PASSIVE DETECTION AND BEARING-ONLY TRACKING OF LARGE-TIME BANDWIDTH SIGNALS USING AN AUV MOUNTED VECTOR SENSOR

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Abstract: *This paper presents experimental results of passive detection and bearing estimation of large time-bandwidth signals between 1.8 and 3.6 kHz using a DIFAR (Directional Frequency Analysis and Recording) vector sensor installed on the eFolaga Autonomous Underwater Vehicle (AUV). The bearing estimation method is based on the product between the pressure sensor and the two orthogonal dipole sensors of the DIFAR. It was implemented both in time and in frequency domain. Extensive data acquisition has been made in underwater gliding navigation, minimizing energy consumption. The collected data allowed to evaluate experimentally the bearing estimation performance in both surface-drifting and gliding mode. The data set was acquired during the Littoral Continuous Active Sonar 2018 (LCAS18) experiment, which took place off the coast of Elba Island, Italy, in November 2018. In this paper, the trial set-up is described. Experimental results on detection and the bearing estimation, both in time and in frequency domain, are presented. The obtained results, combined with the vehicle's persistence, suggest new approaches to acoustic surveillance in a completely autonomous way.*

Keywords: *AUV, Vector Sensor, Direction of Arrival Estimation, DIFAR.*

1. INTRODUCTION

Sonar systems can be divided into active and passive. In active sonar, the system emits a pulse of sound and listens for echoes. Conversly, a passive sonar system just listens to sounds emitted by the target that one is trying to detect. Active sonar can be subdivided into two categories: Continuous Active Sonar (CAS) and Pulse Active Sonar (PAS). Typically, in CAS long-duration waveforms are transmitted with a repetition interval similar to the one used with the traditional PAS. In PAS systems, a short continuous wave or a frequency modulated (FM) pulse is usually transmitted, followed by a relatively long transmission-free period of time to allow receiver to listen for the possible echoes. CAS for AntiSubmarine Warfare (ASW) in littoral waters could have many advantages with respect to the classical PAS. CAS systems transmit and listen for the possible echoes simultaneously, optimising the total energy of the signal and enhancing the detection and tracking performance. This results in the increased update rate of sonar contacts while maintaining the same Pulse Repetition Interval (PRI). Regardless of the specific system used (i.e., PAS or CAS), the state of the art in an active ASW is based upon the deployment of active/passive sonobuoys, on the use of hull-mounted and variable depth sonar deployed from surface ships and on the deployment of towed arrays from submarines. All of these systems can become components of multistatic applications. Recently, alternative approaches involving the use of Autonomous Underwater Vehicles (AUVs) have been suggested. This could lead to significant advantages such as savings on personnel costs, reduced workloads, reduced exposure to dangerous tasks and an improved decision-making under stress. This paper describes ongoing developments at the SEALab, a joint laboratory between the Naval Support and Experimentation Centre (CSSN) of the Italian Navy and the Interuniversity Center of Integrated Systems for the Marine Environment (ISME), in the use of an AUV equipped with an Acoustic Vector Sensor (AVS). Examples of detection and bearing estimation of underwater sources using AVS are addressed in [1]. Similar applications such as the use of a compact volumetric array mounted on an underwater glider have been investigated in [2]. These compact sensors are well suited to be used in light systems, where space is limited, such as an AUV. This paper shows that using a DIFAR (Directional Frequency Analysis and Recording) AVS integrated on the e-Folaga AUV [3] it is possible to track the azimuth of different types of acoustic signals in a multistatic scenario. Experimental results of passive detection and bearing estimation of large time-bandwidth signals, which allow extrapolation of the information in multiple frequency sub-bands, between 1.8 and 3.6 kHz are presented. The recent at-sea successes have demonstrated that the use of AUVs provides an alternative approach to acoustic surveillance. The paper is organized as follows: Section 2 describes the applied methodologies and the developed algorithms; In section 3 the experimental set-up is described; Section 4 reports a selection of the results obtained. Finally, conclusions are reported and discussed in section 5.

2. METHOD

The DIFAR AVS consists of a centrally placed omnidirectional hydrophone, two particle motion sensors arranged orthogonally around it and a built-in compass. In the original configuration the signal arriving at the sensors, together with the compass signal, were processed by the electronics of the sonobuoy forming the so-called “complex signal” to be transmitted via VHF [4]. The integration between the AUV and the AVS is based on the original DIFAR electronics: the modulated signal is acquired and stored within the developed acoustic payload. A pre-processing stage is necessary to demodulate the three signals from the sensors described above. Demodulation software has been implemented in MATLAB. Once the signals of the single sensors have been this way computed, the arctangent-based method [5] has been applied to estimate the bearing of an acoustic source. For an acoustic wave propagating horizontally and arriving at the sonobuoy at an azimuthal angle β, the three sensor outputs can be written in the following form:

$$x_o(t) = x(t) \tag{1}$$

$$x_s(t) \approx x(t)\sin\beta \tag{2}$$

$$x_c(t) \approx x(t)\cos\beta \tag{3}$$

where the subscripts *o, s, c* denote omni, sine, and cosine [6]. The angle β is measured clockwise from north. The bearing of an acoustic wave arriving at the vector sensor from a certain direction β with respect to the North can be estimated in the time domain by:

$$\hat{\beta}(t) \approx \text{arctan2}\,[x_s(t)\cdot x_o(t)\,,\; x_c(t)\cdot x_o(t)] + \alpha \tag{4}$$

where $x_{\mathbf{o}}(t)$ is the signal acquired by the omni-directional hydrophone, $x_s(t)$ and $x_c(t)$ are the signal at the two particle motion sensors. α represents the angle on the horizontal plane between the magnetic and true North (magnetic declination due to the position on the Earth's surface), that is calculated by the implemented MATLAB software starting from the GPS position provided by the vehicle. The function arctan2 is the four-quadrant inverse tangent which returns values in the interval [-π, +π]. Differently from the arctangent, arctan2 uses the signs of both arguments to determine the quadrant of the result. In a similar way, the bearing estimator can be implemented in the frequency domain also:

$$\hat{\beta}(f) \approx \text{arctan2}\,[\text{real}\{X_s^*(f)\cdot X_o(f)\}\,,\, \text{real}\{X_c^*(f)\cdot X_o(f)\}] + \alpha \tag{5}$$

where real stands for the real part operator and the asterisk represents the complex-conjugate operator.

3. DESCRIPTION OF AT-SEA TESTS - LCAS'18 EXPERIMENT

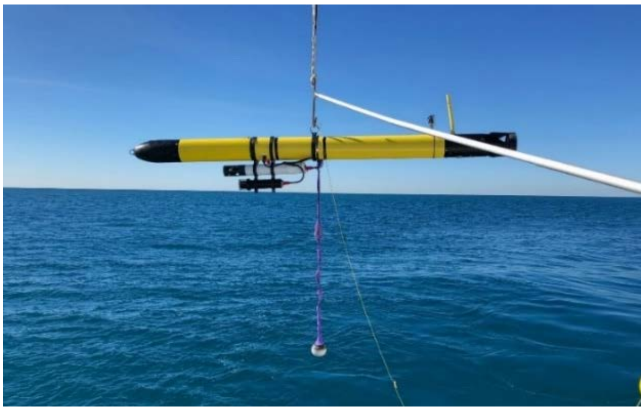
The LCAS'18 (Littoral Continuous Active Sonar) experiment took place off the coast of Elba Island, Italy, in November 2018, in the context of a Multinational-Joint Research Project (LCAS MN-JRP) with the Centre for Maritime Research and Experimentation (CMRE). Water depth was between 100 and 200 meters. The research vessels NRV Alliance and CRV Leonardo took part in the experiment towing respectively an acoustic source capable of CAS - PAS transmissions over the frequency band of 1800 – 3600 Hz and an echo-repeater system which repeated the received signal transmitted by the Alliance in order to simulate a target. There was also a fixed source called DEMUS which transmitted PAS signals. CSSN staff was embarked on the N/O Astrea, a ship owned by the Italian Institute for Environmental Protection and Research (ISPRA), which was tasked by the CMRE. The experiment considered in this paper took place on November 24th-25th, 2018. The eFolaga AUV was deployed from N/O Astrea.

4. SELECTION OF EXPERIMENTAL RESULTS

A selection of results obtained by applying the described processing to data collected during the LCAS'18 experiment is reported. In addition to the vector sensor, the eFolaga AUV was equipped with an EvoLogics acoustic modem working in the frequency range 17 - 34 kHz. Furthermore, an EvoLogics USBL modem was deployed and towed from N/O Astrea in order to track the vehicle during underwater navigation. The vehicle also hosted an Idronaut CTD multiparameter probe to collect environmental data necessary to predict the propagation of sound in water.

4.1. PROCESSING THE SINGLE CAS-PAS SIGNAL

On November 24th, 2018, the NRV ALLIANCE towed a sonar source which was transmitting a CAS LFM in the bandwidth 1800 – 2600 Hz with a duration of 20 seconds and a Pulse Repetition Time (PRT) of 20 seconds. At the same time, the source was transmitting a PAS signal in the band 2.7 – 3.5 kHz with 1 second of duration. The PRT was the same. Fig. 1 (left) shows a photo of the vehicle during the deployment. An example of sound speed profile measured on November 25th is shown in Fig. 1 (right). It can be seen the profile is almost iso-velocity.



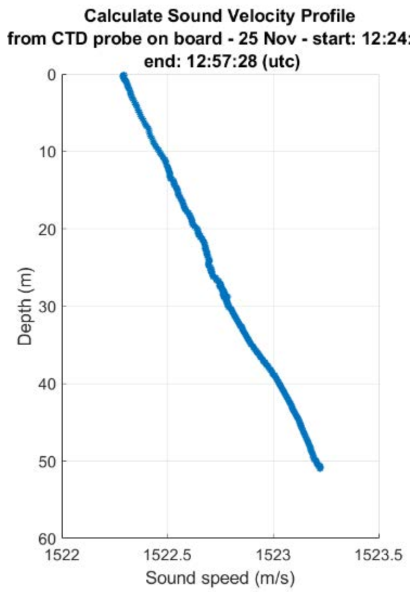


Fig. 1: (Left) Vehicle deployment. The two payloads: acoustic modem and acoustic vector sensor, are clearly visible. (Right) Sound Speed Profile measured from the CTD probe on board the vehicle.

A single CAS and PAS pulse has been selected in order to evaluate the detection and bearing performance of the developed system, applying both frequency and time-domain algorithms. The vehicle was on the surface during the data acquisition, waiting for a mission command by an operator. The acquired signal was filtered in the band 1.8 – 2.6 kHz for CAS signal and 2.7 – 3.5 kHz for the PAS. First, estimates were obtained in the frequency domain using (5) on the whole 20 seconds block of signal. If the calculated Signal to Noise Ratio (SNR) in the block was less than 5 dB the estimate was not considered. In order to reduce the number of estimates, we just considered one sample in a 1 Hz band, if detected. Figure 2 represents the estimates obtained for the CAS signal emitted by the source on board Alliance, which was underway at 3.5 knots at an average distance of 12430 meters from the vehicle. The source can be considered static in the 20 seconds block of data. It can be seen that using the frequency domain estimator it is possible to obtain estimates reliable with the reference ground truth.

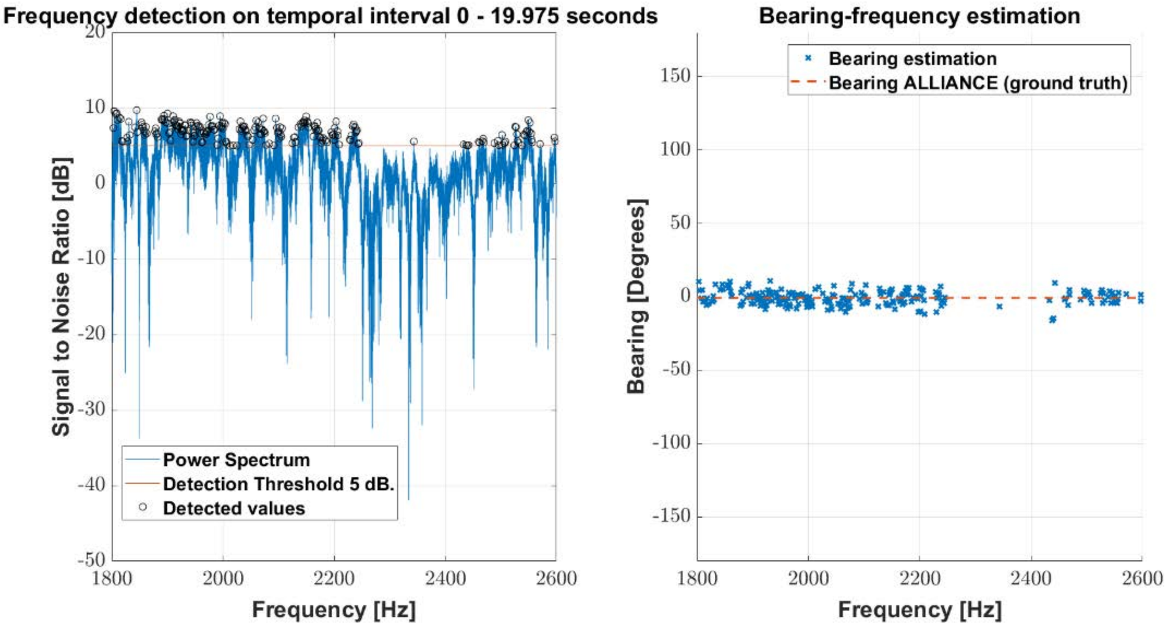


Fig. 2: (Left) Signal to Noise Ratio on the Omni sensor. (Right) Bearing-frequency estimates of a single CAS waveform.

Then we applied the described algorithm from (4) to estimate the bearing of the source in the time domain. Only one detection (if successful) per 0.5 seconds data block was considered. Figure 3 shows the obtained results:

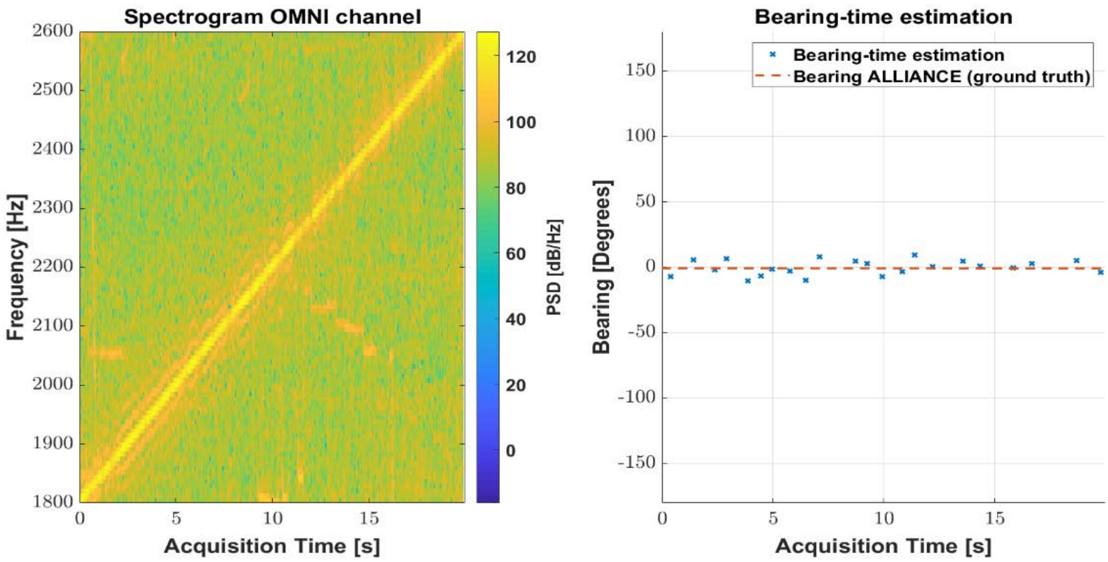


Fig. 3: (Left) Spectrogram of the received signal in which the CAS signal is clearly visible. (Right) Bearing-time estimates of the single CAS.

The same processing was applied to the PAS signal and finally, sub-band processing was applied to the CAS. The sub-bands were obtained by band-pass filtering the FFT of the signal of interest with the duration of the temporal blocks being proportional to the bandwidth. Each sub-band was processed by a threshold detector as in the case of single signal. Table 1 summarizes the achieved results.

Number of Sub-bands	1	1	2		4			
ID	Single PAS	Single CAS	Sub-band CAS nr.1	Sub-band CAS nr.2	Sub-band CAS nr.1	Sub-band CAS nr.2	Sub-band CAS nr.3	Sub-band CAS nr.4
Time block length [s]	1	20	10	10	5	5	5	5
Frequency Start [kHz]	2.7	1.8	1.8	2.2	1.8	2.0	2.2	2.4
Frequency End [kHz]	3.5	2.6	2.2	2.6	2.0	2.2	2.4	2.6
Detection Threshold [dB]	5	5	5	5	5	5	5	5
Nr. Detections (time domain)	2	22	12	12	6	6	5	5
Nr. Detections (frequency domain)	85	232	122	89	43	55	35	35
Mean bearing-time error [degrees]	4.64	0.58	0.13	-0.02	-1.70	-1.22	-0.75	1.00
Mean bearing-freq. error [degrees]	5.35	0.1	-0.85	-0.02	-0.27	-1.73	-0.66	0.68
Std dev error time domain [degrees]	5.09	5.85	2.26	2.07	3.58	2.32	2.45	0.96
Std dev error frequency domain [degrees]	5.01	4.68	3.24	3.29	3.10	2.05	2.68	1.59

Table 1: Statistical indices of the applied processing on CAS, PAS, and sub-bands of a CAS.

The results are very promising in terms of bearing error especially when considering the large source-receiver distance and the oscillations of the sensor due to the vehicle's surface drift. Applying sub-band processing on the CAS waveform, results in an improvement in terms of standard deviation error with respect to the first case, both in time and frequency domain. This could be attributed to the higher SNR obtained on each sub-band; analysis over a shorter time duration was probably accompanied by smaller movements of the DIFAR sensor, effectively improving bearing estimates.

4.2. THE EFFECTS OF VEHICLE NAVIGATION ON DATA-PROCESSING

On November 25th, 2018, the NRV ALLIANCE, underway at 4.2 knots, with the source at 80m depth, transmitted a CAS LFM in the band 1800 – 2600 Hz with a duration of 18 seconds and a Pulse Repetition Time (PRT) of 20 seconds. The Alliance track is shown in figure 4.

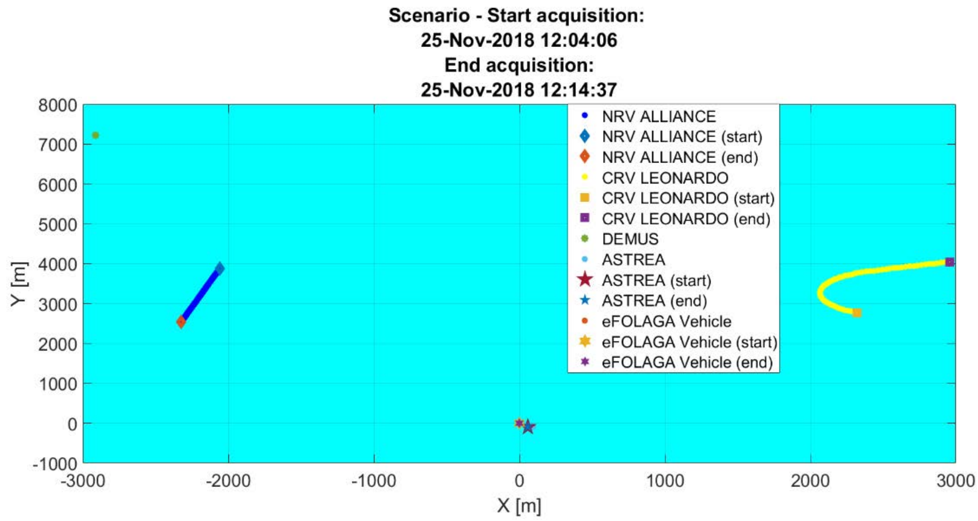


Fig. 4: Scenario of the selected experimental results. The vehicle is at the origin of the reference system. The blue trace is the NRV Alliance track which was towing the sound source.

Processing was accomplished by filtering the DIFAR signal in the sub-band 1800 – 2600 Hz in order to analyse the CAS signal. The distance between the vehicle and the Alliance varied between 4395 and 3443 meters, while the relative bearing with respect to the vehicle varied between 332 and 317 degrees. Detection contacts were extracted from the data (by applying (4)) when the SNR of the omnidirectional channel exceeded a threshold of 5 dB. Figure 5 (top) shows the extracted detection contacts and its bearings. The eFolaga tasks are shown in figure 5 (bottom) while it was acquiring the data. The vehicle started from the surface in a stationary mode, then it varied its buoyancy to reach a depth of 30 meters and started to perform gliding navigation between 30 and 50 meters.

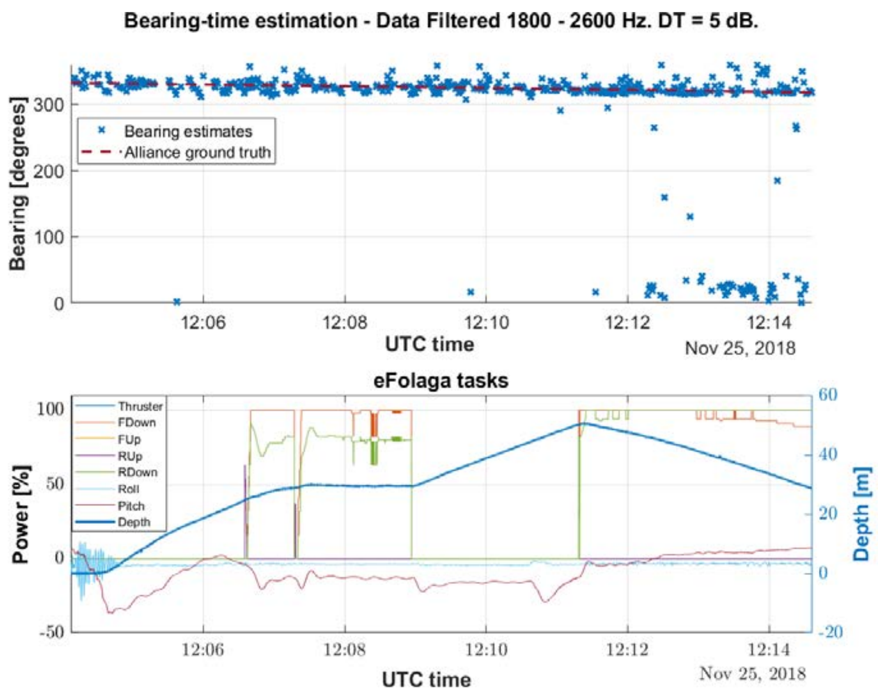


Fig. 5: (Top) Detection contacts and associated bearings. (Bottom) The eFolaga tasks while acquiring data.

At 12:11:30 (UTC) the vehicle activated the pumpjet in order to return to the surface, leading it to assume a positive pitch angle. This could have compromised subsequent bearing estimates, producing significant outliers. In addition, the ground truth was obtained from the Alliance GPS and the last GPS fix of the vehicle when on the surface, due to the absence of transponder fixes in the temporal block considered. Considering the results before 12:11:30, there are 300 detections, with a mean bearing error of 0.6 degrees and a standard deviation of 19.6 degrees. Applying the sub-band processing in the range 1.8 - 2.2 kHz and 2.2 - 2.6 kHz and considering the same temporal length of the signal, we obtained a standard deviation error of 11.9 and 7 degrees respectively for the first and second sub-band signal. A mean bearing error for each sub-band of -2 and -2.7 degrees was observed. In this case, the detection events are respectively 213 and 188.

5. CONCLUSION

This paper discussed the capability of an AUV mounted vector sensor to estimate the bearing of real sources in a multistatic scenario. Time and frequency domain implementations of bearing estimation have been presented. It has been demonstrated, with field data, that a vector sensor integrated into an AUV is able to track different types of low frequency sources, while drifting on the surface and also during subsurface gliding navigation. Furthermore, the equipment used in the acoustic payload are of low cost and the implemented methods have low computational demand, making them suitable for use in real-time processing.

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