h decreases and if the beam power $NBP_h(\varphi_h)$ decreases.

The directivity achievable by one LOFAR line is described by the narrowband beam pattern $NBP_h(\varphi)$ near the bearing φ_h of the maximum. This pattern is called narrow narrowband beam pattern $NNB_h(\varphi)$.

$$NNB_h(\varphi) = NBP_h(\varphi) * AWW(\varphi - \varphi_h) \text{ for } h = 1 - H$$

Near the strongest direction the narrow narrowband beam pattern retains the shape of the line beam pattern. Outside of the angle weighting window $NNB_h(\varphi) = 0$.

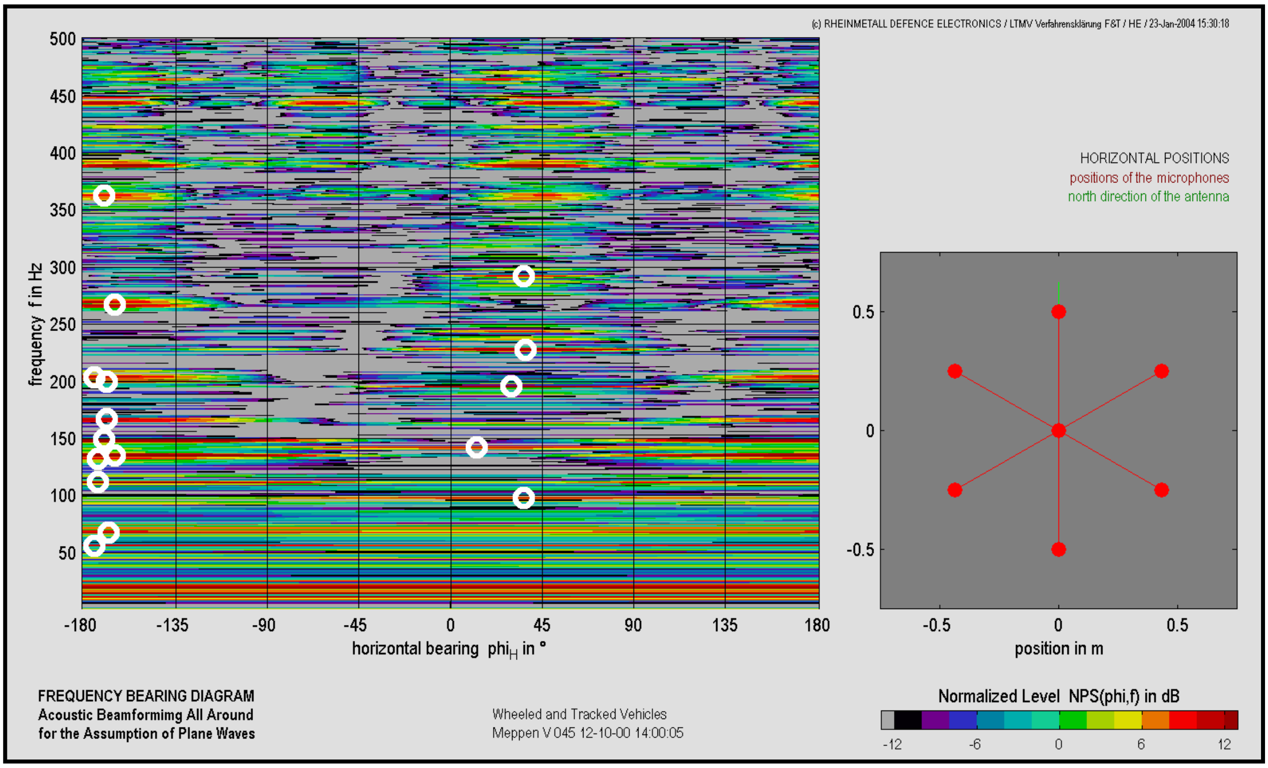

Figure 6: Frequency bearing diagram for a short time signal

In every short time interval for the received sensor signals the LOFAR lines produce a set of narrow narrowband beam pattern, see Fig. 5 and 6. The periodic components generated by one source approximately point at the same direction. Two sources can be discriminated if their bearings differ more than the precision of the measurements described by the angle-weighting window. The strength of the narrow narrowband beam pattern is a measure of the line power normalized to spectral broadband noise. The normalized level of a weak line is just over 0 dB and the normalized level of broadband noise is near 0 dB.

4.0 SELECTION OF THE STRONGEST OBJECTS

The previous beamforming process produces several narrow narrowband beams for every short time segment. One or more objects generate these beams. Therefore the next step of signal processing includes:

- Accumulating the narrow narrowband beams of one target
- Separation of the narrow beams to recognize different objects
- Determination of the target strength

The sum of all H narrow narrowband beams $NNB_h(\varphi)$ is called the accumulated narrow-beam pattern $ANB(\varphi)$:

$$ANB(\varphi) = \sum_{h=1}^{H} NNB_h(\varphi)$$

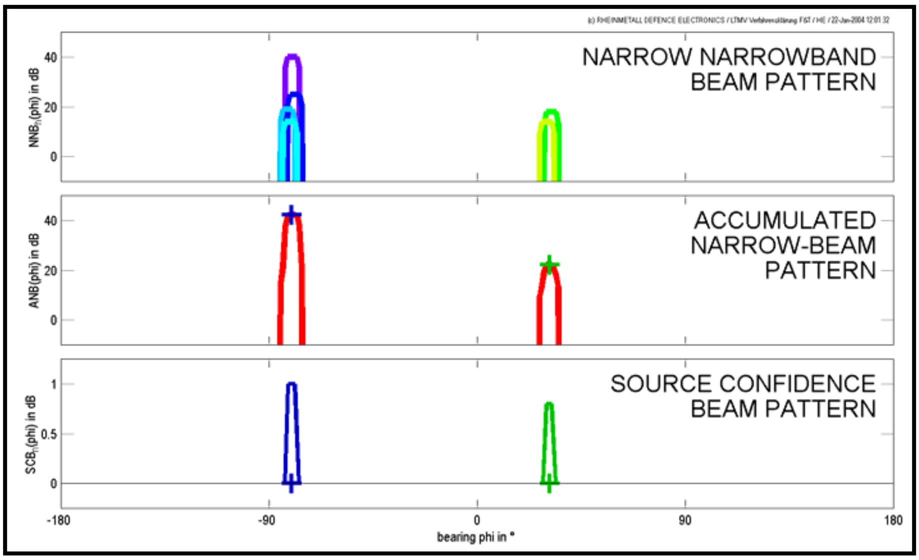

Figure 7: Detection of periodic sound sources by accumulating narrow narrowband beams

This accumulating process is demonstrated in Fig. 7. The upper diagram is identical to the lower diagram of Fig. 5. The different acoustic sources are simply detected by peak detection in the accumulated narrow-beam pattern $ANB(\varphi)$. In Fig. 7 crosses of different colours mark these beams $ANB_n(\varphi)$, where the index n denotes the index of the detected sources. After the first peak is detected, all spectral lines belonging to this object are eliminated to disable side peaks due to minor lobes of the spectral lines. Subsequently the detection process is repeated to select the next object.

The certainty of detection increases with the number and the strength of the lines. This dependency is expressed by a measure of confidence [Becker 1996]. The source confidence beam pattern $SCB_n(\varphi)$ is calculated for each of the N selected sources:

$$SCB_n(\varphi) = \boldsymbol{C}\{ ANB_n(\varphi), H_n(\varphi)\} \text{ for } n = 1 - N$$

The confidence $\boldsymbol{C}\{P, h\}$, $0 \leq \boldsymbol{C}\{P, h\} \leq 1$, increases with the power P and with the number of lines h. The characteristics of the confidence function $\boldsymbol{C}\{P, h\}$ are similar to those of the probability function of a continuous variable P in statistics for a fixed number of lines h.

The source confidence beam pattern $SCB_n(\varphi)$ is a measure of the detection certainty as function of the bearing φ, see Fig. 7. The maximum of $SCB_n(\varphi)$ indicates the desired bearing estimation φ_n to the n-th object. If a source exhibits many strong components the confidence $SCB_n(\varphi_n)$ is near 1. For few weak lines the source confidence is near 0. The beam width can be described by an angle-weighting window depending on the signal to noise ratio of the accumulated narrow-beam pattern of the source confidence beam pattern. The beam width is narrow for a strong object and wide for a weak object.

The recognition of the periodic sound sources is repeated in every short time intervals one after another. Fig. 8 shows the time bearing plots using conventional beamforming and LOFAR lines beamforming. An acoustic antenna (7 microphones, ∅ 1 m) received the sound signatures of three ground vehicles during a time segment of 60 s. The intensity in the left diagram describes the sound pressure level in dB [rel. 20 µPa]. Grey points mark the maxima of the beam pattern in each short time interval. The intensity in the right diagram describes the confidences of the selected objects. Per short time interval a maximum of three objects is extracted.

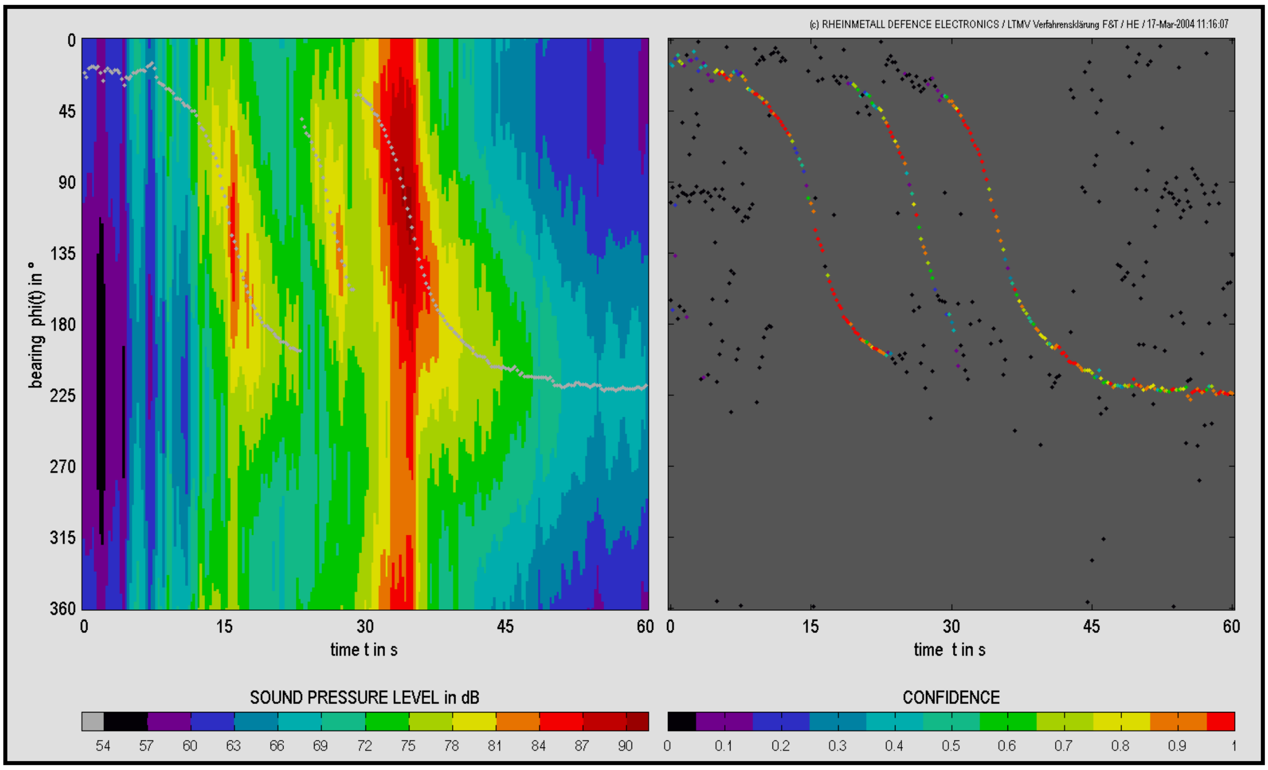

Figure 8: Time bearing plots of conventional beamformer and LOFAR lines beamformer

The LOFAR lines beamformer permits the detection of multiple objects even for very small arrays. Approaching objects are detected earlier and departing objects are observed for a longer time especially if a convoy of vehicles passes the acoustic antenna. Therefore extended tracking of acoustic sources is possible. In Fig. 8 the improved performance is demonstrated at the beginnings and the endings of the tracks. Even the weak central vehicle can be recognized earlier and tracked over a longer time period.

5.0 SUMMARY

The sound signatures of many vessels, ground vehicles and aircrafts exhibit strong periodic components in the low frequency range from 20 Hz to 200 Hz. In the spectral domain their power is concentrated in narrow bands. This knowledge is used to improve the performance of a small acoustic array for the recognition and tracking of sound sources by assuming that one spectral peak from one spatial bearing is generated by one sound source.

The idea is, to use rugged receivers for detecting the largest signal portions and to apply reliable estimators for calculating the source directions without assuming a priori knowledge of the signal parameters. Because the spectral lines in the low frequency range are used the proposed method is called LOFAR lines beamforming. The signal processing is done in three steps:

- Selection of the strongest spectral lines
  by spectral normalising the power spectral density of every short time interval
  and detecting the narrowband lines in the normalised power spectrum

- Selection of the strongest directions
  by conventional beamformimg of the LOFAR lines
  and extracting the narrow narrowband beams by the angle-weighting window

- Selection of the Strongest Objects
  by detecting of the periodic sound sources in the accumulated narrow narrowband beam pattern and determining the source confidence beam pattern

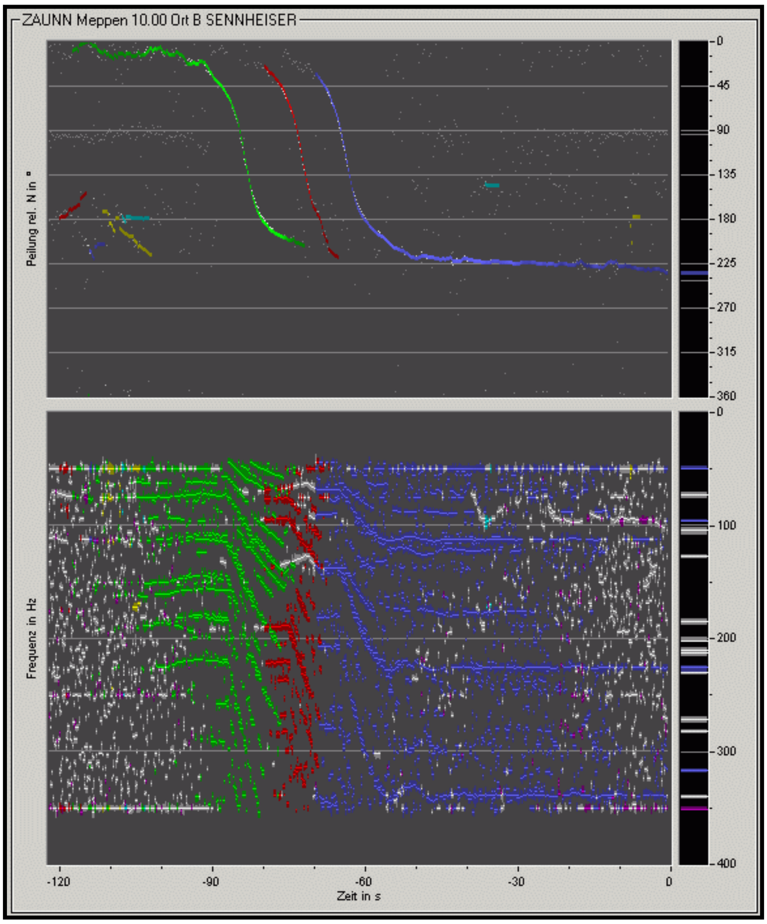

Figure 9: LOFAR lines spectrogram and source confidence time bearing plot

Fig. 9 demonstrates the efficiency of the LOFAR lines beamformer. Three ground vehicles passed the small microphone array. Near the closest point of approach the vehicles changed the course from south to southwest and accelerated from 30 km/h to 60 km/h. In the lower diagram the selected lines, which are used for beamforming, are coloured. In the upper diagram the target tracks of the source confidence are marked in the same colour.

The LOFAR lines beamformer operates like a spatial and spectral comb filter. The spectral line pattern and the confidence beam pattern are assigned and combined to recognize and track different targets with periodic sound sources. The LOFAR lines beamformer permits the detection of multiple objects even for very small arrays. Approaching objects are detected earlier and departing objects are observed for a longer time especially if a convoy of vehicles passes the acoustic antenna.

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