DIRECTION OF ARRIVAL ESTIMATES WITH VECTOR SENSORS: FIRST RESULTS OF AN ATMOSPHERIC INFRASOUND ARRAY IN THE NETHERLANDS

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Abstract: *The Royal Netherlands Meteorological Institute has continuously operated an outdoor atmospheric infrasound array containing 37 pairs of particle velocity sensors (Microflown) and 6 pressure sensors in the north of the Netherlands in the fall of 2008***.** *As initial results, we detected transients caused by distant aircrafts and calculated their Direction of Arrival (DOA). A nearby sound-source, probably an agricultural vehicle passing on the nearby road or field, could be tracked. Furthermore, we compare DOA estimates using the amplitudes of the vector components of the particle velocity measured at single stations with those of classical beamforming and discuss the prospects for underwater applications.*

Keywords: *atmospheric infrasound, Microflown, direction-of-arrival estimate, vector sensor, localization*

1. INTRODUCTION

In this paper, we present results of atmospheric infrasound measurements acquired with an array located in the North of the Netherlands. Atmospheric infrasound is being measured as part of the global network of the Comprehensive Nuclear-Test-Ban Treaty (CTBT). Arrays of micro-barometers for measuring infrasound that are currently deployed typically have an aperture in the order of 0.5 to 3 km. Arrays of this size are difficult to realise and maintain.

Recently developed acoustic vector-sensors [1], devices that measure individual components of vector quantities, can provide a solution to this problem. A measurement of the three components of particle velocity at one position namely enables the calculation of the Direction of Arrival (DOA) of waves, even those with wavelengths either much larger or much shorter than the array aperture. Based on theoretical studies [1],[3] it is expected that vector-sensor arrays can be much smaller than conventional arrays while the detection performance and resolution in DOA estimation can be retained.

For the same reason, vector-sensors are of interest to underwater applications. Large arrays are difficult to handle or cannot be deployed from Autonomous Underwater Vehicles (AUVs) where the space is often limited. Unfortunately, there is a limited availability of vector-sensor data for underwater applications. For this reason, the experiences with atmospheric vector sensors are relevant to underwater applications as well. Here, we study the results of an experiment conducted by the Royal Netherlands Meteorological Institute (KNMI) in the framework of the astronomical Low Frequency Array (LOFAR, www.lofar.org). The aim of the experiment is to investigate, among others, the performance of particle velocity sensors for determining the DOA of atmospheric infrasound

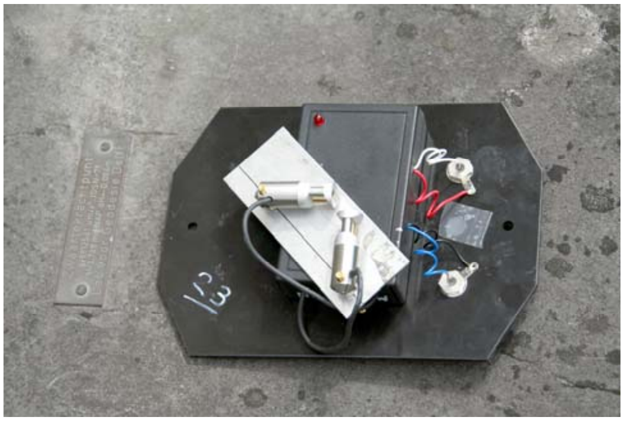

Fig. 1: *A photograph of a measurement station. The Microflown probes are oriented perpendicular and are mounted on the electronic box. The coloured wires lead to the connectors for the signal cables. A probe is 1/2 inch wide.*

2. EQUIPMENT

The array consists of 6 pressure sensitive microphones (Infineon, SMM 310) and 72 commercially available particle velocity sensors, called Microflowns. [1]. A Microflown consists of two heated parallel wires. Air moving across the wires will cool the wires, changing their electrical resistivity. The up-wind wire will be cooled more than the downwind wire, causing a measureable difference in electric resistivity. One Microflown measures the flow of air in one direction with a figure of eight sensitivity.

Each measurement station has 2 orthogonally placed Microflowns mounted on an electronics box. Fig. 1 is a photograph showing a station without the protective cover. The installation of each station is based on a housing for a thermometer, as used by the KNMI. It consists of a hard-pvc bottom-plate and two ‘saucers’, with a radius of 13 cm, stacked together with a 2 cm gap between them. The lower saucer has a large hole (7 cm radius) to accommodate the setup. In the following, we will use the phrase ‘*EW-flown’* to designate the Microflown with its most sensitive direction oriented EW and ‘*NS-flown’* for the other, perpendicularly oriented, Microflown.

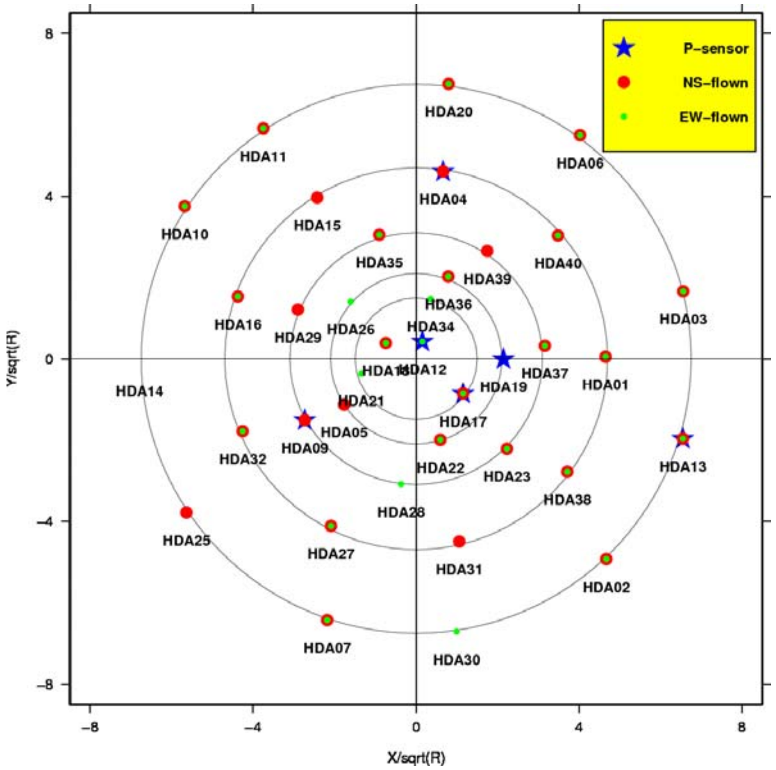

Fig. 2*: The array lay-out based on the NORESS array. The axes are scaled by the square root of the distance to the centre (R) for visualisation purposes. The radii of the circles are 2.2m, 4.6m, 9.9m, 21.4m, 45.9m, respectively. The symbols indicate which sensors are present (and functioning) at each station.*

The array consists of 37 stations and has a NORESS-like lay-out [4]. The NORESS-array geometry is based on 4 concentric rings spaced at log-periodic intervals to create many different inter-station distances, which guarantees an optimal performance of the array in terms of the resolution for DOA. The innermost ring, the A-ring consists of 3 elements and a central element. The B-ring has 5 stations, the C-ring has 7 stations and the D-ring has 9 stations. This gives a total of 25 stations. This array has a fifth ring, containing 11 elements, and an additional station close to the central element, which makes a total of 37 stations. The radius of the E-ring is thus 45.9 metres, making full use of the approximately 100 by 100 metres of grass-land available. The array lay-out is shown in Fig. 2.

The recordings are low-pass filtered, i.e. anti-aliased, and subsequently digitized at 200 Hz using the NI-6225 analogue-digital-convertor. The data are stored on disk in 2 minute segments and the off-line processing is done on tapered time-windows of 512 samples.

3. RESULTS

3.1 Initial results

We analysed the pressure data for transients using the Fisher detector. This detector extracts coherent signals out of the continuous recordings, on the basis of their signal-to-noise ratios. As expected, there were large day-night variations; during the night, the main source of noise, that due to wind, is much lower, resulting in many more detections.

From the detections, we selected data from a – presumed - local sound source, to crudely compute the location of the source; we assumed straight paths from the source at ground level to the receivers. Using the Neighbourhood Algorithm [5], we calculated the source position by maximizing the Fisher-value of the recorded signals. This allowed us to track the sound source, probably an agricultural vehicle working the fields. For the remainder of this manuscript we will focus on Direction of Arrival calculations.

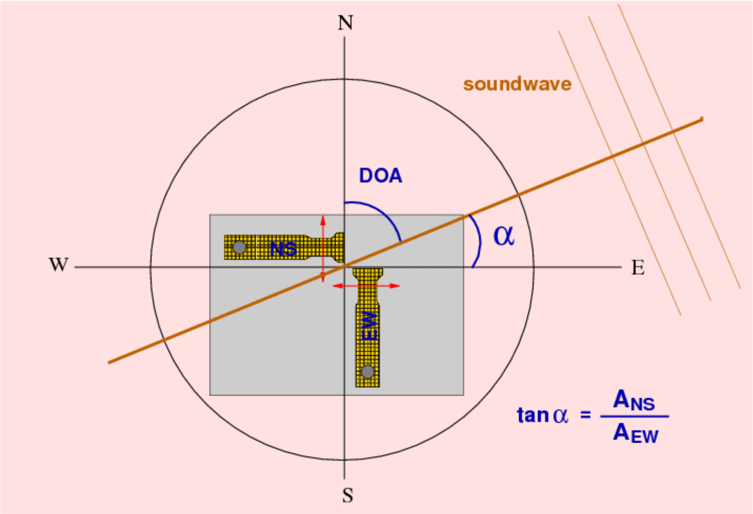

Fig. 3*: A schematic of a measurement station defining the angles used. The thin, two-headed red arrows show the sensitive direction of the velocity probes. The DOA is the angle of the incoming sound wave with the North.*

3.2 DOA estimation using signal amplitudes instead of phase-differences

Fig. 3 is a schematic drawing showing the orientation of the sensors and an incoming sound wave. The angle α is calculated using the formula

$$\alpha = 0.5 \arctan\left(2\, G_{12}/(G_{11} - G_{22})\right) \quad \text{modulo } (\pi/2), \tag{1}$$

with G_{12} the cross-correlation between the NS and EW flowns, G_{11} the auto-correlation of the NS-flown and G_{22} the auto-correlation of the EW-flown. The correlations are calculated over time-windows of 0.3 seconds (60 samples). After choosing $0<\alpha<\pi/2$ and using the sign of G_{12}, the DOA is known modulo (π). Addition of a pressure sensor will completely remove this ambiguity.

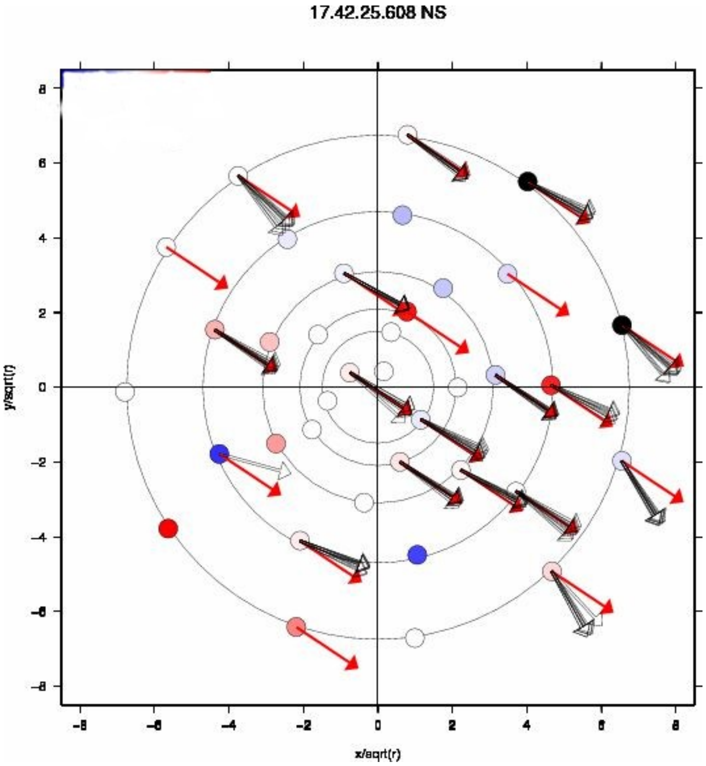

Fig. 4: DOA results. The red arrows all point to the same direction; namely the direction of arrival of the sound with the maximum Fisher value, as calculated using phased beamforming of 2.5 seconds of data. The hollow black arrows point in the direction as calculated from each 0.3 seconds of amplitude data.

Fig. 4 shows the results of processing of 2.56 seconds of selected data (512 samples).Transient detection using the Fisher detector and classic phased array beamforming over the 2.5 seconds resulted in the filled red arrows. These arrows are plotted, originating from every station with two operating Microflowns. The hollow black arrows point in the DOA-estimate as derived using formula (1) for each station for all time-windows of 0.3 seconds within the 2.5 seconds time-interval.

The observations reveal the following characteristics: 1) Only for stations with two functioning Microflowns can the DOA be calculated. However, some of the sensors had poor signal to noise ratio or were temporarily not functioning. Therefore, some stations do not show a resolved direction (hollow black arrow). Furthermore, when the signals on the EW- and NS-flown were too different; i.e. the absolute value of their normalized cross-correlation was below 0.3, at least one of the channels is too noisy to produce accurate results. Note that this will prevent DOA-estimates close to either N, E, S or W, because then one of signals is very small compared with the other one. 2) There seems to be a lot of variability in the directions, also per station, compared with the phased array beamforming solution. This can be due to local (wind) noise or because of actual (local) changes in the DOA over the 2.5 seconds, over which the beamforming calculated its (average) DOA estimate. 3) Some stations, notably the ones in the SE-corner seem to have a bias. This is probably due to a constant difference in sensitivity of the EW and NS sensors at those stations. It illustrates that the gauging of the instruments should be done accurately.

4. CONCLUSIONS AND UNDERWATER PROSPECTS

As in air, the directional information of (transient) underwater sound can be retrieved from a single station with a vector sensor combined with a pressure sensor; impossible when using only a single hydrophone.

Combining multiple vector-sensors in an array enhances the resolution in the directional beam pattern due to the cardioid response of vector sensors. Theoretical studies indicate that line arrays of directional sensors can have a directivity index approximately 5 dB larger than that of an identical line array of pressure sensors [6]. In addition, it has been shown that estimating the DOA of transients for sound with wavelengths that are either large or small compared with the array aperture is possible. So, an array of vector sensors can distinguish between ambiguous arrival angles, for instance due to spatial aliasing in a coarse array, because a single vector sensor contains information on the DOA.

Furthermore, vector sensors are able to remove the left-right ambiguity of towed arrays when the particle velocity vector-sensor is combined with a pressure sensor.

As a result of these properties, vector sensors are of special interest for applications on an AUV and for distributed sensor networks for passive monitoring. On AUVs, the space is limited. By using vector sensors, resolution in beamforming can be retained using arrays with short apertures. For distributed sensors, the estimation of the DOA is of fundamental importance in order to combine data acquired at different locations.

5. ACKNOWLEDGEMENTS

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