Sound localization for Sediment-Generated Noise (SGN) measurement

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Abstract

SGN is a surrogate bed-load monitoring methodology with the potential to allow economical, continuous measurement of coarse bed load in streams using passive acoustics. While the magnitude of recorded sound has been shown in some cases to be well-correlated with bed load transport, substantial work is still needed before the technique is ready for wide-spread deployment. Past efforts to develop SGN as a surrogate bed load monitoring technology have revealed that little information on underwater sound propagation in natural stream channels is currently available. Most of the work on acoustic propagation that has been done in shallow water that is directly relevant to SGN deployment has been in support of bioacoustics research, where the lack of shallow, freshwater acoustic research has been noted. Our recent efforts to address the basic processes of SGN have further highlighted the importance of understanding sound propagation in natural stream channels. Previous measurements of sound propagation in both a snow-melt driven, natural gravel-bed stream (Halffmoon Creek, CO) and a shallow sand/gravel bed stream (Goodwin Creek, MS) provided an initial step towards the goal of the proposed work but revealed many new questions relevant to SGN development. Two key problems highlighted by this preliminary work were the variable acoustic environments created by stream geometry and the production of flow-induced noise around the hydrophone. We address the source area problem by attempting to map detected SGN signals from the stream bed in real-time through the design and development of a 2-D phased hydrophone array to locate the sound sources spatially on the riverbed. Two-dimensional phased arrays have been used in many fields including aeroacoustics research for the localization of sound sources on an airframe. Such a device, suspended from a floating platform, will provide information in larger mobile bed applications of the spatial distribution of bed movement as well as a de facto measurement of the source region for SGN signals. Empirically mapping the acoustic source region would aid the development of calibration relations for SGN deployments on larger rivers.

Introduction

Accurate bed load measurement using direct measurement methods is difficult and expensive (Kuhnle and Southard, 1988; Kuhnle, 1989; Gray et al., 1991; Bunte and Abt, 2005). Passive acoustic instrumentation is well suited for remote, continuous deployment, is non-intrusive, and integrates sound from a finite area, decreasing bias caused by spatial heterogeneity of bed load transport. Challenges of using passive acoustics to measure bed load include the generally unknown size of the interrogated area of the bed and the unknown acoustic interactions of SGN with fluvial environments (Rigby, 2017). One potential means of mitigating these challenges is the
use of phased acoustic arrays for sound localization on the river bed. Such arrays can map the sound emission from the river bed in two dimensions for multiple frequencies, eliminating the uncertainty in interrogated area. This technology has the potential to provide immediate qualitative maps of bed load variability in time and space across a river cross-section from continuous monitoring. In addition, boat-mounted arrays may allow mapping bed load activity over long river reaches. Additional work may further allow calibrated phased-array monitoring for continuous, quantitative bed load measurement using SGN.

The use of phased microphone arrays for localizing aeroacoustic sources has seen increasing use in the recent past with the development of advanced data-processing algorithms. CRAFT Tech has developed an acoustic source localization (ASL) toolbox to perform frequency-domain beamforming calculations on aeroacoustic flowfields using a variety of techniques. The main beamforming program in the toolbox has been parallelized to run on multiple processors, which allows for beamforming calculations to be performed on multiple frequencies simultaneously, thereby reducing the time for these calculations. Beamforming provides the phased array system with directionality by effectively amplifying the sound from a region in space while attenuating sound from other regions. For a collection of $M$ microphones that comprise the phased array system, the classical approach, called the delay-and-sum (DAS) beamformer consists of selecting appropriate delays, $\Delta M$, and weights, $w_M$, in order to steer or focus at desired points in predefined grid region of interest. More information about the DAS procedure can be found in (Humphreys et al., 1998).

This project focused on developing a hydrophone-based phased array design that could be used to localize acoustic sources for underwater applications such as SGN. A schematic of the measurement setup is shown in Figure 1, where $D$ is the aperture of the phased array, which is
located at an offset of $Z$ meters from the steering/interrogation plane. The primary products sought in this work were the phased array design specifications including the number of hydrophones, the coordinate locations of the sensors, and theoretical beamforming performance characteristics of the array system based on the following design parameters and constraints that are considered desirable for the phased array system for SGN applications:

- Array dimension: 1 m$^2$ (approximate, to facilitate field application),
- Scan plane dimensions: 20 m (width) \times 5 m (length),
- Array plane offset: 1 m – 5 m (water depth),
- Frequency range: 1 kHz – 20 kHz (expected SGN signal band),
- Nominal resolution between sources: 0.25 m (spatial resolution on the bed).

**Methods**

For this application two array designs were evaluated, namely the multi-arm spiral array and the Underbrink array, the latter of which is a modification/enhancement of the former to obtain better array response. The multi-arm spiral array design is based upon using a number of spirals, equally rotated about the origin (Underbrink, 2002). The procedure for determining sensor locations is to select the maximum and minimum radii, $r_{\text{max}}$ and $r_0$, the number of spiral arms, $N_a$, the number of sensors per arm, $N_{m}$, and the spiral angle, $\nu$. The equation for the first arm, in polar coordinates, yields sensor locations that are equally spaced on a spiral. This spiral arm is then repeated $N_a$ times and equally rotated about the origin to yield the coordinates of the multi-spiral array.

The Underbrink array is a modified version of the multi-spiral design, wherein the sensors are placed in the center of equal-area segments. In order calculate the sensor locations, one selects the same parameters as for the multi-arm spiral array. Following this, the area of the array is divided into $(N_m-1)$ equal area annuli, which are further divided into equal area segments, with sensors placed at the center of these segments. Finally, an inner circle of sensors is added at $r_0$ to improve the high-frequency MSL.

![Figure 2. Candidate array designs for acoustic source localization using hydrophone sensors. Multi-spiral array (left) and Underbrink array (right) showing large and small aperture sub-arrays to cover the full frequency band of interest.](image-url)
Results

After testing a number of different combinations of parameters for the multi-spiral and Underbrink array design, initial array designs for 5 m x 5 m scanning plane were constructed using 15 hydrophones with three different apertures to span the frequency range of interest from 5 kHz to 20 kHz. Updating the scanning plane dimensions to 20 m x 5 m to reflect a realistic interrogation of a river cross-section resulted in the need for a total of 21 sensors to fulfill the design specifications. With this increase in the number of sensors, the frequency range of interest could be covered using only two phased-array apertures for the multi-spiral design ($D=0.40$ m and 0.90 m) and the Underbrink design ($D=0.30$ m and 0.60 m). Figure 2 shows the sensor locations for the two array designs, each containing the sensor placements for the desired apertures. Following this, MSL calculations were performed for both array designs and all apertures to obtain the array response over the frequency range of interest; these results are shown in Figure 3. The superiority of the performance of the Underbrink array can be clearly seen over the entire range of frequencies in that this array design significantly reduces the amplitudes of the maximum sidelobes, allowing for a deterministic localization of the acoustic sources.

![Figure 3](image.png)

Figure 3. Results of the mean sidelobe level (MSL) calculations, which is an indicator of the dynamic range, for the different array types and apertures.

For the model results presented here, the two-dimensional phased array will be located in the $Z=0$ plane (water surface) and will be used to scan a rectangular XY plane that is 20 x 5 m² (river bed), located at $Z = 4$ meters (water depth). Results will be presented for four source frequencies ranging from 5 kHz – 20 kHz in steps of 5 kHz using the Underbrink array; the array aperture is
chosen based on the source frequency. To begin with, we use the traditional DAS beamforming algorithm to localize a point source located at \((x,y,z) = (0,0,4)\) meters. Figure 4 shows the beamform maps for the ideal point source at the various frequencies. The figures on the left show surface plots, normalized by the value of the array response at the source location, and the figures on the right show the projection of the surface plots, presented as constant contour levels (in decibels). In addition to constant contour levels, these plots also show the location of the first stationary points, depicted as the dashed lines, surrounding the main peak; the MSL value is the maximum value of the array response outside this region.

Figure 4. Beamform maps showing the array response to a single point source at \((x,y) = (0,0)\) for various source frequencies; from top to bottom: 5 kHz and 10 kHz, using array with large aperture; 15 kHz and 20 kHz, using array with small aperture.

Conclusions

We have presented the first step in a novel use of acoustic beam forming technology for application to bed load monitoring using the passive acoustics of SGN. We adapted existing
model design algorithms from aeroacoustics to design a phased array of hydrophones for underwater application. The resulting multi-spiral and Underbrink arrays provide 0.25 m spatial resolution over an interrogation plane 20 m by 5 m in up to 4 m of water depth. Such dimensions and resolution are believed to be appropriate for fluvial applications, and model results indicate the ability of the array designs to resolve sound sources on these scales. Following the design of the phased array system, we plan to build and test a prototype array using idealized sources in a laboratory setting, following which we will deploy the arrays in the field to localize acoustic sources in underwater applications.

References