Passive Broadband Source Localization in Shallow-water Multipath Acoustic Channels

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Abstract—This paper addresses the problem of direct-path passive broadband localization of a shallow-water acoustic source with a sparsely distributed set of sensors in the presence of uncertain multipath propagation. The classical approach to broadband source localization with sensors spaced many wavelengths apart involves time delay estimation (TDE) via generalized cross-correlation (GCC) methods. In shallow-water scenarios, however, multipath arrivals yield spurious peaks in cross-correlation outputs resulting in anomalous estimates of source location. In this paper, cross-correlations are normalized by an expected direct-path delay and geometrically averaged over multiple array orientations in order to disambiguate multipath returns from direct-path arrivals. In shallow-water channels, this allows for more robust estimates of the intersensor time delay due to direct-path propagation. Simulation results indicate a significant improvement in source localization performance over GCC methods operating in multipath environments.

I. INTRODUCTION

Broadband source localization with multiple sensors is traditionally accomplished by time delay estimation (TDE) via generalized cross-correlation (GCC) methods [1], [2]. For example, the GCC between two sensors can be used to estimate target bearing by finding the time-lag that maximizes the cross-correlation between filtered versions of the received signals. Originally developed for non bottom-interacting, deep-water scenarios, GCC methods typically assume only direct path propagation between the source and each receiver is present. GCC is capable of performing well in noisy environments, however, in shallow-water scenarios, it is not as robust to multipath propagation [3], [4].

In shallow-water channels, multipath is caused by multiple reflections off of the ocean’s surface and bottom. Multipath propagation gives rise to attenuated and time-delayed replicas of the original transmitted source arriving at the receiver. These correlated multipath returns cause unwanted peaks in the cross-correlation output often resulting in anomalous source location estimates when using GCC methods assuming a direct-path model.

Instead of assuming only direct-path propagation, matched field processing (MFP) techniques allow for multipath to be incorporated into the propagation model [5]. Matched field processing functions by matching the received signal to an assumed propagation model for numerous hypothesized source locations. In shallow-water, MFP methods often assume complex propagation such as predicted by a normal-mode model [6]. However, a drawback of MFP is that it is not robust to errors in assumed environmental parameters which can be commonly made in such complex propagation conditions [7].

In this paper, the multipath arrivals will be treated as nuisance components and we focus on estimating the time lag that corresponds to the predictable direct-path from source to receiver. This will be accomplished by using a rotating baseline array to combine cross-correlograms from multiple array orientations. Cross-correlograms will be normalized by a hypothesized direct-path time delay, then geometrically averaged across array orientation. This process effectively averages out peaks in the cross-correlation due to multipath returns arriving at different elevation angles and allows for more robust estimates of source bearing in shallow-water. The corresponding signal model, algorithm and simulation results will be presented in the following sections.

II. SIGNAL MODEL

In this paper, we generalize the direct-path model assumed in GCC methods to suit the problem of estimating the direct-path time delay in the presence of unwanted multipath arrivals. Consider a two element sensor array in a shallow-water channel. The received signals at sensors 1 and 2 are given by

\[
x_1(t) = s(t) * h_d(r_0, t) + n_1(t)
\]

\[
x_2(t) = s(t - \tau_d(\theta)) * h_d(r_0, t) + n_2(t),
\]

where \(s(t)\) is the source waveform, \(\tau_d\) is the relative direct-path time delay between sensors due to a source with bearing, \(\theta\) and \(h_d(r_0, t)\) is the multipath channel impulse response, excluding the direct-path, from the source at location, \(r_0\), to the \(k^{th}\) sensor. The additive noise term, \(n_k(t)\), is assumed to be uncorrelated and Gaussian. In comparison to 1 and 2, the classic direct-path model assumes \(h_1 = h_2 = 1\). GCC methods when applied to the model of (1) and (2) often give spurious estimates of the direct-path time delay, \(\tau_d\), because of the multipath terms. While matched field processing methods have been applied to the model of (1) and (2) assuming \(h_k(r_0, t)\) is known as a function of hypothesized source location, they are
known to be extremely sensitive to mismatch in the assumed environmental model [7].

In order to solve for the direct-path delay in (1) and (2) without detailed modeling of $h_k(r_0, t)$, in this paper, multiple pairs of sensors with baselines at different orientations, $\alpha$, are assumed available. Thus for the $\ell^{th}$ orientation observed data is given by

$$x_{\ell_1}(t) = s(t) * h_{\ell_1}(r_0, t) + n_{\ell_1}(t) \tag{3}$$
$$x_{\ell_2}(t) = s(t - \tau_d(\theta, \alpha)) * h_{\ell_2}(r_0, t) + n_{\ell_2}(t). \tag{4}$$

In this paper, $h_{\ell_k}(t)$ is given by

$$h_{\ell_k}(r_0, t) = \sum_{n=1}^{N} a_{n\ell_k} \delta(t - \tau_{n\ell_k}(r_0)), \tag{5}$$

where $N$ is the total number of multipaths, $a_{n\ell_k}$ is an attenuation factor and $\tau_{n\ell_k}(r_0)$ is the relative multipath time delay of a source positioned at $r_0$ for the $n^{th}$ path, at the $k^{th}$ receiver and $\ell^{th}$ array orientation. For our purposes, the term $\tau_{n\ell_k}(r_0)$ is derived using the method of images. Thus, the source is mirrored across the rigid boundaries of the waveguide and time delays due to the imaged sources are calculated by finding their distance to receivers 1 and 2 and dividing by the nominal speed of sound for a given array orientation.

Ideally, the cross-correlation between two sensors for a single source would yield a peak corresponding to the direct-path delay. Figure 1 shows a cross-correlation output between two sensors that are separated by a distance of 1 m where only the direct-path is present. The target is located at a bearing of 60° relative to broadside of the array. The dashed line represents the true direction of the target. In severe multipath, the cross-correlation output isn’t so ideal. Figure 2 shows the same scenario in a multipath channel containing $N = 5$ propagation paths from the source to receiver. The direct-path time delay is completely masked by correlated multipath arrivals in Figure 2. The goal of this paper is to isolate the direct-path time delay from other multipath delays enabling a more accurate time delay estimate.

### III. Algorithm

This section will discuss the algorithms that will be implemented in simulation. A brief review of GCC methods will be provided in the first subsection. In the following subsection, the proposed method of combining cross-correlograms at multiple array orientations will be discussed.

#### A. GCC

The generalized cross-correlation method was first proposed in the mid 1970's [1]. Although it was derived from the ideal signal model, it is often used as a means of source localization in multipath environments [8], [9]. The GCC is formed by adding a weighting term, $\Phi(f)$, to the cross-correlation function and can be expressed as

$$\Psi_{GCC}(\tau) = \int_{-\infty}^{\infty} \Phi(f) S_{x_1x_2}(f) e^{j2\pi f \tau} df, \tag{6}$$

where $S_{x_1x_2}(f)$ is the cross-spectrum of the received signals at sensors 1 and 2. The time delay that maximizes 6 given by,

$$\hat{\tau}_{GCC} = \arg \max_{\tau} \Psi_{GCC}(\tau), \tag{7}$$

is the GCC time delay estimate.

The choice of weighting function is important since its goal is to emphasize the GCC function at the true value for the relative time delay, $\tau_d$, of interest. Several weighting functions have been used with GCC to improve time delay estimates in various environmental conditions [2]. Two of the more common implementations, used in this paper, include the maximum likelihood weighting and the phase transform, or PHAT weighting.

PHAT weighting was developed as an ad hoc weighting technique that normalized the cross-spectrum by its magnitude. In other words, the weighting function, $\Phi(f)$, is given by

$$\Phi_{PHAT}(f) = \frac{1}{|S_{x_1x_2}(f)|}. \tag{8}$$

Maximum likelihood weights can be expressed in terms of the coherence function as [1]

$$\Phi_{ML}(f) = \frac{|\gamma_{12}(f)|^2}{|S_{x_1x_2}(f)| (1 - |\gamma_{12}(f)|^2)}, \tag{9}$$

![Fig. 1. Illustrative example of cross-correlation for direct-path propagation](image1.png)

![Fig. 2. Illustrative example of cross-correlation for multipath propagation](image2.png)
where $\gamma_{12}(f)$ is given by
\[ \gamma_{12}(f) = \frac{S_{x_2x_2}(f)}{\sqrt{S_{x_1x_1}(f)S_{x_2x_2}(f)}}. \] (10)

Both GCC-ML and GCC-PHAT techniques work well in ideal environments that contain only direct-path propagation from source to receiver. In multipath scenarios, however, these methods often suffer from anomalous estimates of the direct-path time delay which will be demonstrated via simulation.

B. Multiple Orientation Geometric Average

Figure 3 depicts the geometry of the passive source localization problem. It is assumed that reflections occur only at top and bottom boundaries in the shallow-water channel. In the figure, an acoustic source is distinguished by a square while two circles represent a horizontal sensor array. The direct-path is depicted propagating from source to receiver as well as a few of the multipath reflections as described by 5. It is assumed that the array can rotate with an angle, $\alpha$, relative to North.

![Fig. 3. Depiction of multipath scenario.](image)

Without loss of generality, assuming the source is in the far field and at zero elevation angle, the relative time delay of the direct-path arrival is a function of array orientation and source bearing given by
\[ \tau_d(\theta, \alpha) = \frac{D}{c} \sin(\theta + \alpha), \] (11)
where $D$ is the receiver sensor spacing and $c$ is the nominal speed of sound. On the other hand, multipath returns will arrive at different elevation angles for a given orientation, making the channel impulse response a function of array orientation. This multipath structure can be exploited by shifting the cross-correlation output at different orientations by the relative direct-path delay given in (11). A peak at the zero lag in cross-correlation output corresponding to the direct-path delay will be demonstrated via simulation.

IV. Simulation Results

A simulation modeling a shallow-water, isovelocity waveguide with the method of images is presented in this section. Only surface and bottom reflections in the multipath channel, illustrated in Figure 3, are considered. For our purposes, the transmitted waveform is a broadband, linearly frequency modulated chirp with a bandwidth of 2 kHz and a center frequency of 4 kHz. Both the receive array and source are positioned 20 meters from the flat bottom of the waveguide and 500 meters apart. The height of the channel is 50 meters. For this particular simulation only a single source is considered. It’s positioned at a bearing of 60° relative to the North which is assumed to be known. Since source bearing is the parameter being estimated, this computation must be made for a set of hypothesized bearings. The output of the geometric average estimator is a function of hypothesized bearing evaluated at the $\tau = 0$ cut of the averaged cross-correlation given by
\[ P(\theta) = \Psi_M(\tau)_{\tau=0}. \] (13)
The bearing estimate is then given by
\[ \hat{\theta} = \arg \max_{\theta} P(\theta). \] (14)
Thus, the hypothesized bearing, $\theta$ that maximizes the zero-lag of the geometrically averaged cross-correlation output is the resulting bearing estimate.

A. GCC Results

A simulation of GCC-ML and GCC-PHAT was conducted for the scenario mentioned above. Figure 4 compares the two GCC methods in a multipath environment for a source located at 60° relative to broadside of the array. In Figure 5, the simulation places a source at 45° in bearing for a 5-path multipath environment. In both cases, the correlated returns off of the top and bottom of the waveguide mask the direct-path and thus make an anomalous estimate of the true time delay.

B. Multiple Orientation Geometric Average Results

This section provides results for the proposed geometric averaging algorithm with a rotating array. For comparison purposes, the simulation parameters are identical to those used in the GCC simulation. For this simulation the array is rotated 180° uniformly in 10° increments. At each increment, a cross-correlogram is taken. The cross-correlogram is then normalized according to (11). Since (11) is a function of the source
bearing that’s being estimated, the normalized correlogram must be computed for a set of hypothesized bearings. Figures 6 and 7 plot the magnitude of the geometrically averaged cross-correlogram evaluated at the zero-lag as a function of hypothesized bearing for a target at 60° and 45° respectively. The geometrically averaged output significantly reduces the number of anomalous estimates and places a peak in the true direction of the target.

V. CONCLUSION

It has been shown in simulation that multipath environments, such as those found in shallow-water, often lead to erroneous time delay estimates when using traditional GCC localization techniques. By using a rotating array to discriminate multipath arrivals at different elevation angles from the direct-path, a more robust estimate of bearing in a multipath environment can be made. Furthermore, the channel does not have to be appropriately modeled as is the case with MFP techniques.

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REFERENCES