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Spectral coherence and hyperbolic solutions applied to time difference of arrival localisation

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ABSTRACT

Time difference of arrival (TDOA) source localisation is based on intersecting hyperboloids from spatially diverse sensor pairs. TDOA is commonly applied to avian source localisation with field studies finding that sources located inside array boundaries are localised with higher accuracy than sources outside the array. We examine the constitutive hyperbolic equations to demonstrate that at locations interior to an array, hyperbolas intersect at large angles translating into higher localisation accuracy with insensitivity to noise and timing errors, and then use the equations to assess expected accuracy in response to noise and timing errors. We also introduce the use of cross-spectral coherence as a requisite for computation of time delays by cross-correlation in order to minimize the likelihood of interference from noise and reduce the need for manual preprocessing of spectrograms or correlation functions. A small-aperture array is evaluated with a field test finding results consistent with analytical solutions suggesting that a lack of sensor spatial diversity coupled with signal timing accuracy is the primary source of localisation error, but that bearing discrimination remains accurate even for a small-aperture and sources external to the array.

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1. Introduction

Acoustic source localisation relying on spatially diverse synchronised microphone arrays is a well-established technique for the study of wildlife [4]. Until recently, use of arrays imposed significant systems-integration, logistical and cost barriers, however, advances in commercial off-the-shelf acoustic recorders have removed these barriers such that autonomous, array-based passive acoustic source localisation has emerged as an important tool in ecological and behavioural studies [6].

In avian studies the microphone array is typically deployed with inter-sensor spacing, or array aperture, of tens of meters to completely surround the study area and provide good localisation accuracy. For example, using a 50 m aperture McGregor et al.[11] reported errors of 6.76 ± 0.56 m in a woodland and 3.68 ± 0.29 m in a meadow, with errors increasing at locations 25 m outside the array to 15.39 ± 3.66 m and 9.37 ± 1.98 m in the woodland and meadow respectively. Bower and Clark [5] found accuracies of 0.82 ± 0.29 m inside a 40 m aperture array rising to 2.13 ± 1.30 m at locations less than 25 m outside the array edge, then degrading nonlinearly to 5.76 ± 3.74 m at distances greater than 25 m from the array edge. Mennill et al. [12] found mean localisation accuracies of 1.87 ± 0.13 m inside arrays with apertures of 25 and 50 m degenerating to 10.22 ± 1.64 m outside the arrays.

In addition to an accuracy dependence on the relative location of the source and array elements, Mennill et al. [12] found that location accuracy was significantly better when the array aperture was smaller (25 m) rather than larger (50 m). This suggests that experiment designers face a trade off between maximization of array aperture to cover larger areas and maintain subjects inside the array, and minimization of aperture to increase accuracy.

Questions regarding optimal spatial configurations of time difference of arrival arrays have been addressed analytically, finding that good sensor placements are spatially balanced and symmetric, and that sensors should be placed as far as practicable from the sources [8]. The optimum spatial arrangement is one that provides a uniform angular array (UAA) with constant angular spacing between array sensors [1]. In terms of the localisation solution, UAAs seek to maintain a uniform angle between the unit vector pointing from each sensor to the source. Square arrays such as those discussed above satisfy this constraint as long as the source is near the centre of the array.

When the location and broadcast time of the acoustic source are unknown, signal processing required for source localisation is

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necessarily based on time difference of arrival (TDOA) estimates between pairs of sensors across the array. Positions satisfying these differences equate to intersecting hyperboloids from multiple sensor pairs, as first used operationally by the British with electromagnetic waves for aircraft localisation and navigation in the Second World War [2]. The time differences can often be efficiently estimated from cross-correlations if the source signal is harmonic and of sufficient duration [16]. In the works discussed above, careful editing of the recordings based on manual examination of spectrograms to exclude portions of the record [13] or to select specific birdsong notes and frequencies [5] were used to prefilter the data before cross-correlations were estimated. McGregor et al. [11] manually examined the cross-correlation functions and excluded data with possibly spurious cross-correlation maxima or those with multiple peaks. These manual processing techniques have the advantage of improving the TDOA and subsequent location estimates, but require time and expertise, and may be subjectively biased.

Having identified the trade off between a large aperture to increase the area of a study plot so that sources are maintained within array boundaries, and decreasing array aperture to improve accuracy, Mennill et al. [12] suggested that future studies should evaluate a range of array apertures motivating us to investigate this question in a general way. Another objective is to explore methods to facilitate automation of the signal processing to reduce the need for manual editing of recordings.

Here, we explore the physical basis and mathematical representation of localisation accuracies for acoustic arrays using TDOA localisation so that the trade off between accuracy and array aperture can be analytically assessed in the design phase of the experiment. We also hypothesize that the increase in accuracy with decreasing array aperture arises from improved signal coherence, and thereby improved cross-correlation estimates resulting in higher fidelity time delay and location estimates. We therefore introduce the use of cross-spectral coherence as an automated prefilter to TDOA estimates in order to assess signal quality and reject noise. A demonstration of these ideas is provided with a small-aperture array field-test.

2. TDOA source localisation

The fundamental physical variables from which source coordinates are estimated are time delays between sensors. Consider two sensors S1 and S2 at Cartesian coordinates $(x_{S1},\ y_{S1})$ and $(x_{S2},\ y_{S2})$ with $y_{S1} = y_{S2} = 0$. They receive coherent energy from a source at times τ_1 and τ_2 respectively so that the TDOA is $\Delta\tau_{12} = \tau_1 - \tau_2$ corresponding to a propagation distance $\Delta d_{12} = v\Delta\tau_{12}$ where v is the propagation velocity. Although we have identified Δd_{12} in relation to a single measurement, the TDOA, the set of coordinates (x, y) which satisfy the TDOA for sensors S1 and S2 is infinite. This set is the hyperbola $H(x, y)$ for which the absolute value of the difference of the distances from (x, y) to the two sensors is a constant. Geometrically,

$$H(x,y) = \sqrt{y^2 + (x - x_{S1}/2)^2} + \sqrt{y^2 + (x - x_{S2}/2)^2} \tag{1}$$

and denoting the inter-sensor distance between S1 and S2 as

$\Delta S_{12} = \sqrt{(y_1 - y_2)^2 + (x_1 - x_2)^2}$ Eq. (1) can be rearranged to a general form recognized as a hyperbola:

$$\frac{x^2}{\Delta d_{ij}^2/4} - \frac{y^2}{\Delta S_{ij}^2/4 - \Delta d_{ij}^2/4} = 1 \tag{2}$$

with $i = 1$ and $j = 2$. This (x, y) is with respect to the axis between S1 and S2 in the local coordinate basis of (x, y). To transform from this local basis to a global one independent of specific sensor pair axis, we apply a rotation matrix from (x, y) to global coordinates $(\hat{x}, \hat{y})$:

$$\begin{pmatrix} \hat{x} \\ \hat{y} \end{pmatrix} = \begin{pmatrix} \hat{x}_0 \\ \hat{y}_0 \end{pmatrix} + \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \tag{3}$$

where $\hat{x}_0 = (\hat{x}_i - \hat{x}_j)/2$ and $\hat{y}_0 = (\hat{y}_i - \hat{y}_j)/2$ are midpoints of sensors S_i and S_j and where $\theta = \arctan\left[\frac{\hat{y}_i - \hat{y}_j}{\hat{x}_i - \hat{x}_j}\right]$ is axis angle between the two sensors in the global frame.

In order to localise a source in the 2-dimensional case at least one more sensor pair is needed to define an additional hyperbola, and generally, a position estimate is obtained from the intersection of hyperboloids corresponding to TDOAs between multiple sets of sensor pairs. Eqs. (2) and (3) can be used to investigate array configurations and their corresponding hyperbolic solutions to gain insights into the dependence of accuracy on array aperture. Ideally, hyperbolas from multiple sensor pairs intersect at a single point providing a precise localisation, in practice, measurement errors and noise make this a rare occurrence. We can also use Eqs. (2) and (3) with noise added to the TDOAs of ideal solutions to investigate the influence of noise or timing inaccuracies on array performance.

3. Array aperture and timing errors

We first investigate the influence of array aperture by computing ideal solutions for arrays with different apertures but equivalent relative sensor configurations. Ideal TDOAs are computed by dividing the difference of Euclidean distances along the unit vector between the source point and two sensors with a propagation speed of v = 343 m/s: $\Delta\tau_{12} = \Delta d_{12}/v$. The configuration we use is a four-sensor equilateral star-array defined for aperture A as S1 = (0, 0), S2 = $(-A, 0)$, S3 = $(-A - \frac{A}{\sqrt{2}}, -\frac{A}{\sqrt{2}})$, S4 = $(-A - \frac{A}{\sqrt{2}}, \frac{A}{\sqrt{2}})$ as illustrated in Fig. 1. In relation to the square arrays considered above it covers a larger area by a factor of 1.7 with an equivalent aperture, and provides a more uniform distribution of sensor to source arrival angles for arbitrary source locations within the array. Since we are considering ideal solutions and drawing general conclusions for illustrative purposes, the exact configuration of the array is not important, similar results are obtained with square or hexagonal configurations.

Fig. 2 shows ideal hyperbolic solutions for the star-array with apertures of A = 4, 8, 16 and 32 m for a source located at (x, y) =

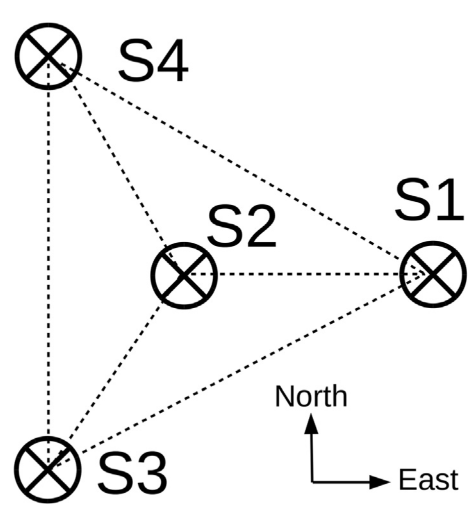

Fig. 1. Array sensor layout for an equilateral star-array. Microphones are denoted S1, S2, S3 and S4. Hyperbolic solutions between the sensor pair S1 and S2 are denoted [S1:S2].

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