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A COMPARISON OF SOURCE LOCALIZATION METHODS WITH VARYING SIZES OF THE PHASED MICROPHONE ARRAY

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Abstract

Since 2020, all commercial aircraft have been mandated to be equipped with ADS-B Out transponders. Despite the many advantages of locating an aircraft with openly available and accessible data, it also has some limitations. Firstly, not all aircraft, such as general aviation, are required to transmit their locations; secondly, due to obstacles such as buildings, a location is not always transmitted at lower altitudes (75-130 m); thirdly, it is vulnerable to cyberattacks. Therefore, while it is convenient to have ADS-B Out data, creating a computationally efficient alternative methodology for determining the aircraft location is advisable. This paper investigates the accuracy, efficiency, and computational cost of two methods of source localization using data taken by an array of microphones: a global optimization (GO) method called the differential evolution (DE) and the conventional beamforming approach (CBF). The real-world data required as input for both methods is obtained with a 64-microphone phased array placed at a distance of 1.14 km from Rotterdam The Hague Airport (RTHA). The 2-dimensional flight trajectories, i.e., azimuth, and elevation relative to the array, obtained from the GO and CBF methods, are compared with the ADS-B Out data for approaching and departing flyovers. Furthermore, the smallest size of an array required for satisfactory localization accuracy is investigated.

1 Introduction

With the aviation industry predicted to grow further in the next two decades, it is essential to develop novel methods to reduce the noise footprint of an aircraft [1]. The current best-practice method for predicting the noise footprint is known as ECAC's Doc.29 [2]. It requires the thrust of the engine (power) and distance between the source and receiver as input and then predicts the noise using the Noise-Power-Distance (NPD) tables. The methodology is subject to several simplifications, for example on physical phenomena such as sound propagation and source decomposition. Hence, it is important to assess and improve, if needed, the model assumptions to ensure the prediction of the noise footprint is accurate. For this, input retrieval methods from the most accurate and openly available sources must be established.

This paper investigates methods of improving the accuracy and availability of the distance input. Recognizing the necessity for having the positional data of an aircraft for improved air traffic management, it is nowadays required for most aircraft to be equipped with an Automatic Dependent Surveillance Broadcasting system Out (ADS-B Out) [3]. ADS-B Out is a surveillance technique that broadcasts the identity of the aircraft and its position, determined by the Global Navigation Satellite System (GNSS), to ADS-B signal receivers set up on other aircraft and on the ground within a given range. The ground stations then transmit the signals to a surveillance processing unit managed by the OpenSky network [4], [5]. The system gives easy access to the positional data for individual aircraft, which is of importance for single-event noise prediction studies such as the work done by [6].

Despite its numerous advantages, there are a few limitations, such as inaccurate information, corrupted position data, altitude data, or the lack of signal transponders [5]. Hence, it is advisable to create a quick and efficient alternative framework for localizing an aircraft, and one such method is studied in this paper. As with most source localization techniques that use the time-of-arrival of the sound wave between different microphones in a phased microphone array, the traditional technique of conventional beamforming in the frequency domain (CBF) is applied in this contribution. It is a robust method that computes the acoustic strength of sources in a predefined grid [7], as such applying an exhaustive search for identifying the location that provides an optimal agreement between measured and modelled differences in time of arrival. In addition to CBF, the global optimization (GO) technique is applied, where an exhaustive search is no longer carried out, but instead, a directed search through the search space is followed.

This paper compares the trends and the individual values of source locations obtained from the various described approaches and verifies the applicability and accuracy of the source locations obtained by the GO method. Furthermore, the convergence behavior, computational time, and accuracy of the GO method, computed by progressively reducing the number of microphones in the phased array, are also investigated. Finally, this paper aims to propose the smallest size of the phased array required for a given accuracy. This method could also be applied to other sources, such as UAVs.

2 Experimental setup

The measurements were taken near Rotterdam The Hague Airport (RTHA), which houses one runway and is located in a densely populated area. The maximum wind speed on the day of 5th September 2023 was 4.63 m/s, and the temperatures ranged from 15 °C to 29 °C, with relative humidity reaching a maximum of 49%. A total of 9 flyovers were recorded, where the average altitude from the center of the array to the nearest point of take-off flyovers was 360 m, and for the one approaching flyover was 230 m. Every flyover was recorded by each of the microphones in the phased array shown in Figure 1. Furthermore, a progressively smaller number of mics described as subsets are given in Table 1. The table indicates the boundaries of the squares that contain the microphone subsets. Subset 4 uses all available microphones. The aircraft location is determined in spherical coordinates θ (°) and ϕ (°) to the center of the array, which are the elevation and azimuthal angles, respectively, while taking an arbitrary value for the range, assuming a plane wave at the array.

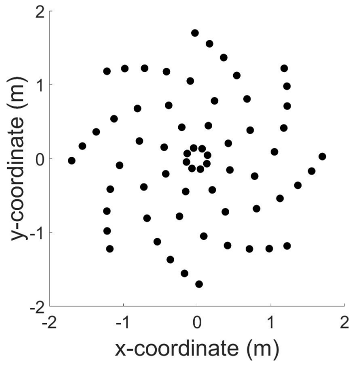

Figure 1: 2-dimensional phased array with 64 microphones.

Array subset	Axis coordinate limits (m)
4	-2:2
3	-1.5:1.5
2	-1:1
1	-0.5:0.5

Table 1: Selection of array subsets depending on the axis limits of the two-dimensional configuration.

3 Source localization techniques

3.1 Conventional beamforming (CBF)

The Conventional frequency domain beamforming is one of the most popular methods for obtaining source localization and source strength. This algorithm is fast and robust and makes use of the phased microphone array by taking the Fourier transforms of the pressure responses recorded by each of the N individual microphones as

$$\mathbf{p}(f) = \begin{pmatrix} p_1(f) \\ \cdot \\ \cdot \\ p_N(f) \end{pmatrix} \tag{1}$$

where $\mathbf{p}(f)$ is the N-dimensional Fourier-transformed pressure vector at frequency f [7, 8]. The beamformer output B_j is computed as

$$B_j(f) = \frac{\mathbf{g}^* \mathbf{C} \mathbf{g}}{||\mathbf{g}||^4}. \tag{2}$$

where $\mathbf{C}$ is the covariance matrix or the cross-spectral matrix (CSM), which is obtained as

$$\mathbf{C} = \langle \mathbf{p}\mathbf{p}^* \rangle. \tag{3}$$

This matrix takes the ensemble average ($\langle\rangle$) of the product of the pressure response vector $\mathbf{p}(f)$ and its complex conjugate transpose, denoted by *. Due to the movement of the acoustic source, i.e., the aircraft, no averaging is done for the current contribution. With the speed of sound, $c = 340$ m/s, the steering vector $\mathbf{g}(f)$ used to find the maximum response within a defined two-dimensional scan grid (grid points denoted by j) is computed as follows:

$$\mathbf{g}(f) = g_{n,j}(f) = e^{-2\pi i f \frac{r_{n,j}}{c}} \tag{4}$$

where $r_{n,j}$ is the distance between the n^{th} microphone and the grid point j. The two-dimensional scan grid is defined in spherical coordinates θ and ϕ. The scanning occurs at an interval of 2.86° in the range of $\theta = 0 : 90^\circ$ and $\phi = 0 : 360^\circ$.

CBF is known as a robust but exhaustive process as its algorithm models the beamformer output in each of the locations in the defined scan grid and identifies the location at which there is a maximum agreement between the modelled and measured values as the location of the noise source.

3.2 Global Optimization (GO)

Unlike the computationally heavy and exhaustive search process of conventional beamforming, global optimization methods find the best match between the measured and the modeled values without requiring a predefined scanning grid. Among numerous GO methods analyzed for source localization purposes, the genetic algorithm known as the differential evolution (DE) has shown to be one of the most appropriate and accurate choices [9]. Differential evolution is an approach that imitates evolution, keeping only the fittest solution members per generation from generation to generation [10]. Several independent DE runs are typically carried out to avoid identifying a local optimum as the global optimum. For this contribution, only two independent runs have been considered. Each of the two independent runs begins with a population of 8 members, which mutate over 100 generations. The multiplication factor is 0.6, and the cross-over probability is 0.6 (Table 2). In this paper, the global minima of the energy function are determined for localization purposes. The energy function is the summation of the square of the difference of the measured phase delay of the signal to the modeled phase delay over frequencies in the range of 400 - 800 Hz [11].

Search parameters	θ, ϕ
Population	8
Number of independent runs	2
Cross-over probability	0.6
Number of generations	100
Multiplication factor	0.6

Table 2: Settings applied for GO of θ and ϕ with DE algorithm.

4 Results

In this section, the estimation of the two-dimensional location of the aircraft as a monopole source from ADS-B Out data, the GO method, and the CBF method is exhibited. For each of the flyovers recorded, the localization is also carried out for subsets of the microphone array.

4.1 Qualitative comparison

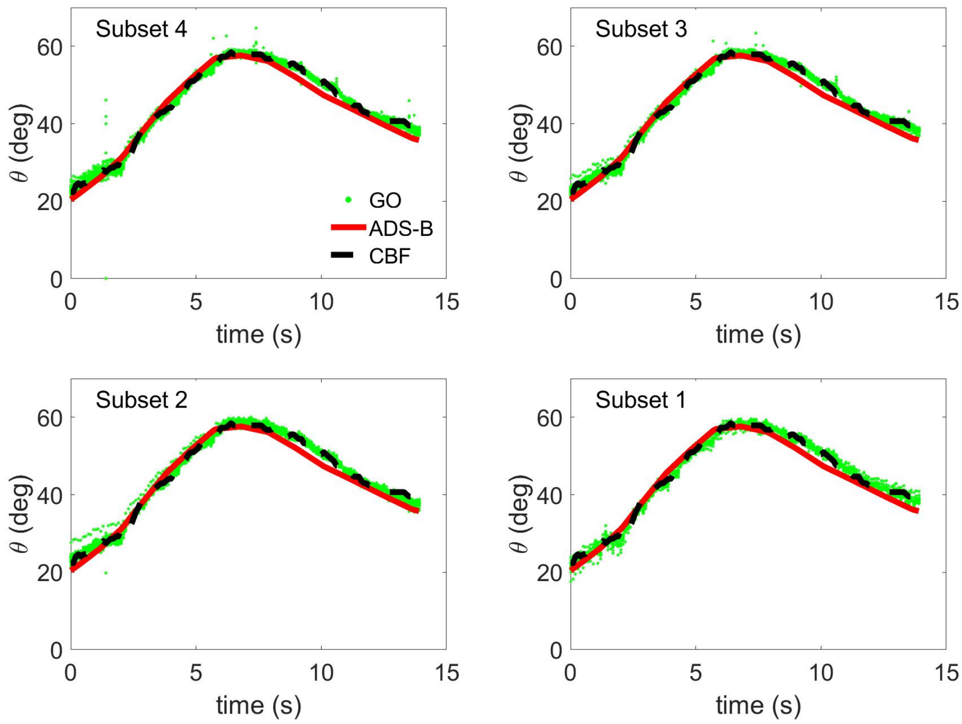

Figure 2: Comparison of estimates of θ obtained from ADSB-Out, CBF, and GO method using various subsets for a single flyover.

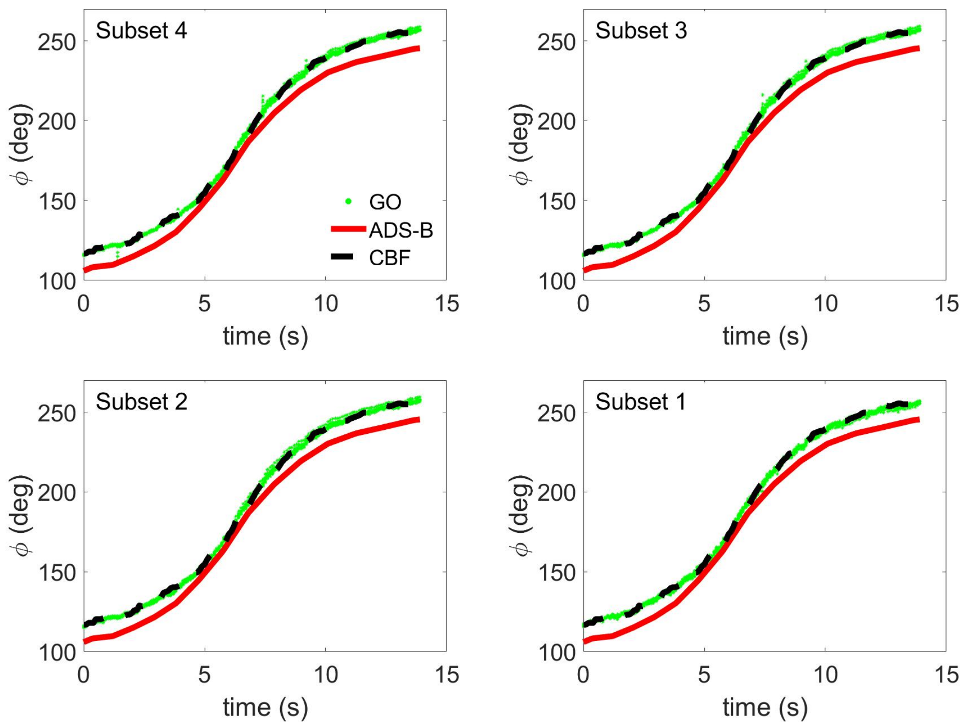

Figure 3: Comparison of estimates of ϕ obtained from ADSB-Out, CBF, and GO method using various subsets for a single flyover.

Typically, for both the CBF method and the GO method of the DE algorithm, as many microphones as available are used for the localization. In this section, however, we vary the number of microphones used to obtain the DE-derived estimates for the aircraft position. Varying subsets whose sizes are described in section 2 are considered. Figure 2 and Figure 3 illustrate the results for these four subsets of the array microphones for a take-off of a B737-700. Here, the aircraft location estimate in spherical coordinates for the various subsets of microphones is represented by green markers. For each time snapshot, multiple estimates are obtained by varying the reference microphone to calculate the phase variation over the array. Also shown are the estimates obtained through CBF using all microphones, represented by the dashed black line. Finally, the accuracy of the calculated values by both methods is determined by comparing them to the relative aircraft locations determined by ADS-B Out data, shown in red. It is necessary to highlight that only the GO method is carried out with different subsets, whereas the CBF curve is only determined using all available microphones. As such, it is easier to check the behavior of the GO method as a function of the microphone subset. The estimates obtained through CBF and GO methods align with better accuracy for varying subsets than with ADS-B, and the estimations obtained with subsets 4 & 1 exhibit very slight differences.

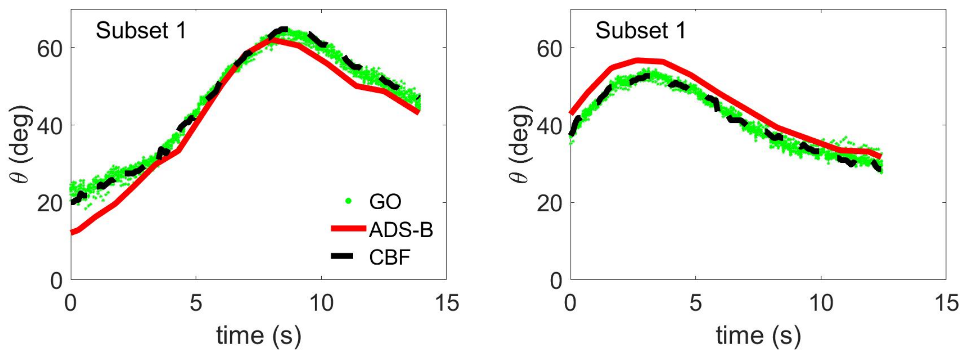

Figure 4: Comparison of estimated θ of two individual flyovers by subset 1.

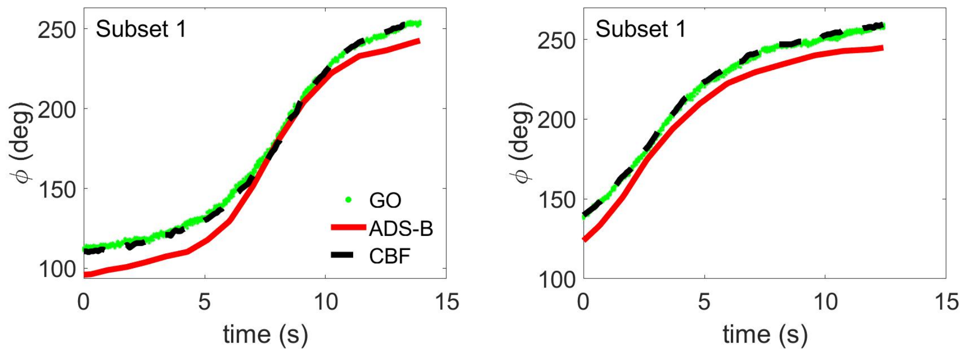

Figure 5: Comparison of estimated ϕ of two individual flyovers by subset 1.

Subsequently, the reliability of the locations estimated by subset 1 (smallest number of microphones) is studied by considering the obtained values for all the flyovers, two of which are illustrated in Figure 4 and Figure 5. The trends of the estimates continue to exhibit good agreement with the values estimated by CBF and obtained from ADS-B Out data.

4.2 Quantitative comparison

Generally, a flyover is described as being overhead when $\theta = 90°$, which is also the closest point in the flight track to the array. However, to generalize the source localization process for most realistic cases when this condition is not met, the dataset considered in this paper does not have any direct flyovers. Hence, it is interesting to determine the location with the shortest distance between the aircraft and the array. The shortest distance is calculated at the maximum value of θ among all estimates (varying reference mics and CBF and ADS-B Out). Thus obtained values from subset 1 are compared in Figure 6. In most cases, the values obtained by ADS-B Out, CBF, and GO align with a difference less than 2°. However, in two cases, the difference is more than 5°. The corresponding values of ϕ are determined from the time step at which the maximum θ values are found. These values align with a difference of less than 5° in most cases. However, these differences remain even when subsets 3 & 4 are used for determining the location with the GO method. It is interesting to note that the choice of subsets does not affect the accuracy of determining the closest point of the track to the array with the given GO method.

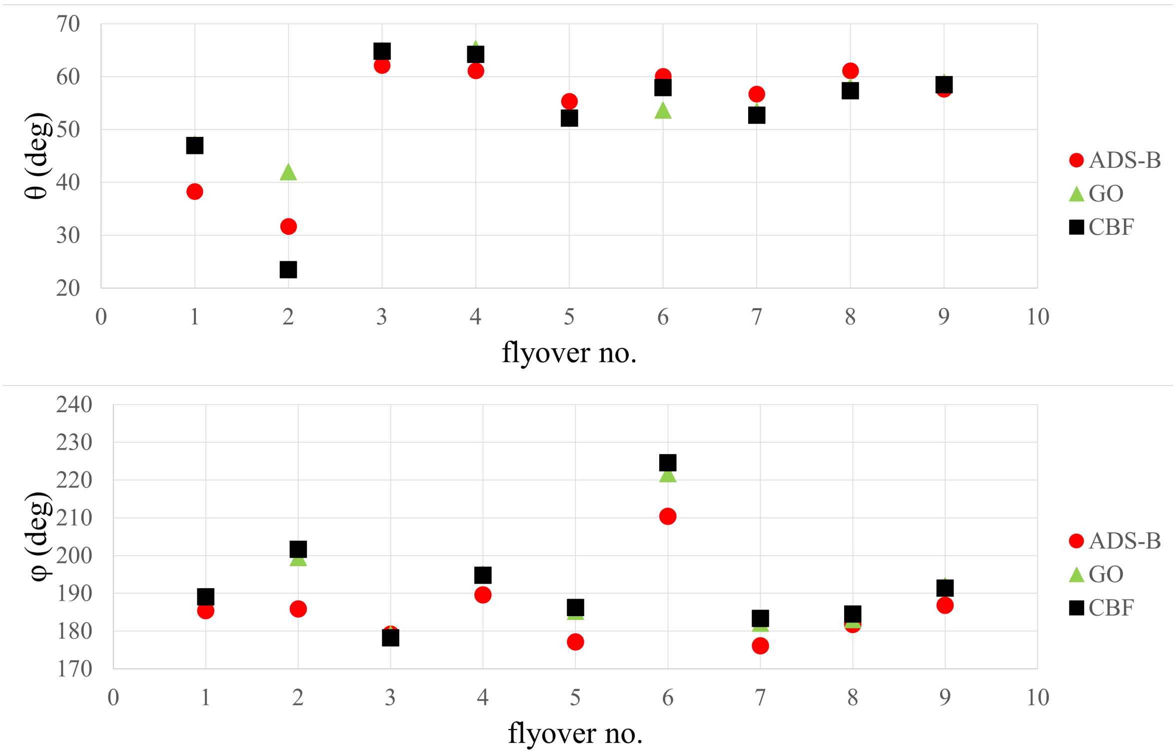

Figure 6: Comparing the locations of each measured take-off flyover at the overhead position obtained by ADS-B, GO, and CBF methods with subset 1.

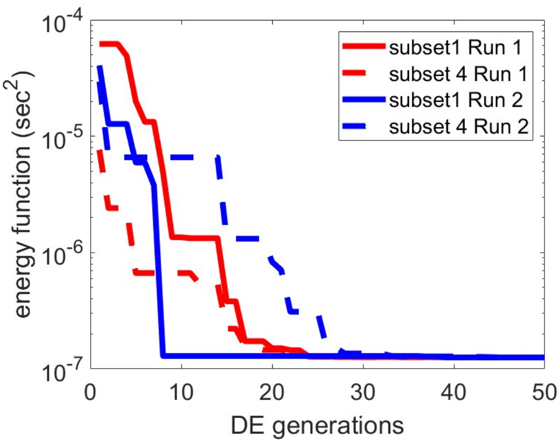

Figure 7: Convergence behavior of two runs of GO method excited by subsets 4 & 1.

In gauging the accuracy and reliability of a specific GO algorithm, computational time and convergence behavior are often discussed. Therefore, the convergence behavior for one flyover is shown in Figure 7. This shows the convergence rate of the minimal value of the energy function in the subsequent generations of the GO method for subsets 4 & 1. The dashed lines represent subset 4, whereas the solid line represents subset 1. Additionally, red lines represent the first run, and blue lines represent the second run. The limited number of independent runs prohibits a further assessment of the convergence behavior. For the runs shown, the required number of generations is about 30. Given a population size of 8, this corresponds to 240 function evaluations.

5 Conclusions

This paper describes the comparison of two types of source localization methods, GO and CBF, and the verification of these results with the ADS-B Out positional data. The qualitative comparison shows that the final localized values from GO and CBF methods align with less than a 3% difference for all the flyovers. This implies that in cases where the noise source location is unknown or the locations obtained from ADS-B Out need to be verified, the much quicker and more computationally affordable option, the GO method, could be taken. Along with establishing the reliability of this method for localizing sources that are mostly 350 (m) away from the array, this paper also proposes that a 1 (m) x 1 (m) non-symmetric array that contains 10-12 mics would give satisfactory two-dimensional locations. Performing the DE algorithm with the signal responses obtained from the mics gives good agreement and is much more computationally affordable than the beamforming method. However, there is an insufficient agreement on identifying the closest point of the flight track to the array for some flyovers, this could be attributed to the lack of reliable altitude parameters, especially from ADS-B Out data.

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