ON THE ADVANTAGES OF WIDEBAND DATA ACQUISITION FOR PASSIVE DIVER DETECTION

Laurent Fillinger, Alan J. Hunter, Mario Zampolli, Martijn C. Clarijs, Koos Verolme

TNO, Oude Waalsdorperweg 63, P.O. Box 96864, 2509 JG The Hague, The Netherlands

Contact author: Laurent Fillinger, laurent.fillinger@tno.nl, tel: +31.888.663.785, fax: +31.703.280.961

Abstract: *Situation awareness is an important component of security that justifies the equipment of sites with monitoring systems. For shore/harbour security, these systems are mostly composed of camera and radar, to monitor the land and the water surface, and of active sonar(s) when the underwater situation is monitored.*

An alternate approach for underwater monitoring is to use a network of passive sonars that detect targets by the sound they radiate. Unlike active sonar, a single passive sonar element cannot estimate the range of a target in the far field, only its direction; but it can characterize the sound radiated by a target, with obvious applications to target tracking and classification. Passive sonars, with frequency characteristics suitable for the target type of interest, have to be deployed as a network so that the source location can be estimated by appropriately crossing the estimated directions.

TNO and the Stevens Institute of Technology are investigating this approach for diver detection and have conducted in 2010 a trial with the support of the Royal Netherlands Navy. A system involved in the trial presented a wide sampling dynamic and frequency range, making it suitable not only for diver detection but also for other forms of processing.

Experimental results demonstrate that the deployed system can be used for diver detection and that its larger-than-required dynamic range enables other applications such as boat tracking and sound speed estimation, that can not only augment but improve the initial diver detection capability.

Keywords: *waterside security, intruder, diver, passive sonar*

1. INTRODUCTION

Monitoring systems constitute an important component of security systems as they provide awareness on the current situation and its development and allow the detection of threats and suspicious behaviours. For shore/harbour security, these systems are mostly composed of camera and radar, to monitor the land and the water surface, and of active sonar(s) when the underwater situation is monitored.

An alternate approach for monitoring the underwater situation is to use a network of passive sonars. Unlike active sonar, passive sonar cannot estimate the range of a target in the far field, only its direction; but it can characterize the sound radiated by a target, with obvious applications to target tracking and classification. Passive sonars, with frequency characteristics suitable for the target type of interest, have to be deployed as a network so that the source location can be estimated by appropriately crossing the estimated directions.

TNO has been investigating this approach for the problem of diver detection. The wide band character of the acoustic emission of scuba [1] (the most common type of underwater breathing apparatus) suggests using a detection system that allows measurement in a wide frequency band. The wide band characteristics of such system make it suitable not only for diver detection, but also for other tasks. For instance, detection of different types of targets relevant to waterside security (e.g. boats) is feasible. Passive sonars can also be used to monitor the environmental condition affecting the sensor performance, such as the noise level and the speed of sound. The knowledge of the value of these parameters allows for sensor performance prediction (e.g. detection range). This also enables improved sensor fusion. In sensor fusion, a lower weight should be given to less reliable sensors [2]; under time varying conditions, the fusion should adapt to these variations, which requires monitoring of the environment.

In this paper, we consider how measurements of such parameters can be performed on a passive diver detection system and discuss their potential benefits. The remainder of the paper presents experimental results demonstrating the performance of a diver detection system. It is followed by some considerations on opportunities for additional measurements and on their benefits.

2. DIVER DETECTION: EXPERIMENTAL RESULTS

The experimental results presented in this paper were obtained using data collected during a trial [3] organized jointly between TNO and the Stevens Institute of Technology (NJ, USA) and held in October 2010 in the harbour of the Royal Netherlands Navy in Den Helder. Fig. 1 presents an example spectrogram and an example correlogram of recorded signals. The spectrogram, computed from the signal of one hydrophone, shows the temporal evolution of the frequency content. The correlogram, computed from the signal of two hydrophones, shows the evolution of the direction of the acoustic sources. The correlogram is computed using the phase transform, which is a generalized cross-correlation [4]. It allows the estimation of the delay of arrival of various signal components on the pair of hydrophones. This delay being function of the direction of the acoustic source, its measurement allows the estimation of the source direction. The general principle for detection and estimation of the source direction is presented in [5]. Fig. 1c presents tracks associated with boats (the more continuous segments) and a diver (dotted track). The diver is detected at each breathing cycle and the frequency content of the corresponding acoustic events can be seen in the spectrogram in Fig. 1a. The diver's inhalations are associated with broadband acoustic emissions that are clearly visible in the spectrogram. Similar plots are shown in Fig. 1b and d. Two divers are present, but at a larger range (350 m against 190 m). Because of the increased transmission loss due to longer propagation distance, the diver signals are barely noticeable in the spectrogram, but still clear in the correlogram (which achieves a better signal to noise ratio by combining the information from two hydrophones).

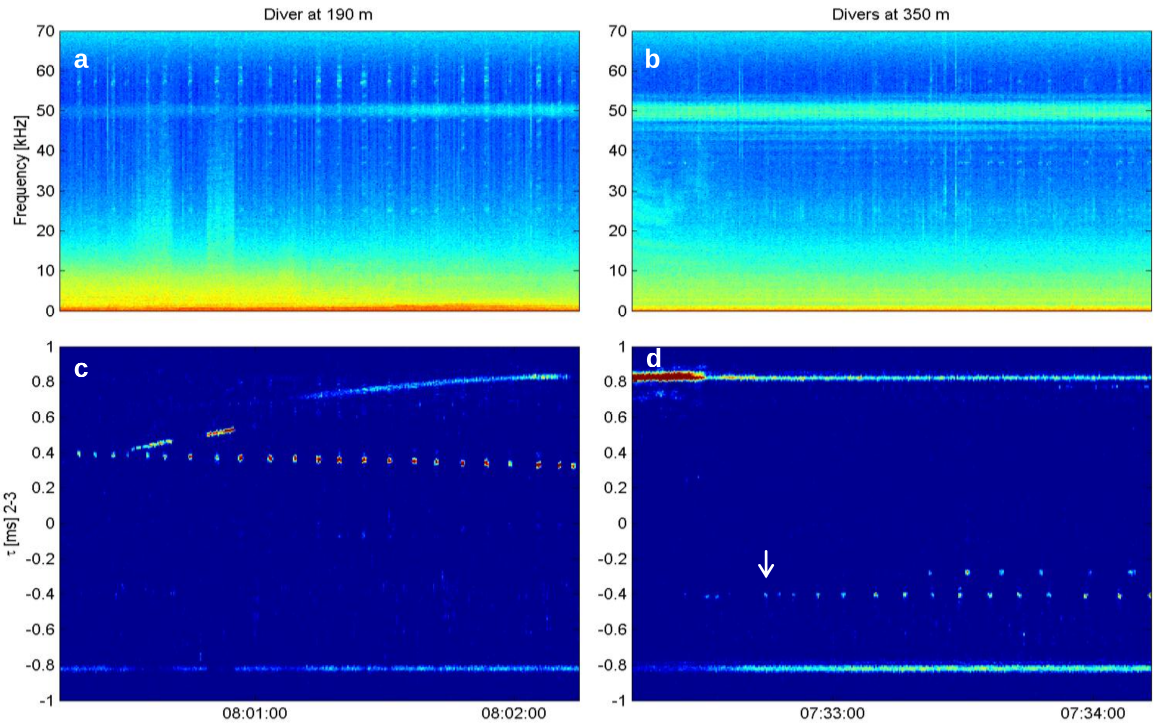

Fig.1: Spectrogram (a,b) and associated correlogram (c,d). Divers (dotted tracks) and boats (continuous tracks) are present in both cases. Diver's breathing is clearly visible in the spectrogram with the diver at 190 m but hardly visible with the divers at 350 m.

Target localization is achieved by crossing the bearing from various passive sonars. This requires the detection of the peaks in the correlogram. Fig. 2a shows the result of such an automatic extraction of peaks for a diver run. The detections are further labelled as low- (red) or high-frequency (green). This was done was analyzing generalized cross-correlations computed over different frequency bands, which allows for a simultaneous analysis of the signal frequency content and directivity. An example of such frequency-delay representation is presented in Fig. 2b and shows components associated with two boats and a diver. While localizing a target by combining the detections from several passive sonars is an easy task when a single target is present and detected by all sensors, the task becomes ambiguous and more complex in presence of multiple targets, missed and false detections and measurement uncertainties. A probability hypothesis particle filter [6][7] is used to circumvent this complexity (presentation of the hypothesis particle filter is out of the scope of this paper). Fig. 2c shows an example of localization results presenting the track of two divers. The axis is in meters; the black squares represent the location of the passive sonars; the ellipses represent the localized targets. The ellipses are located at the estimated target location, their size represents the localization uncertainty and their colour indicates the time of detection (from blue for early detections to red for the latest detections). Under this representation, a consistently localized target appears as a rainbow track. This is the case for the two divers that were passively detected and localized at 350 m in an operational harbour. False localizations on the other hand do not display a clear geographical or temporal (colour) pattern.

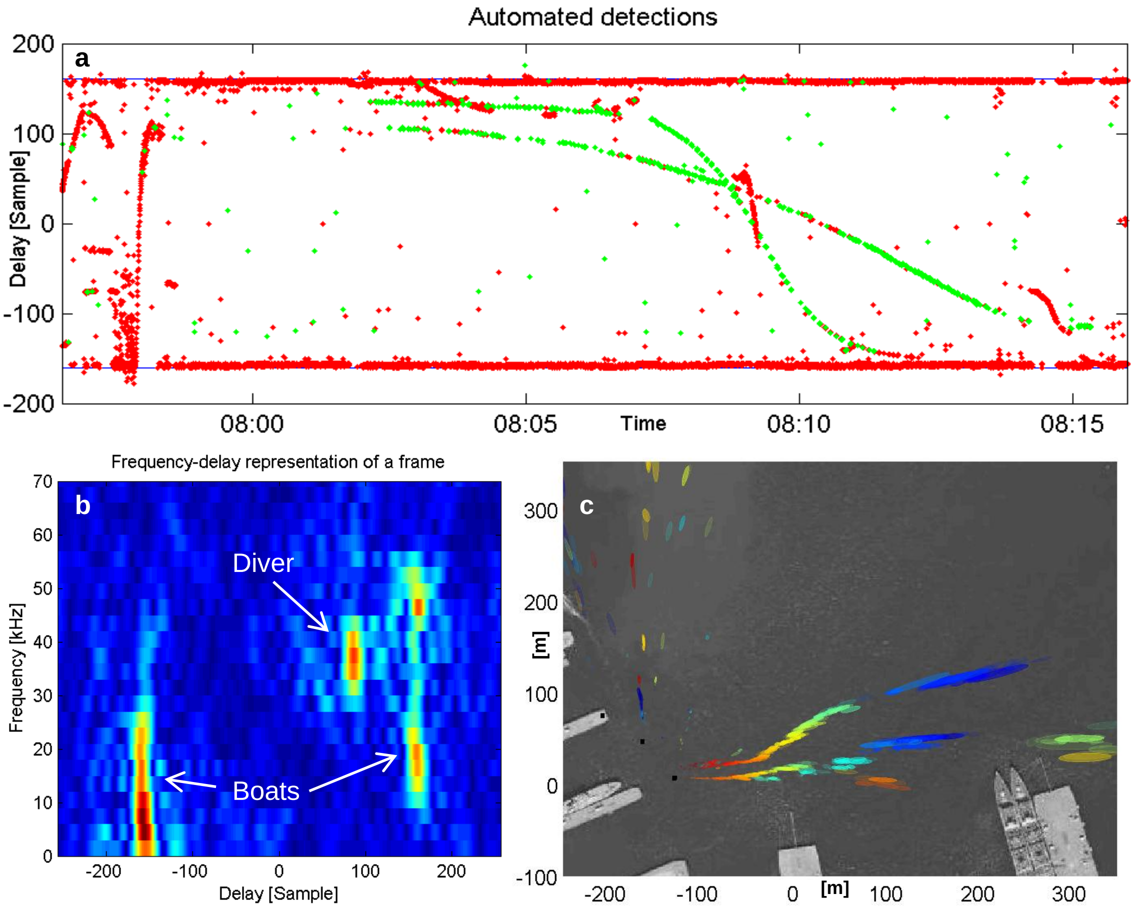

Fig.2: (a) Delays automatically detected in the correlation, color indicate frequency content (HF: red, LF: green). (b) Frequency-delay representation of a frame. (c) Localization obtained by combining the detections from three nodes (black squares). A localized target is represented by an ellipse located at the estimated target position. Its size represents the localization uncertainty and its color the time of detection (from blue to red). The two rainbow tracks correspond to divers.

Fig. 3 illustrates the dynamic of signal encountered in the trial and presents typical examples of the power spectral density of detected signals. Thin lines show examples of measured power spectral density in very quiet (almost no ship traffic) and very loud conditions (ship passing nearby the sensors). The thick lines represent the power spectral density for an automatically detected diver's inhalation and just before detection. Two situations are considered: high signal to noise ratio (SNR) in Fig. 3a and low SNR in Fig. 3b. The detection with low SNR is indicated by an arrow in Fig. 1d. The difference in power spectral density before and during the inhalation is obvious at high SNR but hardly noticeable at low SNR. This indicates that the signal that was detected at low SNR was about or below the level of ambient noise.

The difference between the loudest (around 1 kHz) and the weakest frequency component (around 40 and 55 kHz) is 80 dB. A dynamic range of 80 dB requires sampling with at least 14 bits ($\log_2(10^{80/20}) \sim 13.3$ bits). Using 16 bits quantization (96 dB dynamic range) set up so that the loudest signals cover the full range without saturation would leave just 3 bits of lower rank for coding the signals whose level is comparable to the weakest observed noise level. With such a poor amplitude resolution on weak signals, detection of a signal at noise level, as reported in Fig. 3b, would not be expected. To detect such a signal, the measuring range should be shifted to lower amplitude signals, which would cause saturation in case of loud noise. Preventing saturation in presence of loud noises while maintaining the possibility of detecting weak signals would require a reduction of frequency range of the system. For instance, if frequencies below 20 kHz had been discarded, the loudest signal to measure would be 30 dB weaker. These 30 dB of available sampling dynamic could be used for proper sampling of signals at (quiet condition) noise level. The drawback of this solution would be that no information on the low frequency acoustic sources would be available. The system used in the experiments performed quantization on 24 bits (145 dB dynamic range). This large dynamic range was sufficient to allow appropriate sampling of both the loudest and the weakest signals: it was not necessary to reduce the frequency range in order to limit the amplitude variation to the sampling dynamic. The result is a system that is able to detect a diver signal near the noise level, that does not saturate is case of a loud low frequency event, and that collects also low frequency information.

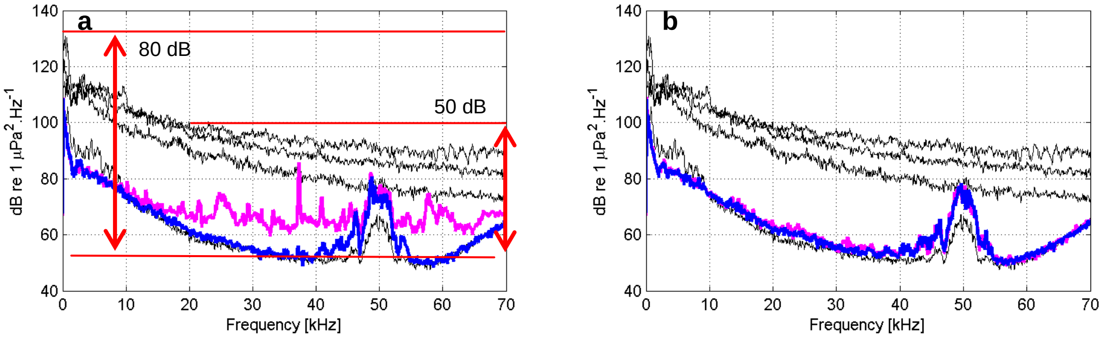

Fig.3: Measured signal dynamic. The thin lines represent the power spectral density in the quietest and loudest conditions encountered during the trial. The thick lines represent the power spectral density during an automatically detected inhalation and just before it for a detection with good SNR (a) and a detection with low SNR (b). The detection shown in (b) is indicated by an arrow in Fig. 1d.

3. ADDITIONAL POTENTIAL FUNCTIONALITIES

In this section, we consider the additional functionalities that can be implemented on such a system in order to detect other targets, predict sensor performance and monitor the sensor and its environment.

3.1. Other targets

As the high frequency information can be used to detect and localize divers, the low frequency information can be used to detect and localize boats (see Fig. 4a), which constitute another type of target relevant to maritime security. Boats are louder than divers and can be detected at a longer range, making them more likely to cause simultaneous detection on multiple passive sonars. The passing of a boat is a likely event that should lead to detections with good SNR. Ships detected and localized can be used as sources of opportunity for other types of measurements.

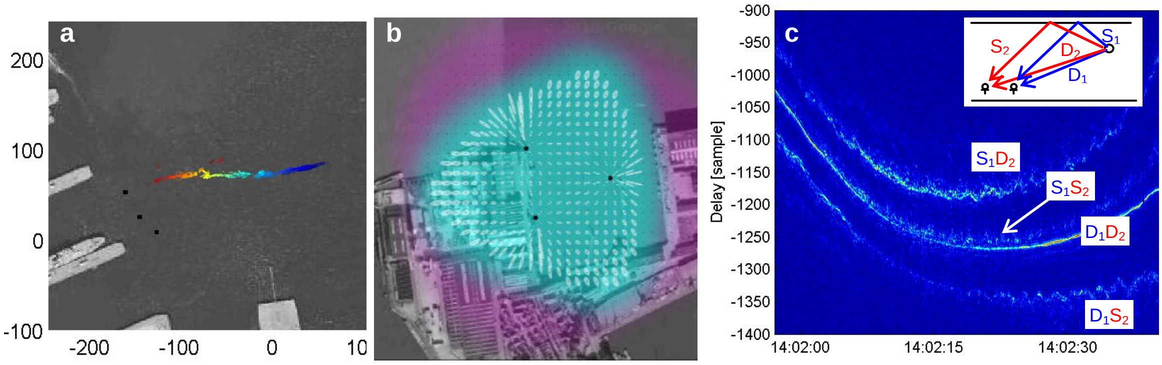

Fig.4: (a) Example of localization of a boat. (b) Illustration of sensor performance prediction (detection range). (c) Detail of a correlogram presenting the direct path and surface interactions.

3.2. Ambient noise measurement – Sensor performance prediction

A signal can be detected if, at the sensor location, the received signal can be separated from the ambient noise. The amplitude of a signal decreasing with propagation, there is a maximum range at which a signal can be detected in a given ambient noise. Variation of the ambient noise is therefore associated with a variation of the detection range. The variation of ambient noise results in a time dependent coverage of the passive sonar network. It is important for security agents to know the coverage of their monitoring system. Sensor performance prediction (either theoretical, empirical or a combination of the two) can be used to predict the detection range (and other relevant parameters such as probability of detection and false alarm rate) from the measured noise level. The wide frequency range of the system used in the trial enables measurement of the ambient noise in frequency range relevant for diver detection. If this measurement is coupled with a sensor performance model, the system can evaluate its detection range from its own measurements (Fig. 4b).

3.3. Speed of sound

The value of the speed of sound is used in the conversion from the measured delay of arrival to the direction of the source. Difference between the assumed speed of sound and its actual value leads to degraded localization. The speed of sound in water is influenced by temperature and salinity, making it evolve with time. Monitoring of the speed of sound should allow keeping localization accuracy independent of the speed of sound variation.

The sensitivity of localization to the error in speed of sound is a function of the particular sensor type and configuration. The correlation results presented in Figs. 1 and 2 were obtained using two hydrophones separated by d = 1.2 m. With sampling at f_s = 192 kHz, the maximum possible delay (that is obtained when the source and the hydrophones are collinear) corresponds to $n_{\max} = d.f_s/c$ ~155 samples, where c is the speed of sound. With these parameters, 10 m/s of variation in speed of sound changes the maximum possible delay by 1 sample, which is hardly measurable. This estimate indicates a low sensitivity to the variation in speed of sound for this configuration: measurement of the maximum possible delay does not allow accurate estimation of the speed of sound. A larger hydrophone spacing would make the direction estimation more sensitive to variation in speed of sound, but would also make speed of sound measurements feasible.

3.4. Measurements with sources of opportunity

Some active measurements can be emulated in passive acoustics using sources of opportunity. For instance, passive acoustic tomographic methods have been proposed to measure temperature profiles using passing ships [8], or channel impulse responses using mammal calls [9]. In the considered case, the ability of the system to detect and localize sound sources can be used to select relevant sources, for instance loud boats detected with good SNR on several sonars and localized with good accuracy.

If the passive sonars return the measured level associated with the detections, the measurements from several sonars could be used to estimate the source level and the transmission loss (knowledge of the target "source level" [intended in the broad sense since it is difficult to define as a precise quantity for extended objects such as ships] can be useful for classification; the transmission loss influences the detection range). However, this approach would not be reliable on sources whose directivity is unknown, which is typically the case for sources of opportunity. A different approach would involve comparison of the measured level corresponding to a same target but measured at different times from the same location instead of measured at the same time from different locations. This can be considered for vessels with predictable behaviours (e.g. vessels used for public transport and following prescribed path at prescribed time). Variation in the level measured at different times would indicate change in the propagation characteristics that can be linked for example to varying temperature (or temperature profile), the state of the sea surface, or currents.

Note that the type of measurements that can be performed using sources of opportunity is not limited to the estimation of the transmission loss. The possibilities depend on the specific details of the passive sonar network arrangement and what it can measure, on the characteristics of the environment where it is deployed and on the characteristics of the sources of opportunity. Fig. 4c provides an example showing the correlation of a signal presenting a strong surface reflection leading to multiple components in the correlation. The smoothest line (main track) corresponds to the correlation of the direct paths to the hydrophones; the tracks on either side correspond to correlation of the direct path to one hydrophone with the reflected path from the other hydrophone. The separation from the main track increases as the source is getting closer: it can be used to estimate the source range. Note also how these tracks are becoming wavy at the end of the figure. At that time, due to manoeuvring, the reflected path interacted with the wake on the surface. Fig. 4c was not obtained with a source of opportunity but using a vessel towing an acoustic source. It was chosen for illustration as it clearly presented several effects (additional component in the correlation, separation that is range dependent, shape influenced by surface state) in a single figure. These effects have also been observed on real sources of opportunity, although separately and less clearly.

4. CONCLUSION

Experimental results obtained during a passive acoustic diver detection trial demonstrating passive localization of scuba divers at 350 m in an operational harbour were presented. An acquisition system with a large bandwidth was used in order to accommodate for the wideband character of the diver emission. Data are therefore available on a large frequency band and can be used for other purposes than diver detection and tracking. Several possibilities have been proposed, including boat detection and tracking and environment monitoring for performance prediction. It has been proposed to use the results of monitoring of the shipping traffic (i.e. vessels positions) to select events suitable for other measurements (e.g. transmission loss, or surface state). This example shows how a versatile system can be used to perform several functions (e.g. noise level measurement and boat tracking in addition to diver tracking) and how the synergy between the functions enables new functionalities (possibility to estimate transmission loss as target position is known by localization) or improve the existing ones (improved localization accuracy due performance prediction linked to environmental measurements).

5. ACKNOWLEDGEMENTS

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