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NoiseSpotter: A rapidly deployable acoustic monitoring and localization system

Kaustubha Raghukumar, Grace Chang, Frank W. Spada, and Craig A. Jones

Abstract— **NoiseSpotter is a cost-effective environmental monitoring system that characterizes, classifies, and provides accurate location information for anthropogenic and natural sounds. It has been developed with the primary goal of supporting the evaluation of potential acoustic effects of offshore renewable energy projects. NoiseSpotter consists of a compact array of three acoustic vector sensors that measures acoustic pressure and the three-dimensional particle velocity vector associated with the propagation of an acoustic wave, thereby inherently providing bearing information to an underwater source of sound. By utilizing an array of three vector sensors, the NoiseSpotter triangulates individual bearings to provide sound source localization, allowing for a characterization of the acoustic signature of specific acoustic sources located in different regions of the ocean. Here, we describe the technological features of the system, and describe its ability to localize the source of controlled acoustic transmissions.**

Keywords—**Acoustic vector sensors, real-time underwater acoustic monitoring, sound localization.**

I. Introduction

NoiseSpotter has been developed as a monitoring technology to support the evaluation of potential environmental effects of marine and hydrokinetic (MHK) energy devices. NoiseSpotter seeks to improve upon traditional acoustic sensing techniques through integration of a compact array of acoustic vector sensors with custom data dissemination technologies to characterize, classify, and provide accurate location information, in near real-time, for anthropogenic and natural sounds.

Traditional acoustic sensing techniques involve the use of hydrophones that measure scalar acoustic pressure. Consequently, acoustic source localization typically requires the use of large arrays consisting of multiple hydrophones [1]. The large size and footprint of hydrophone arrays can therefore make it difficult to deploy using a small vessel in energetic environments near operational MHK devices. An attractive alternative to the use of large hydrophone arrays are compact arrays of acoustic vector sensors. A vector sensor measures three-dimensional (3D) acoustic particle velocity in addition to acoustic pressure on a single sensor. The vector measurement inherently provides directional information (acoustic bearing) to a source of sound. A vector sensor array (VSA) can therefore triangulate individual measured bearings to provide sound source localization, and thereby help characterize sound specific to a source. MHK devices are expected to emit low intensity sounds on the order of 110–130 decibels (dB) referenced to 1 microPascal (re uPA) at 1 m [2]. Therefore, in order to characterize MHK sounds, it is important to be able to distinguish it from other sources of sound such as boats, marine mammals, and fish choruses.

The objectives of this paper are to: (1) describe technological aspects of the NoiseSpotter including results from in-water field measurements and (2) demonstrate the utility and feasibility of vector sensors to locate a known, controlled acoustic source.

II. The NoiseSpotter system

Several hardware improvements have been made to the NoiseSpotter over its two-year development process to date, with the primary goal of obtaining the highest quality acoustic particle velocity and pressure data while maintaining relatively easy at-sea deployment and recovery operations. All hardware configurations involve the VSA, which is comprised of three Geospectrum Technologies Ltd. vector sensors: two model M20-40s and

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K. Raghukumar, G. Chang, F. Spada, and C. Jones are all with the Marine Sciences and Engineering Practice Group at Integral Consulting Inc. 200 Washington Street Suite 201 Santa Cruz, CA 95060 U.S.A. (emails: kraghukumar@integral-corp.com; gchang@integral-corp.com; fspada@integral-corp.com; cjones@integral-corp.com).

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one M20-100. All three sensors measure tri-axial particle velocity and omnidirectional pressure (total of four measurement fields) between 100 Hz and 5 kHz, while the M20-100 also provides digital compass readings using an integrated inertial motion unit. Described in this paper is the third iteration of the NoiseSpotter, termed the NoiseSpotter V3.

A. Hardware

NoiseSpotter V3 consists of a 1.25 m x 1.25 m bottom-mount fiberglass grate with three modular frames, each housing a vector sensor draped in custom flow noise shields (Fig. 1). A custom low-power, low-noise data acquisition system (DAQ), in pressure housing rated to 200 m (developed in collaboration with Proteus Technologies LLC and Pacific Northwest National Laboratories [PNNL]), was mounted to the bottom grate along with two rechargeable 32 AHr Sartek battery packs. An inverse catenary mooring was employed to decouple surface motions from the bottom platform. The NoiseSpotter V3 system was designed to operate autonomously for up to three weeks without servicing. In-water tests indicate that the V3 hardware configuration is suitable for small-vessel (~8-m in length) operations in quiescent and energetic environments.

Fig. 1. NoiseSpotter V3 being deployed in Sequim Bay, Washington, USA.

The flow noise shields, developed in collaboration with Noise-Control Engineering, were constructed of 1050 ballistic nylon wrapped around a baffled PVC tube in which a vector sensor was suspended. Extensive laboratory tests of 1050 ballistic nylon revealed that it is acoustically transparent and significantly reduces flow inside the noise shield. Therefore, reduction in flow noise is expected due to reduction of flow inside the shield. Further, because of its acoustic transparency, VSA measured acoustic signals are not affected.

The use of individual frames to house each vector sensor enables modularity of the VSA. This enables rapid reconfiguration of the vector sensors for different expected environmental conditions. For example, location estimates of lower frequency sounds (<1 kHz) require at least 1 m horizontal spacing for sensors whereas a more compact and hand-deployable arrangement of sensors can be used to geolocate higher frequency sounds.

B. Field Testing

A series of field trials were conducted in and near Sequim Bay in July 2018, in collaboration with PNNL. The field sites (Fig. 2) represented a quiet shallow site (SB2, water depth 26 m) and an energetic tidal channel (Marine Science Labs [MSL], water depth 7-10 m).

Fig. 2. Map of NoiseSpotter testing locations.

System performance was tested to evaluate data quality, ease of deployment and recovery, flow noise removal, and performance of location estimation algorithm. At each location, the NoiseSpotter was deployed on the sea bottom, with an inverse catenary mooring to the sea surface such that surface-induced motions are decoupled from the sensor platform. A controlled acoustic source (icTalk®, Ocean Sonics Ltd.) was deployed over the side of a vessel (R/V Strait Science) 1 m below the sea surface, and programmed to repeatedly transmit a series of low-frequency pulsed sinusoids, followed by chirps. The acoustic signals spanned the frequency range 100 Hz to 3 kHz, at a source level of 120 dB re 1 μPa at 1 m. Testing at the SB2 location typically involved the repeated transmission of the controlled acoustic signals at source-receiver separations of 50 m, 200 m, 500 m and 1000 m. Due to the more involved effort required to moor the boat in the energetic tidal channel at MSL, the boat was allowed to drift past the sensor platform to/from a distance of 500 m, while continuously transmitting the controlled acoustic signals. Additionally, ambient noise measurements were made at all locations to characterize the noise floor, evaluate flow noise contributions, and to assist in acoustic propagation modelling.

C. Data Quality

Twelve analogue channels (x, y, z, and pressure for three sensors) of time-synchronized VSA data at 24 bits and one digital channel (orientation) were successfully recorded by the custom DAQ, at a synchronous sampling rate of 20 kHz per channel. Pressure and particle velocity data are presented for the controlled acoustic source transmissions recorded in quiescent conditions (at SB2), a source of opportunity (a passing boat) in Sequim Bay, and ambient noise spectra in energetic conditions (at MSL) to demonstrate data quality.

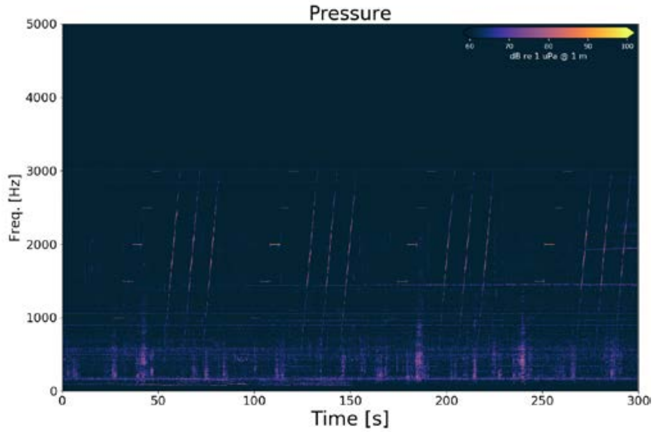

Fig. 3. Pressure as measured on a single vector sensor in 26 m deep water at the SB2 location, Washington, USA.

Fig. 3 shows the low-frequency pulsed and swept acoustic transmissions, as received on the NoiseSpotter when deployed at SB2, at a distance of 200 m from the controlled source. Transmitted signals are clearly discernible, and any artifacts due to electronic and self-noise such as spectral lines are not evident. Low-frequency ambient noise below 1000 Hz is also evident, and generally free of self-noise artifacts. The horizontal lines indicative of electronic noise are not visible in acoustic spectrograms; vertical motions induced by cable strum are also absent from data (Fig. 3). The quality of data recorded by the custom DAQ is observed to be very high and suitable for location estimation without further data filtering.

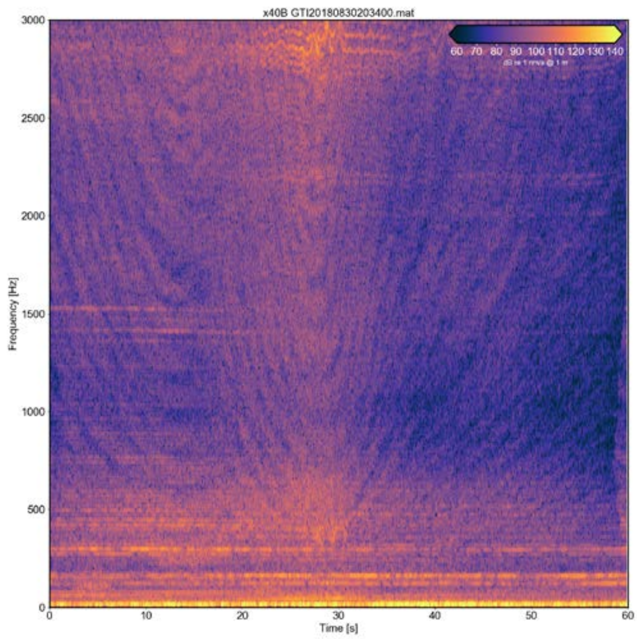

Fig. 4. Particle velocity on x-channel of vector sensor M20-040, measured in Sequim Bay, Washington, USA.

Fig. 4 shows particle velocity measurements made on the x-channel of one vector sensor, the M20-040. The unique acoustic signature of a passing boat is seen as the characteristic Lloyd's mirror interference pattern for passing vessels [3], generated as the interference between the surface-reflected and direct path to a bottom-receiver. In addition to the interference pattern, spectral lines that are characteristic of a boat's propeller are also visible, lending further confidence in the NoiseSpotter's low self-noise, allowing for measurement of ambient sounds.

Finally, the ability of the NoiseSpotter to remove flow noise was evaluated by deploying the system in an energetic tidal channel during an incoming and outgoing tide, with and without the ballistic nylon flow shield. Fig. 5 shows results from the flow noise evaluation tests, with noise spectra calculated for frequencies below 1000 Hz over two 30 minute-long acoustic pressure data segments. The flow noise shield is observed to effectively reduce flow noise by approximately 9 dB at less than 250 Hz. While Fig. 5 displays improvements in flow noise removal when applied to the pressure channels, similar results were observed for the particle velocity channels (data not shown).

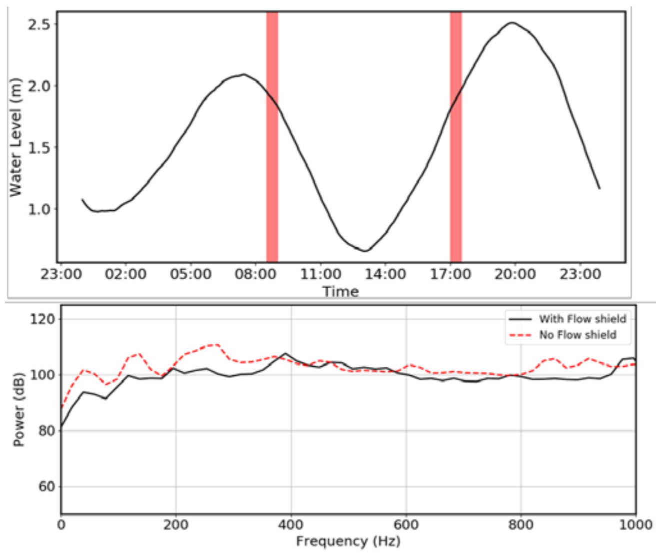

Fig. 5. Demonstration of flow noise removal efficiency at energetic tidal channel. The upper channel shows tidal elevations, with the red boxes indicating periods when spectra were calculated with and without the flow noise removal shield.

III. ACOUSTIC LOCATION ESTIMATION

A key principle of long-distance underwater acoustic propagation is that sound travels along discrete paths between a source and a receiver. Given the uniqueness of the acoustic field between a source and receiver, a variety of techniques can be employed to determine the location of a sound source (e.g., [4]). These techniques vary in hardware complexity, accuracy, and computational efficiency based on the underlying physical assumptions.

The NoiseSpotter is a platform that can improve upon the method of direction of arrival estimation by using acoustic vector sensors that measure triaxial particle velocity in addition to acoustic pressure. Each vector sensor has the ability to determine the bearing of an acoustic source. With multiple time-synchronized vector sensors located on the array, the essential principle of the proposed technology is that the source can be geo-located by triangulation of particle velocity vectors measured across the array [5, 6].

The basic principle of triangulation using a vector sensor array is illustrated in Fig. 6. Here, a plane wave impinges upon a linear array of acoustic sensors. For a given angle of incidence, the signal received on each channel of the acoustic array is offset by a frequency-dependant phase relative to that received on neighbouring channels. Plane-wave beamforming [4] acts by phase-shifting the signal on each channel, followed by coherently summing over the array. The larger the number of array channels, the greater the array gain, and better the suppression of incoherent random noise, while reinforcing a coherent signal. A vector sensor makes four acoustic measurements on each sensor. Therefore, a vector sensor array, such as the NoiseSpotter, can exhibit four times the array gain as a traditional hydrophone array with the same number of physical sensors.

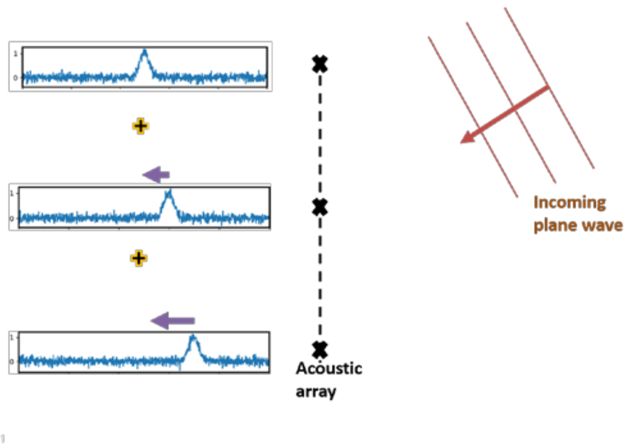

Fig. 6. Principles of plane-wave beamforming applied to an acoustic array.

Having established adequate data quality of the NoiseSpotter V3, bearing estimation of the acoustic source can be demonstrated. The technique for bearing estimation calculation involves segmenting the time series into discrete one second-long segments (20,000 points at a sampling frequency of 20 kHz). One thousand and twenty-four- (1024-) point Fast Fourier Transforms (FFTs) are computed on each 1 s data segment and plane-wave beamforming is applied in the frequency domain following the methods outlined by Santos et al [4]. This method yields a dominant azimuth and elevation angle for each time segment, estimates of which are then stitched together for the entire time series.

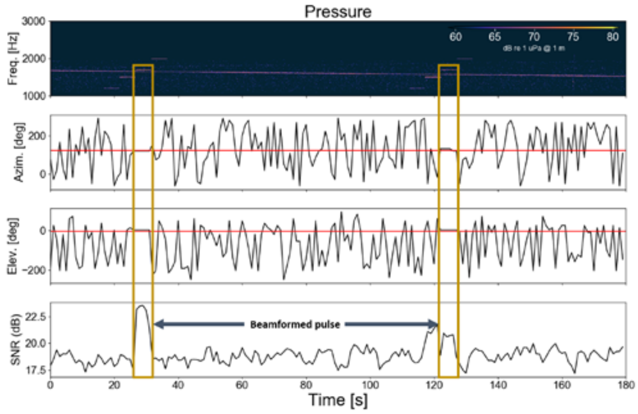

Fig. 7. Beamforming location estimation algorithm applied to a 3-minute data segment collected in August 2018. Source pulses of interest at 2 kHz are outlined in orange.

Bearing estimation was conducted for multiple six minute-long time series of controlled acoustic source transmissions that were obtained at various source receiver separations (50 m, 200 m, 500 m and 1 km) during in-water field testing. Figure 7 shows an example of elevation and angle estimates obtained for a 3 minute-long time series when the source is located 200 m from the receiver. Shown in the upper panel is a spectrogram of the received signal, which shows the evolution of the frequency content of received signals. Receptions of the controlled source transmissions are seen as the step-like progression in energy across frequency as an evolution of time. Estimates of azimuth and elevation angle during these periods are seen to closely track the true bearing of the source. Outside of the periods where the source was transmitting, the bearing angles exhibit significantly larger deviations from the true bearing, consistent with isotropic ambient noise that has no dominant direction.

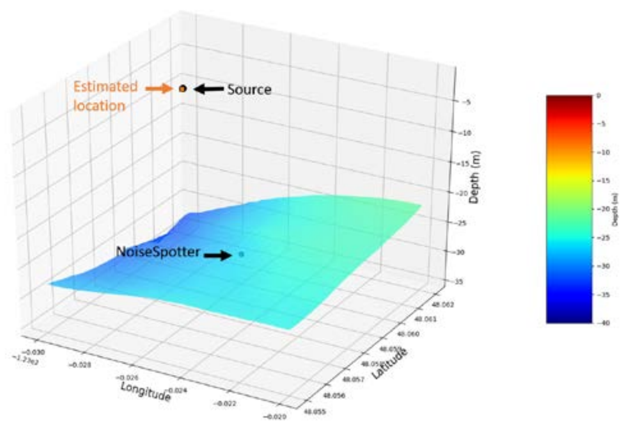

Fig. 8. True (black) and estimated (orange) controlled source locations relative to the NoiseSpotter V3 (blue), which were separated from the source by 200 m. The difference between true and estimated locations is 3.6 m (2% of separation distance).

Having estimated the three-dimensional bearing angle to the source, the true location of the source (Fig. 8) is estimated assuming a known source depth. This assumption is valid when trying to associate measured signals with MHK devices, whose locations are known in the water column. The estimated source location is seen to be co-located with the true source location, with an estimation error of 3.6 m, or 2% of the source-receiver separation distance.

IV. SUMMARY

This paper presented the performance characteristics of the NoiseSpotter, an easily deployable self-logging vector sensor array. The results of field trials were presented in a variety of environments that showed excellent data quality in each of these environments with regard to discerning controlled source transmissions and sources of opportunity. The ability to mitigate flow noise, key in energetic environments, was demonstrated in a tidal channel with approximately 9 dB reduction of flow noise at 200 Hz. The in-water tests indicate that the V3 hardware configuration is suitable for small-vessel (~8-m vessel length) operations in quiescent and energetic environments.

The ability of the NoiseSpotter to estimate the location of a source of sound was demonstrated using plane-wave beamforming techniques applied to a vector sensor array. The compact size of the vector sensor array allows for beamforming array gain comparable to much larger hydrophone arrays. Location estimates of the controlled source were found to be within 2% of the source-receiver separation.

V. FUTURE CONSIDERATIONS

The next steps in the NoiseSpotter development progress involve implementation of on-board processing to estimate source locations and key acoustic parameters. This will allow for the near real-time telemetry of acoustic data metrics via a satellite, cellular, or radio frequency link to a shore-based station. This capability will allow for rapid assessments of sound generated by natural and anthropogenic sounds in the vicinity of MHK devices, thus helping retire potential risk associated with MHK sound.

Further progress on the location estimation algorithm will involve estimating the true location of a source without any assumptions regarding source depth, while taking into account multipath reflections that can be expected with longer range acoustic propagation.

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