

Assessment of Aircraft Detectability Using Global Optimization Techniques for Identifying Flyover Events in Low-Noise Region

Si Anh Doan

Delft University of Technology

Assessment of Aircraft Detectability Using Global Optimization Techniques for Identifying Flyover Events in Low-Noise Region

by

Si Anh Doan

Responsible Supervisor:	M. Snellen
Daily Supervisor:	A. Amiri Simkooei
Daily Supervisor:	A.S. Jayanthi
Daily Supervisor:	A.M. Morin
Project Duration:	December, 2025 - August, 2026
Faculty:	Faculty of Aerospace Engineering, Delft

Cover <https://www.pexels.com/photo/dynamic-shot-of-airplane-in-flight-against-blue-sky-34021509/>

Preface

This thesis is the final deliverable of my journey to obtain the degree of Master's of Science in Aerospace Engineering at the Delft University of Technology. The research surrounds my main interest throughout my study at TU Delft, which is aircraft noise. Through this project, I was exposed to many aspects surrounding aircraft noise and learn new things such as regulation, modelling, different measuring and processing techniques. Hence, the project felt extremely personal and rewarding.

I would like to thank my supervisors Anandini, Amy, Alireza and Mirjam for their guidance and patience with me in the last 8 months. They helped me keep my focus on the bigger picture, refine my objective and provided exceptional insight throughout the research. Without them, this thesis would be nowhere close to what it is now.

*Si Anh Doan
Delft, August 2026*

Summary

Current aircraft noise monitoring terminals (NMT) struggle to detect aircraft in regions where background noise is comparable to the aircraft's contribution, referred to as low-noise regions. This research assesses aircraft detectability in these low-noise regions using Global Optimization (GO) as an alternative to threshold-based detection of NMTs and examines how the measured noise levels compare to ECAC Doc. 29 under these conditions. First, three reference flights were inspected to identify the best frequency range for localization. The best localization results were obtained for 100-1000 Hz frequency bands, which is as per expectation, as generally, it is the higher frequencies that are dampened out quicker by atmospheric absorption. The distributions of localization errors across two different parameters have been examined (elevation angle and azimuthal angle). The elevation is the angle from the ground horizon to the aircraft, and the azimuthal angle is the lateral angle to the aircraft. It was concluded that while the elevation angle estimates had good agreement at high elevation, at low elevation angles where most of the measurements were taken, the estimate by GO is unreliable for classifying successful localization. Thus, success criterion of $-17.5^\circ \leq \epsilon_\phi \leq 4.8^\circ$ is defined.

Applying this criterion, the localization success rate is analyzed as a function of distance for the measured aircraft types (B738, A320, E190, A21N, B38M and A359) and operation types (takeoff or landing). Assuming a success rate threshold of 70% for detection, a maximum detection range was determined for different combinations of aircraft types and operation types. For takeoff operations, localization success rate declines with distance, and detection range depends strongly on aircraft type. Newer and quieter aircraft types (B38M and A21N), showed a significantly lower detection range compared to older and larger aircraft types (B738, E190, A359) during takeoff. For landing operations, however, localization success rates were lower for all aircraft types. This is expected, as landing operations have lower engine power settings and therefore lower noise emissions compared to takeoff.

Comparison of measured and ECAC Doc. 29 modelled noise levels for takeoff operations showed agreement between 3500-5000 m for A320, E190 and A21N. In the same range, the model overpredicts by 3 dB for the B738. The A359 noise level was underpredicted for all distances recorded. Beyond 6000 m, the model underpredicted measured noise levels. This could be due to the model only predicting noise emitted by the aircraft, while the measurement includes background noise. For landings, there is no agreement between the measured and modelled noise levels at any recorded distance.

Lastly, the measured noise level shows that GO can successfully detect aircraft at distances where the measured sound level is similar to the background noise level. Hence, the GO-based methods can improve detection where aircraft might go undetected by current NMTs.

Contents

Preface	i
Summary	ii
Nomenclature	iv
1 Introduction	1
1.1 Research objective	2
1.2 Research structure	2
2 Data acquired	3
2.1 Acoustic experimental data	3
2.2 Automatic Dependent Surveillance Broadcasting (ADS-B)	4
3 Methodologies	6
3.1 ADS-B Data Processing	6
3.2 Acoustic Measurement Processing	7
3.3 Error threshold and localization frequency range	11
3.4 ECAC Doc. 29 Model	12
4 Discussion of Results	15
4.1 Localization frequency and success criterion	15
4.2 Maximum detection range based on localization success rates	17
4.3 Measured and Modelled noise levels	20
5 Conclusions and recommendations	22
5.1 Conclusions	22
5.2 Recommendations	22
References	23
A Localization Results of Individual Recordings	25
B Literature Study	28
B.1 Propagation of sound	28
B.1.1 Atmospheric attenuation	28
B.1.2 Geometrical spreading	28
B.1.3 Doppler effect	28
B.1.4 Ground reflection	29
B.2 Noise measurement	29
B.3 Source localization methods	30
B.4 Noise modelling	30
B.5 Research gap	31

Nomenclature

Abbreviations

Abbreviation	Definition
NMT	Noise Monitoring Tower
GO	Global Optimization
A320	Airbus A320
A21N	Airbus A321neo
A359	Airbus A350-900
ADS-B	Automatic Dependent Surveillance-Broadcast
B38M	Boeing 737 MAX 8
B738	Boeing 737-800
DE	Differential Evolution
DFT	Discrete Fourier Transform
E190	Embraer 190
ECAC	European Civil Aviation Conference
FFT	Fast Fourier Transform
GNSS	Global Navigation Satellite System
GO	Global Optimization
KNMI	Koninklijk Nederlands Meteorologisch Instituut
NADP	Noise Abatement Departure Procedure
NMT	Noise Monitoring Tower
NOMOS	Noise Monitoring System (Amsterdam Schiphol Airport)
NPD	Noise-Power-Distance
PSD	Power Spectral Density
RANOMOS	Rotterdam Airport Noise Monitoring System
RTHA	Rotterdam The Hague Airport
SAE	Society of Automotive Engineers
WHO	World Health Organization

Symbols

Symbol	Definition	Unit
$B_{j,k}$	Beamforming output at position ξ_j , frequency f_k	
c	Speed of sound	m/s
d_{ground}	Ground distance between array and aircraft	m
d_{slant}	Slant distance between array and aircraft	m
f	Frequency	Hz
F	Differential Evolution multiplication factor	-
$g_{j,n}$	Steering vector for position ξ_j , microphone n	
G	Differential Evolution Generation index	-
h	Aircraft altitude	m
$L(f)$	Power spectral level	dB
L_A	Measured A-weighted sound pressure level	dB
$L_{A,modelled}$	Modelled A-weighted sound pressure level	dB
i, r_1, r_2, r_3	Differential Evolution Population indices	-
k	Frequency index	-
n	Microphone index	-
ρ	Density	[kg/m ³]

Chapter 1

Introduction

After the COVID-19 pandemic, the global aviation industry officially recovered in 2024 and is expected to continue growth as demand increases. Global passenger traffic is projected to grow at a compound rate of 3.2% from 2024 to 2043 [18]. However, the steady increase in air traffic places a burden on communities surrounding airports in the form of immediate annoyance and adverse health effects related to long-term noise exposure. Noise annoyance is regarded by experts to be the main effect of environmental noise [10]. The World Health Organization (WHO) identifies environmental noise as one of the top environmental risks to health, with studies associating long-term noise exposure with sleep disturbance, increasing occurrence of hypertension and cardiovascular disease, and impaired cognitive performance in children [1].

Hence, to regulate aircraft noise, the effect of aircraft noise is often considered with the L_{den} and L_{night} metrics. These metrics describe the average sound exposure level, often over a full year. They attempt to reflect noise annoyance by applying penalties to noise events occurring during the evening (19:00-23:00) and night time (23:00-7:00). To address the findings on the effect of environmental noise, in 2018, WHO recommended that the average aircraft noise exposure should not exceed 45 dB L_{den} and 40 dB L_{night} [19]. Despite this, current EU reporting thresholds are 55 dB L_{den} and 50 dB L_{night} , and population exposure estimates based on these thresholds may underestimate the health impact of exposure [4]. Furthermore, these metrics are not suitable for describing annoyance caused by individual events to link with residents' complaints [15], and airports continue to report complaints from well outside of the reporting noise contours. For example, Rotterdam The Hague Airport (RTHA) annual report shows complaints originating from areas beyond the statutory 48 dB L_{den} contour [3, 21].

For an aircraft event to cause annoyance, it must be detected and perceived by an individual. This suggests that beyond long-term noise exposure, the perception of individual aircraft events is also important to monitor. Establishing a reliable method of detecting aircraft is therefore necessary for linking community annoyance to aircraft flight events. However, current monitoring practices struggle to detect flights in regions where background noise can be comparable to the aircraft's contribution. Aircraft noise monitoring systems such as NOMOS (Amsterdam Schiphol Airport) and RANOMOS (Rotterdam The Hague Airport) register aircraft event when the noise levels exceed a set threshold defined by the background noise at each location. This is done to prevent false noise events coming from background noise in the vicinity of the NMT. However, the threshold also means aircraft events below this threshold go undetected [22]. Since 2022, an improved algorithm was implemented which links the recorded noise to flights via RADAR data regardless of volumes ¹. However, a study by Van der Griff et al. [31] analyzing NOMOS measurements around Schiphol airport from 2017 to 2024 concludes that aircraft often go undetected at distances over 10,000 ft, or 3 km, and for newer and quieter aircraft, 40% of flights are not measured below this distance. Additionally, it is unclear whether ECAC Doc. 29 model - the method for predicting aircraft noise for regulatory compliance and planning - can accurately predict

¹<https://news.schiphol.com/improved-noise-measurements-in-the-area-around-schiphol/>

the noise level at large distances from the aircraft in low-noise regions. Accurate noise modelling is important as it is the standard method to assess the effect of aircraft noise on communities.

An alternative method to detect aircraft events is using a microphone array, which enables beamforming, a method that exploits the delay between the signal received by the microphones to identify the direction of the aircraft [6, 7]. Beamforming performs localization by exhaustively searching over an entire scanning grid parallel to the array, and in cases where the distance is not known, multiple grids at varying distances may be necessary. This makes beamforming computationally expensive. Moreover, there is a knowledge gap in existing literature for aircraft detection in low-noise regions, where L_{den} falls within 45-55 dBA, as most research was done at smaller distances to obtain higher quality measurement where background noise level is significantly lower than the signal from the aircraft.

In this research, aircraft detection is performed using a 2D microphone array and an alternative source localization method to beamforming called Global Optimization (GO) [13]. In contrast to beamforming, GO does not need a predefined scan grid, only boundaries for the search parameter space. In this context, the parameters are positional parameters of the source relative to the array. Because localization is based on the spatial coherence of the received signals instead of only sound pressure level, it is theorized that GO, similar to beamforming, can detect aircraft at greater distances than threshold-based methods, while eliminating the need to predefine a scan grid, therefore reducing computation time. Aircraft detectability is then quantified and analyzed in relation to the distance, aircraft type and operational procedure. Additionally, while the ECAC Doc. 29 model predictions pose possible inaccuracies that are inherent to the model as well as the inputs chosen for this study, this research still aims to compare ECAC Doc. 29 predicted and measured noise levels to identify underlying patterns at large distances.

1.1. Research objective

Therefore, the objective of this MSc project is to experimentally determine the detection range of aircraft flyovers and identify trends in aircraft detectability based on distance, aircraft type and operational procedure. This is done by taking dedicated measurements with a microphone array in low-noise regions, and for which the GO algorithm is chosen as the localization method. By comparing GO localization results to reference aircraft positions obtained from trajectory data, the localization success criterion is first established. Then, the detection range for different aircraft types and operational procedures can be determined from the localization success rate. The measured noise levels are compared to ECAC Doc. 29 prediction to assess the model's behavior under these conditions.

Two research questions were formulated to support the research objective. These research questions are:

- What is the relationship between aircraft detectability and distance from the array, aircraft type, and operational procedure?
- How do the measured aircraft noise levels compare to the predicted levels by the ECAC Doc.29 model, for different aircraft types and operational procedures?

1.2. Research structure

First, Chapter 2 describes the data acquired for this research, the experimental setup and the ADS-B data. Chapter 3 presents the steps taken in the processing of ADS-B data, acoustic data, as well as ECAC Doc. 29 model setup. Chapter 4 discusses the results of the research and answers the research questions. Finally, Chapter 5 presents the conclusions drawn from this research and gives recommendations for future work.

Chapter 2

Data acquired

This chapter describes data acquired for the determination of the aircraft detectability. First, Section 2.1 describes the measured aircraft flyovers and the setup with which the acoustic measurements were acquired. Secondly, Section 2.2 describes the reference Automatic Dependent Surveillance-Broadcast (ADS-B) trajectory data.

2.1. Acoustic experimental data

For this research, measurements were collected on 4 different days, October 7th and 8th, 2025 and April 14th and 15th, 2026 near Pijnacker, Netherlands. The location is about 3.3 km away from the runway of RTHA, represented by a pink dot in Figure 2.1. This location was chosen to be in a low-noise region and allow for measurements of both takeoff and landing traffic at RTHA, while minimizing the background noise from the surrounding community. Meteorological data is obtained from the Koninklijk Nederlands Meteorologisch Instituut (KNMI) ¹ and shown in Table 2.1. A wide range of weather conditions was captured during these measurement days, with measurements in October having higher wind speed compared to those taken in April, and April 15th having a large variation in temperature. Additionally, the method of deciding the recording length differs between the October and April measurement days. For October, the measurements started when an aircraft became audible to the researchers operating the array and ended when it was no longer audible. However, preliminary analysis of the October measurements showed that the detection range using GO is beyond the recorded distance. Subsequently, for April measurement days, the recording length is decided based on the estimated distance of the aircraft from the array location, which was monitored live using information from the Flightradar24 application ². Measurements for April begin when the aircraft begins accelerating (for takeoff) or is approximately 10000 m away from the array (for landing), and measurement ends when the aircraft is approximately 10000 m away from the array (for takeoff) or begin rollout (for landing).

¹<https://www.knmi.nl/over-het-knmi/about>

²<https://www.flightradar24.com/>

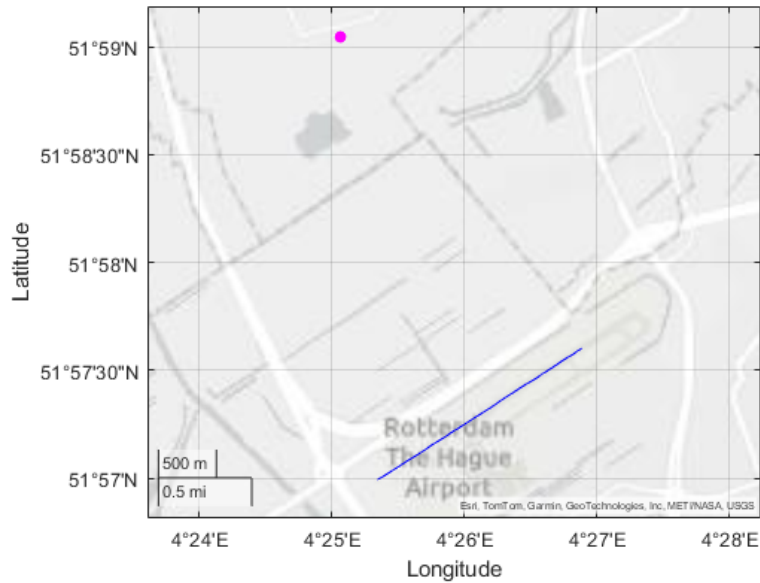


Figure 2.1: Location of microphone array (pink dot) and RTHA airport runway (blue line).

Table 2.1: Weather conditions during days of measurements, obtained from the KNMI.

Day	Temperature	Wind speed
October 7	16-18° C	15-20 km/h
October 8	14-17° C	7-13 km/h
April 14	12-15° C	1-3 km/h
April 15	11-20° C	3-7km/h

Table 2.2: List of flights based on aircraft type and operational procedures.

Aircraft type	Departure	Arrival
B738	18	13
A320	5	2
E190	3	5
B38M	3	0
A21N	2	3
A359	1	0

The number of flyovers measured for both October and April with aircraft types and operational procedures are given in Table 2.2. six aircraft types were recorded, which are Boeing 737-800 (B738), Airbus A320 (A320), Embraer 190 (E190), Boeing 737MAX8 (B38M), Airbus A321neo (A21N) and Airbus A350-900 (A359). The most common aircraft type across all recording days is the B738.

Acoustic measurements were recorded using a phased microphone array. The 2D microphone array, which can be seen in Figures 2.2 and 2.3, consists of 64 microphones spread over 8 spiral arms with higher density of microphones in the middle of the array. This configuration, known as the Underbrink array, produces a low maximum side lobes level across a large range of frequency compared to other array geometries [20]. This is important for localization, where side lobes can cause localization algorithms to identify an incorrect source location rather than the aircraft position. The microphones were mounted on the metal arms and connected to the data acquisition unit which records signals at a sampling frequency of 62.5 kHz. The array was placed flat on the ground to capture the flyovers. To minimize the effect of reflection from both the array and the ground, the metal arms are covered with sound absorbent foam which extends past the outermost microphones. Wind shields are also placed over all microphones to reduce wind-induced noise. The array orientation with respect to true North was measured with a compass. This orientation is accounted for before comparison with the reference aircraft position.

2.2. Automatic Dependent Surveillance Broadcasting (ADS-B)

Automatic Dependent Surveillance-Broadcast (ADS-B) is a surveillance technology that allows aircraft to use a Global Navigation Satellite System (GNSS) to determine their own position and broadcast it



(a) Without sound absorbent foam and wind shield.



(b) With sound absorbent foam and wind shield.

Figure 2.2: Microphone array used for noise measurements.

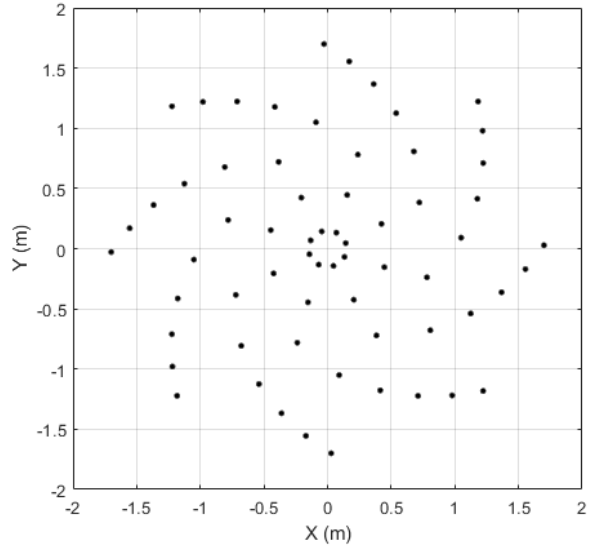


Figure 2.3: Configuration of the phased microphone array.

periodically to other aircraft or ground stations without requiring external interrogation. For this research, ADS-B data is obtained from the OpenSky Network and treated as reference aircraft position [23]. The OpenSky Network consists of volunteer-operated receivers distributed globally, and the network collects ADS-B messages and provides them through openly accessible databases.

ADS-B data obtained from OpenSky provides the aircraft position in terms of latitude, longitude and altitude. ADS-B was chosen as the reference aircraft position for two reasons. First, ADS-B data is reported in 1 s intervals, providing higher temporal resolution than radar track data, which typically reports in 4 s intervals. Secondly, since OpenSky is open for academic use, it provides a transparent source of trajectory data without relying on proprietary tracking data such as radar data.

However, it also has its own limitations. ADS-B messages may be lost because of radio interference or simultaneous message transmissions [29]. Additionally, although this research treats aircraft position derived from ADS-B as a reference, it is not the absolute truth. Verbraak et al. [32] have aimed to assess the quality of ADS-B data and found that 95% of flights show a cross-track horizontal accuracy better than 51 meters when compared to radar track data or on-board data.

Chapter 3

Methodologies

First, section 3.1 describes the processing steps required to calculate the aircraft position relative to the array from the acquired ADS-B trajectory data. The steps taken to calculate the measured noise level and localization from the acoustic measurements are described in section 3.2. Then, section 3.3 describes how the localization error is quantified. Finally, section 3.4 describes the input and modelling assumptions used to obtain the modelled noise levels.

3.1. ADS-B Data Processing

To compare the reference position with localization results, the coordinates of the aircraft need to be represented by the relative elevation angle θ and azimuthal angle ϕ with respect to the microphone array, defined in Figure 3.1. The haversine formula, Equations 3.1-3.3, is used to determine the ground distance between two points based on their latitude and longitude coordinates

$$d_{ground} = r\Theta \quad (3.1)$$

$$\theta = 2 \arcsin \sqrt{\text{hav}\Theta} \quad (3.2)$$

$$\text{hav}\Theta = \text{hav}(\Delta\psi) + \cos\psi_1 \cos\psi_2 \text{hav}(\Delta\lambda) \quad (3.3)$$

where hav denotes the haversine function, defined as $\text{hav}(\Theta) = \sin^2(\frac{\Theta}{2})$, and $\Delta\psi = \psi_2 - \psi_1$ and $\Delta\lambda = \lambda_2 - \lambda_1$ represent the differences in latitude and longitude between the aircraft and the array in radians. The three-dimensional distance between the aircraft and the array, defined as the slant distance d_{slant} , and the elevation angle θ , are calculated as

$$d_{slant} = \sqrt{d_{ground}^2 + h^2} \quad (3.4)$$

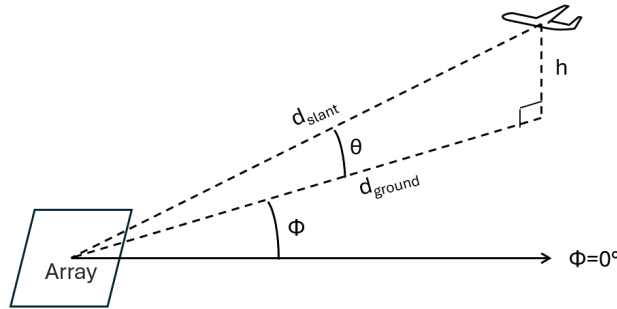


Figure 3.1: Definition of positional parameters of aircraft relative to the array on the ground.

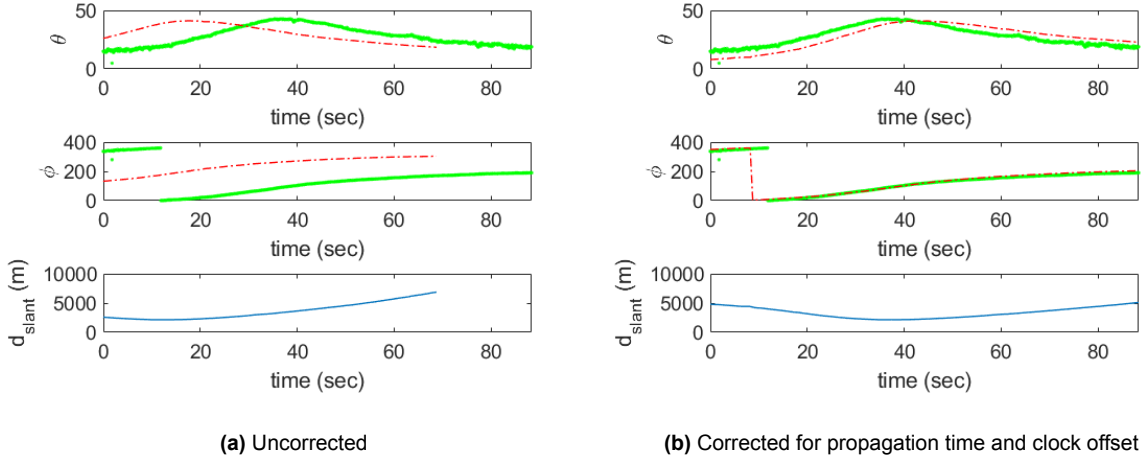


Figure 3.2: Corrections to ADS-B positional data (red) to match localization results (green) for a B738 takeoff.

$$\theta = \arctan \frac{h}{d_{ground}} \quad (3.5)$$

where h is the aircraft altitude. Finally, the azimuthal angle can be calculated via the initial bearing β of the aircraft

$$\beta = \arctan \frac{\sin \Delta \lambda \cos \psi_2}{\cos \psi_1 \sin \psi_2 - \sin \psi_1 \cos \psi_2 \cos \Delta \lambda} \quad (3.6)$$

$$\phi = \beta - \beta_{array} \quad (3.7)$$

where β_{array} is the array orientation with respect to true north.

To account for the time delay between noise emission at the source position and sound received at the array, the ADS-B data is corrected for time alignment with the localization results. This correction is the second term of Equation 3.9, where d_{slant} is the slant distance and $c = 340$ m/s is the speed of sound in air.

$$t_{receiving} = t_{emit} + \Delta t_{propagation} = t_{ADS-B} + \frac{d_{slant}}{c} \quad (3.8)$$

Aside from the propagation delay, there is also a fixed clock offset between the ADS-B clock and the measurement system's clock, specifically for the October measurement campaign. The cause for this incorrect time information may result from clock drift or inaccurate clocks [17]. This offset is determined iteratively by manually adjusting for the offset amount by 0.1 s until the propagation-corrected localization result of a close flyover aligns well with the ADS-B track. The offset is $\Delta t_{offset} = 18.4$ s for October measurement days and $\Delta t_{offset} = 0$ s for the April measurement days. Both corrections are applied in Eq. 3.9. An example of the localization result and ADS-B comparison before and after the corrections is shown in Figure 3.2.

$$t_{receiving} = t_{emit} + \Delta t_{propagation} + \Delta t_{offset} = t_{ADS-B} + \frac{d_{slant}}{c} + \Delta t_{offset} \quad (3.9)$$

3.2. Acoustic Measurement Processing

Before analysis, the mean of each microphone signal was removed to eliminate any offset.

$$p'(t) = p(t) - \text{mean}(p(t)) \quad (3.10)$$

First, the uncalibrated effective sound pressure recorded by each microphone was inspected. The comparison can be seen in Figure 3.3. Since all microphones are exposed to the same acoustic field, large and consistent deviations across different recordings indicate a bad microphone. Microphones showing abnormal raw signal amplitudes (mic 57 for October) were excluded from the analysis that

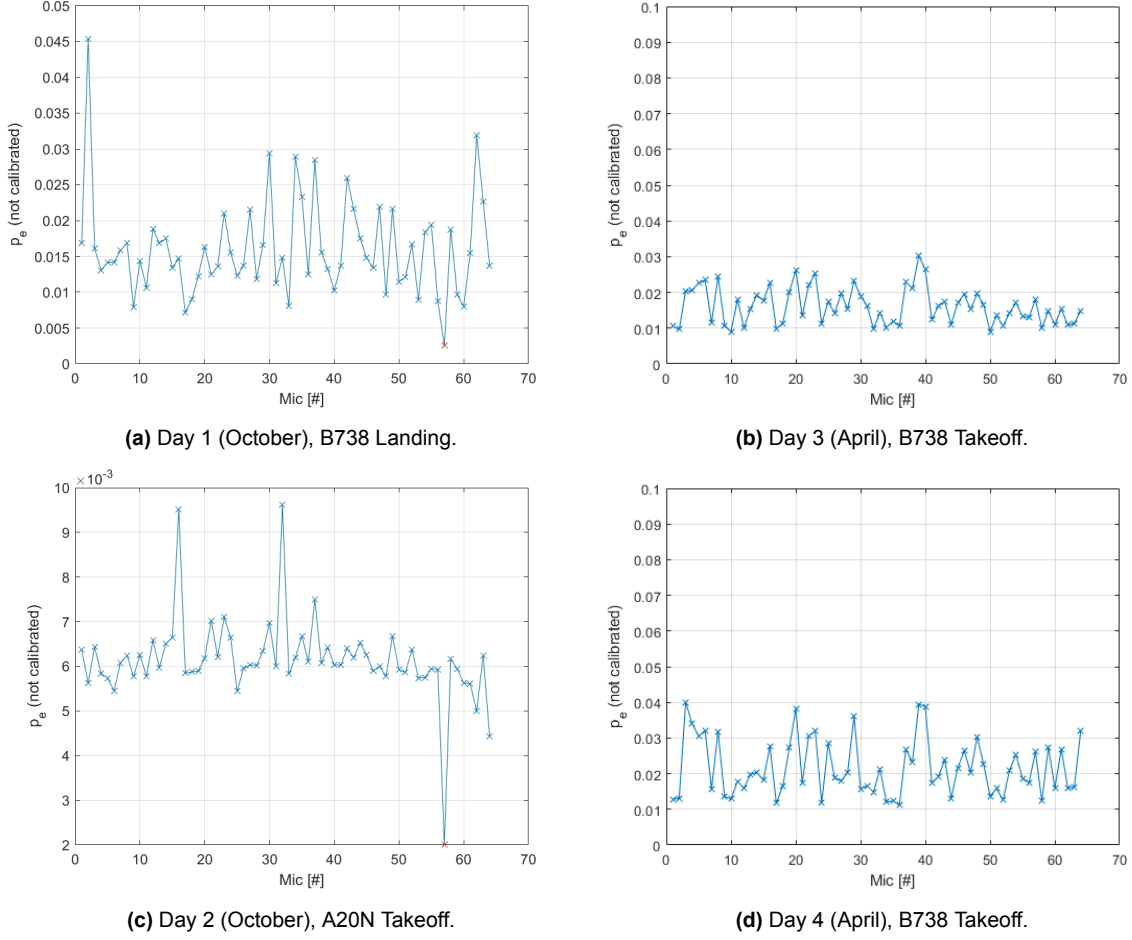


Figure 3.3: Examples of the uncalibrated effective pressure measured by each microphone for different flights. Excluded microphones are highlighted in red.

followed. The signals are then processed in the frequency domain. This allows the spectral content of the signal to be examined and A-weighting, which accounts for human perception of noise, to be applied before noise level calculations. The Power Spectral Density (PSD), which measures how the power of a signal is distributed across different frequencies, in units Pa^2/Hz can be calculated from the pressure spectrum via the Discrete Fourier Transform (DFT).

$$P_k(f) = \Delta t \sum_{n=0}^{N-1} p_n e^{-2\pi i k n / N_{DFT}} \quad (3.11)$$

$$\vec{P}(f) = \begin{pmatrix} P_1(f) \\ \vdots \\ P_N(f) \end{pmatrix} \quad (3.12)$$

$$S(f) = \frac{P(f)^2}{N_{DFT} \Delta f} \quad (3.13)$$

Here, N_{DFT} is the number of samples considered for a DFT and Δf is the frequency resolution of the FFT, k is the frequency index and n is the time index. A window length of 0,1 s, corresponding to $N_{DFT} = 6250$ was selected for the rest of the processing. This resulted in a localization for every 0.1 s, allowing for minimal smearing from the aircraft's motion during each time segment. To reduce spectral leakage, an effect caused by segmentation of the signal for DFT that results in spreading of a

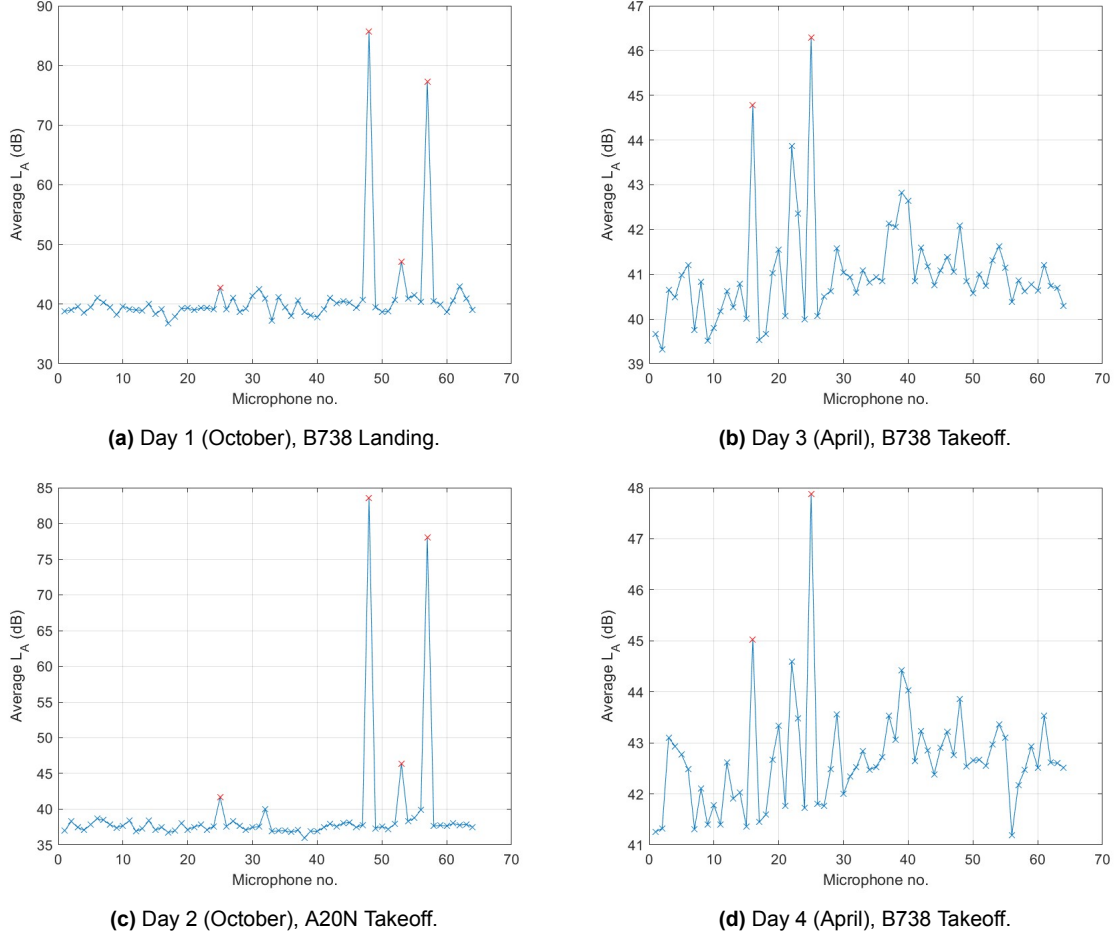


Figure 3.4: Examples of the time-averaged L_A measured by each microphone for different flights. Excluded microphones are highlighted in red.

signal's energy to neighboring frequencies, a Hanning window was applied prior to the DFT. The Power Spectral Level relative to the reference pressure $p_{e,0}$ is then

$$L(f) = 10 \log_{10} \left(\frac{S(f)}{p_{e,0}^2} \right). \quad (3.14)$$

The reference effective pressure $p_{e,0}$ is 2×10^{-5} Pa, corresponding to the threshold of hearing. As the range of p_e observed in different scenarios spans different orders of magnitude, the decibel scale is often used [24]. A-weighting is then applied to $L(f)$ to reflect human perception. The A-weighting function is given by Equation 3.15 and the resulting A-weighted sound pressure level L_A is calculated using Equation 3.16.

$$\Delta L_A(f) = -145.528 + 98.262 \log f - 19.509(\log f)^2 + 0.975(\log f)^3 \quad (3.15)$$

$$L_A = 10 \log_{10} \left(\Delta f \sum 10^{\frac{L(f) + \Delta L_A(f)}{10}} \right) \quad (3.16)$$

A second check was done to identify microphones with calibration errors by comparing the L_A averaged over time for each microphone, as shown in Figure 3.4. Similarly to the uncalibrated pressure check, microphones showing consistently abnormal average noise levels across different recordings (mics 25, 48, 53 in October; mics 16, 25 in April) were excluded from following analysis.

To visualize the sound signal, a spectrogram averaged over all microphones was made for each flight. A spectrogram shows how the spectrum of a sound signal varies with time at different frequencies. The

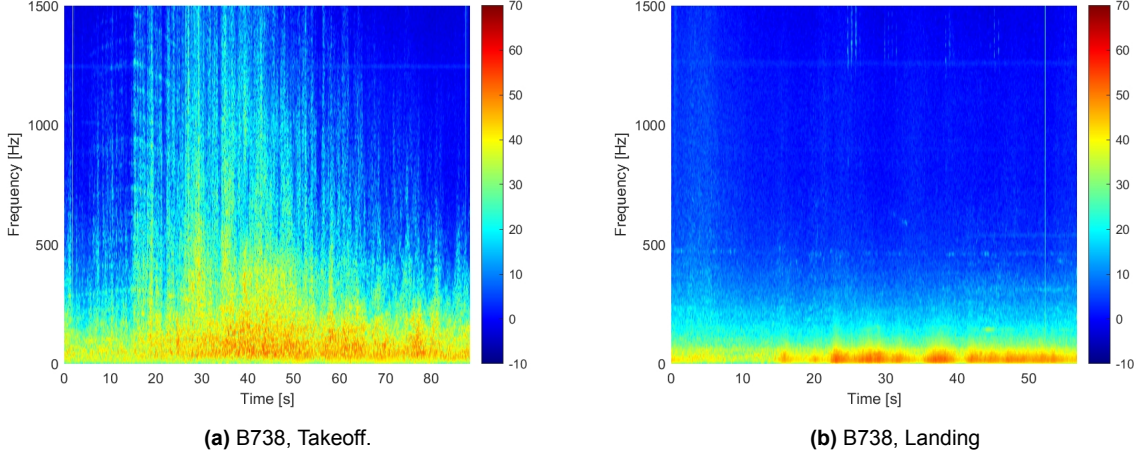


Figure 3.5: Examples of microphone-averaged spectrograms for B738 in two operational procedures.

Band	Frequency
1	100-1000 Hz
2	100-500 Hz
3	500-1000 Hz
4	100-250 Hz
5	250-500 Hz

Table 3.1: Frequency bands considered for localization.

horizontal axis represents time, the vertical axis represents frequency, and the third axis, often represented by a color scale, indicates the power in the dB scale. The time bin size is 0.1 s. Two examples of microphone-averaged spectrograms for a takeoff and a landing can be seen in Figure 3.5. It is observed that, across all recorded flights, the frequency responses are broadband and strongest under 1000 Hz. For takeoffs that were measured at smaller distances, tones that exhibit gradual frequency shifts from the Doppler effect can be seen at frequencies above 500 Hz, such as in Figure 3.5a. It can also be seen that, towards the end of the recording where the distance between the array and the aircraft increases, the tones are no longer captured, as higher frequencies are dampened by atmospheric attenuation. This is not observed for any landings (Figure 3.5b). Different ranges of frequency, defined in Table 3.1, were considered for localization.

Next, the algorithm to search for the location of the sound source is implemented. First, considering a potential location of a sound source with coordinates ξ_j , a steering vector can be constructed

$$g_{j,n} = \exp(-2\pi i f \Delta t_{j,n}) = \exp[-2\pi i f(\xi_j - x_n)] \quad (3.17)$$

where x_n are the locations of N microphones, and $\Delta t_{j,n}$ is the time delay between emission time at ξ_j and reception time at x_n . The steering vector describes the relative amplitude and phase at each microphone, assuming the sound had originated from ξ_j . Applying the steering vector to the measured pressure spectrum and summing over all microphones gives the output for that potential source location

$$B_{j,k} = \sum_n P_n(f_k) g_{j,n} \quad (3.18)$$

This function, based on the output of a Conventional Beamforming algorithm, is maximized when the candidate position ξ_j coincides with the true source position, since only then do the microphone signals combine in-phase. The function provides a method to evaluate potential source locations. However, the presence of side lobes, visualized in Figure 3.6, will affect the optimization, as they are local optima that may prevent the algorithm from finding the global optimum. Global Optimization (GO) treats the search for the location of the sound source as an optimization problem [13]. For this research, the cost

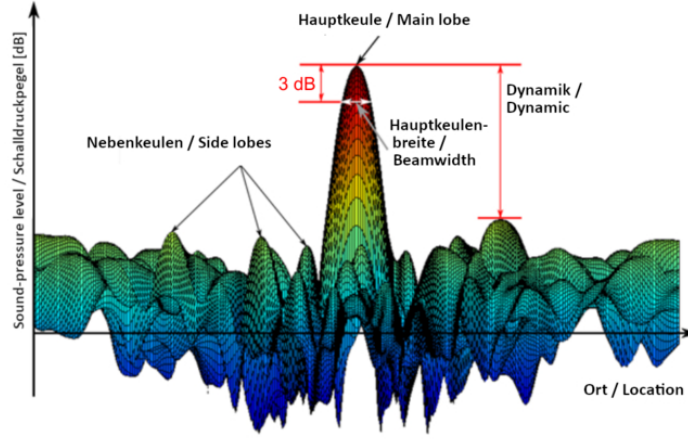


Figure 3.6: Visualization of the main lobe and side lobes in a map of beamforming output [8].

function z is defined by the beamforming output, which is summed across a defined frequency range; and since the algorithm minimizes the cost function, the negative is taken.

$$z_j = - \sum_k |B_{j,k}| \quad (3.19)$$

The cost function is then minimized when the candidate position coincides with the true source position. The frequency ranges considered for the cost function are shown in Table 3.1, and the best performing frequency range is determined in section 4.1.

For this research, a variant of the genetic algorithm known as Differential Evolution (DE) is used to obtain the source position. This method has been shown to be able to escape side lobes in previous studies [11, 16]. To optimize a cost function, genetic algorithms start with an initial population of q randomly chosen combinations of parameter values m . DE mimics natural evolution, where well-performing members of the population have a higher probability to reproduce [28]. The parameters are optimized over many generations by replacing a given combination of parameters with its successor if the successor has a lower cost. New candidate solutions are generated through mutation and crossover [28]. During mutation, a mutant is created by adding the scaled difference between two population members to another population member.

$$m_{i,G+1} = m_{r_1,G} + F(m_{r_2,G} - m_{r_3,G}) \quad (3.20)$$

where F is the multiplication factor. i, r_1, r_2, r_3 are indexes where r_1, r_2 and r_3 are chosen to be different from i . After mutation, the mutant is combined with the original candidate through crossover. The crossover rate p_c determines the probability that a parameter of the mutant is copied to the candidate. The process is repeated for a number of generations N_{gen} , and full independent reruns are done to assess for local optima.

For this application, the search parameters are two angular coordinates describing the source location: azimuth angle ϕ and elevation angle θ , and the slant distance d_{slant} . However, the localization results for d_{slant} is not considered, as it was found that GO struggles to find the height of the aircraft, which aligns with findings by Hoff [11]. Instead, d_{slant} is assigned to the noise level of the aircraft via interpolated ADS-B data, after correction for time alignment described in section 3.1. The summary of settings for the GO algorithm is shown in Table 3.2.

3.3. Error threshold and localization frequency range

The localization accuracy was evaluated by comparing the estimation by GO with the time-aligned reference positional data obtained from ADS-B. ADS-B data was recorded in intervals of 1 second, whereas the localization algorithm produced an estimate every 0.1 second. Thus, the ADS-B trajectory was linearly interpolated between time stamps to match the localization's time resolution. For each

Search parameters	ϕ, θ, d_{slant}
Cross-over rate p_c	0.55
Multiplication factor F	0.6
Number of independent runs N_{run}	2
Population size q	32
Number of generations N_{gen}	150

Table 3.2: Settings used for localization program.

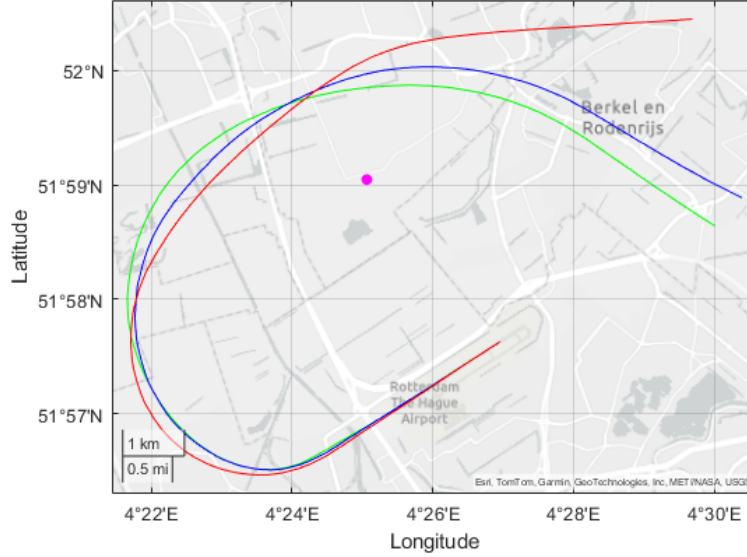


Figure 3.7: Flight paths of 3 flights selected as reference. Microphone array position is represented by a pink dot.

localization time step, the localization error is calculated as the difference in azimuth and elevation angles estimated by the GO and the interpolated ADS-B data. To account for differences in aircraft types and operation types, the recordings were first grouped according to these parameters.

$$\epsilon_{\theta} = \theta_{GO} - \theta_{ADS-B} \quad (3.21)$$

$$\epsilon_{\phi} = \phi_{GO} - \phi_{ADS-B} \quad (3.22)$$

Before the detection range can be determined, a criterion for successful localization must first be defined. Using a subset of flights that captured a wide range of ϕ and θ , the localization accuracy is analyzed. These flights are suitable for understanding the error of localization, but are not representative of the rest of the data set. The threshold established from the analysis of these flights is interpreted as an estimate of reference localization accuracy for classifying localization success in other flights. Three departure flights (two B738 and one A21N) were selected for this analysis. These flights have flight paths, which can be seen in Figure 3.7, that provide measurement at relatively higher elevation angles and shorter slant distances than the rest of the data. Under these conditions, noise measurements are of higher quality, and localization is expected to be most successful. This allows for characterization of the error threshold for localization success in section 4.1.

3.4. ECAC Doc. 29 Model

Having established the calculation of measured noise levels in section 3.2, the ECAC Doc. 29 model is then used to compute the modelled noise levels of the measured flights, such that it can be compared to experimental results. Comparison of the modelled noise levels against measurements enables the assessment of the behavior of the model at the distances recorded. The model is semi-empirical: by combining aircraft thrust and operational data, Noise-Power-Distance (NPD) tables, flight trajectories

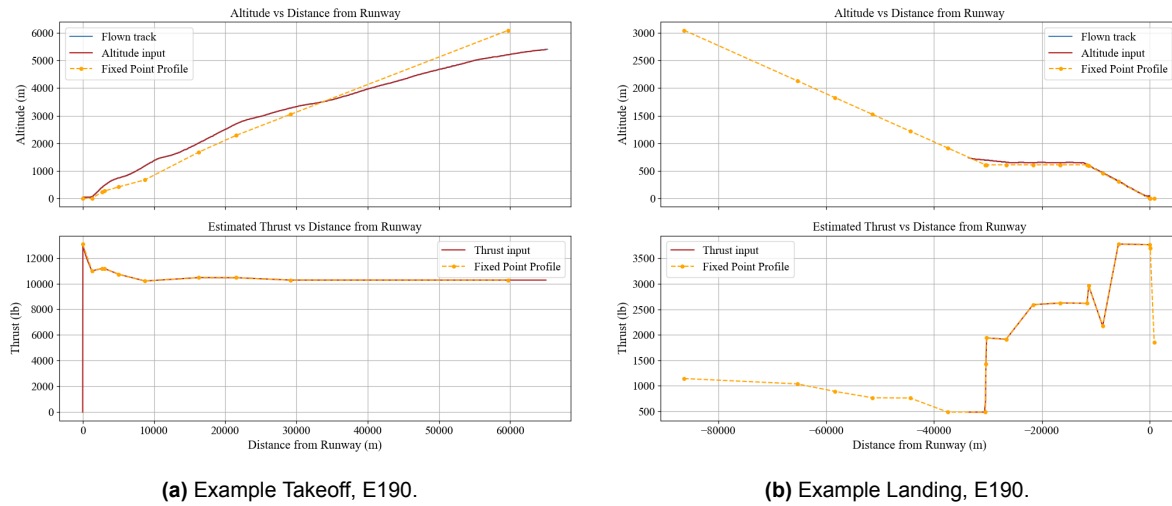


Figure 3.8: Comparison of flown altitude and fixed-point-profile (top) and interpolated thrust input (bottom).

Stage Length	1	2	3	4	5	6	7	8	9
Trip Length Range (nm × 1000)	0-0.5	0.5-1	1-1.5	1.5-2.5	2.5-3.5	3.5-4.5	4.5-5.5	5.5-6.5	>6.5

Table 3.3: Definition of stage length input for ECAC Doc. 29 model.

and appropriate corrections, the aircraft noise level can be calculated. For every point along the aircraft trajectory, the aircraft position and engine thrust setting are determined. The thrust setting is then used to interpolate the NPD tables corresponding to the aircraft type, which provide the reference A-weighted sound level as a function of source-to-observer distance. The reference sound level is subsequently corrected for operational and environmental effects to obtain the predicted sound level at the receiver.

Aircraft noise emission depends strongly on engine thrust [2], especially during departure. Direct thrust parameters are often difficult to obtain, and different methods have been developed to estimate thrust. Merino-Martínez et al. [14] proposed a method to estimate engine fan setting $N1\%$ and net thrust from acoustic measurements. This method, however, is not applicable to this research, as the tonal noise component from the engine fans is attenuated and unidentifiable at these distances. For this research, the thrust is estimated using fixed-point profiles. Using the altitude information from ADS-B tracks, the thrust value is linearly interpolated between profile points.

For all departures considered in this research, the Noise Abatement Departure Procedure (NADP) 2 was assumed. This procedure is documented by the International Civil Aviation Organization [12]. A comparison of the altitude and the interpolated thrust, for a recorded departure and arrival, and the fixed-point profile used is shown in Figure 3.8. This comparison is done for all modelled flights, and these examples provide a good representation of the observations from this comparison. Here, the altitude input and the flown track are the same, and it can be seen that the flown track altitude slightly deviates from the altitude of the fixed-point profiles, especially for takeoff. Consequently, this assumption introduces a source of uncertainty into the predicted noise levels, as the standard thrust profile is not strictly enforced and real flight operation often deviates from it.

Furthermore, the NPD tables require a stage length input as an estimate for aircraft weight and corresponding performance. The stage length is defined by the trip length as shown in Table 3.3. For this research, the stage length was unavailable for individual flights, and a constant stage length of 2 was assumed for all departures. The difference in L_A caused by different stage length assumptions is shown in Figure 3.10a. It is noted that the difference between stage length 1 and 2 is only about 0.1 dB, while it is much more significant between stage length of 2 and 3. The measured flights have a true stage length between 1 and 2, and the uncertainty from this assumption is considered acceptable.

For this research, the aircraft flight trajectory input is provided by the ADS-B track, described in section

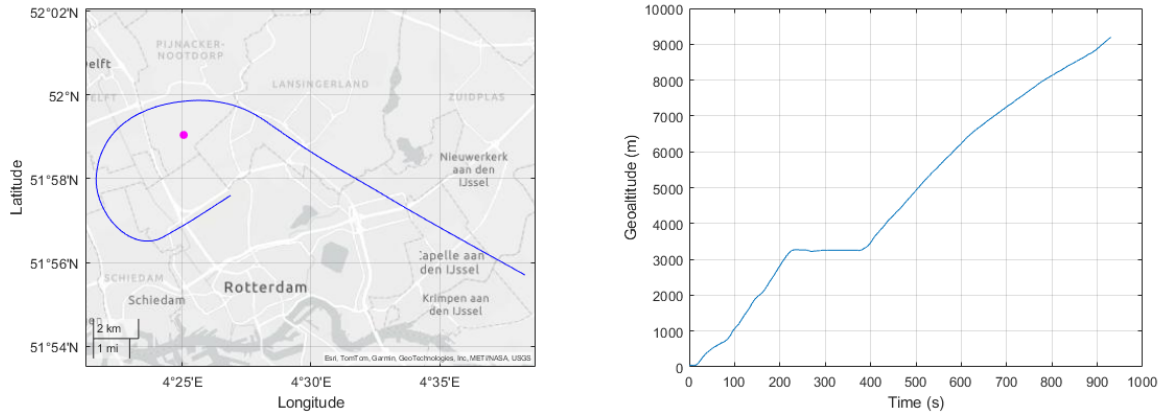


Figure 3.9: Example of unprocessed ADS-B data with ground track (longitude and latitude) on the left and altitude on the right.

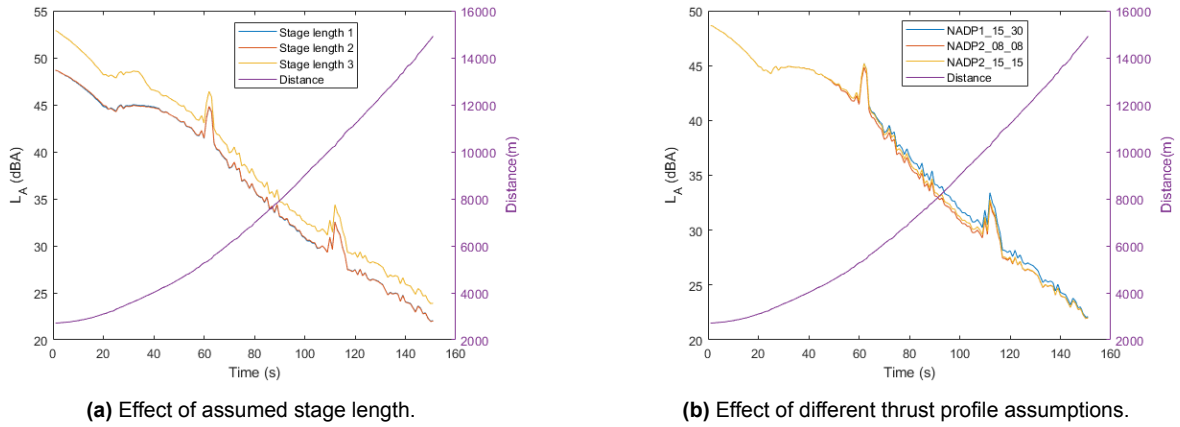


Figure 3.10: Effects of modelling assumptions for a B738 Takeoff.

2.2. An example of an ADS-B track of a recorded flight is illustrated in Figure 3.9. Struempfel and Hübner [30] compare the result of modelling with real flight tracks and modelled flight tracks and found that real flight tracks provide a more accurate prediction. With the described thrust and positional inputs, the reference A-weighted noise level is calculated, based on the aircraft type and its NPD tables. However, data for the B38M is not available. For this aircraft type, a proxy profile for the B737 was selected. The proxy profile allows for noise prediction of these flights but likely introduces a significant modelling uncertainty, since a correction for this proxy profile assumption is not known for the B38M.

A series of corrections are applied to the reference A-weighted level L_{NPD} to obtain the sound level at the receiver. This consists of corrections for engine installation ΔL_{inst} , lateral attenuation ΔL_{lat} , acoustic impedance ΔL_{imp} , and weather attenuation $\Delta L_{weather}$. These corrections are described by the Society of Automotive Engineer (SAE) in AIR-1751 and AIR-5662 [27, 26] and in ECAC Doc. 29 Volume 2 [5]. They account for deviations of real flight from the reference measurement conditions under which the NPD data were obtained. Therefore, meteorological data is necessary for acoustic impedance and weather attenuation correction and is obtained from the KNMI ¹.

$$L_{A,modelled} = L_{NPD} + \Delta L_{inst} + \Delta L_{lat} + \Delta L_{imp} + \Delta L_{weather}, \quad (3.23)$$

Finally, the modelled A-weighted noise level $L_{A,modelled}$ at the array's position is obtained. The predicted noise level for each flight segment have an associated slant distance to the array. These noise level prediction are compared to the measured noise level, presented as a function of distance, to assess the behavior of the model in section 4.3.

¹<https://www.knmi.nl/over-het-knmi/about>

Chapter 4

Discussion of Results

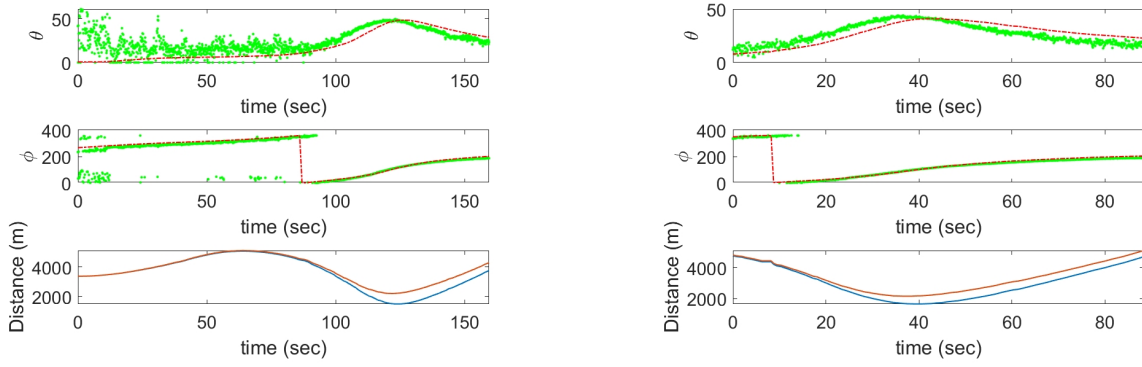
This chapter discusses the results obtained by applying the data processing steps described in Chapter 3. First, Section 4.1 establishes the best frequency range for localization and defines an error threshold to classify localization estimates as successful or unsuccessful. Section 4.2 applies this criterion to answer the first research question and determine the detection range for each aircraft type and operational procedure. Finally, section 4.3 compares the measured noise levels to predictions by the ECAC Doc. 29 model and addresses the second research question.

4.1. Localization frequency and success criterion

The localization error varies for each time step, either due to uncertainty in the estimation or a failure in localizing the aircraft. To classify each point of localization as a success or a failure, a quantitative criterion for detection must be defined. Localization is performed for all selected flights, described in section 3.3 with the frequency ranges previously defined in Table 3.1. Figure 4.1 compares the Band 4 (100-250 Hz) GO localization results with the ADS-B reference trajectories for the selected flights. It can be seen that in all three cases, the algorithm successfully and continuously tracks the source direction for most of the recording. Combined with covering a large range of θ and ϕ , these recordings are thus suitable to be reference measurements to evaluate localization performance of the frequency range. However, it can be seen that at lower elevation angles, θ localization results are scattered and inaccurate. Considering that the rest of the data set is obtained at low θ , this suggests that θ estimates are not reliable enough to define a criterion for successful localization. To further evaluate the localization accuracy, Figure 4.2 shows the error distribution of Band 1 (100-1000 Hz) localization for the selected flights. It can be seen that ϵ_θ distribution is quite uniform in comparison to ϵ_ϕ distribution, which reflects the unreliable localization at lower θ as discussed above. ϵ_ϕ distribution is concentrated between approximately -12° and -15° and not zero. To define a criterion for successful localization, a range of acceptable error is established based on the distribution of ϵ_ϕ .

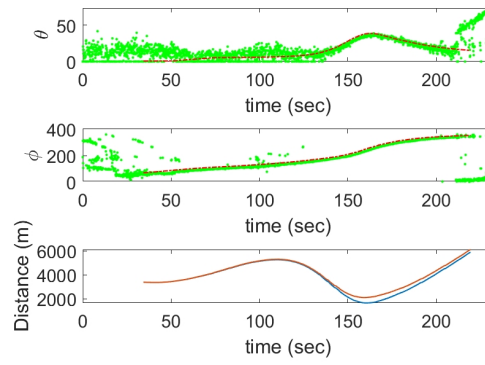
The distributions of azimuth error ϵ_ϕ for each frequency band considered were compared in Table 4.1. The 2.5th and 95th percentiles are used to define the range of acceptable error based on the localization error distribution of each band. The median is similar across all bands, while the interval width is significantly larger for Bands 3 and 5, indicating poorer localization performance. These bands account for frequencies between 250-1000 Hz, which suggests that these frequencies contribute little to localization and that the noise signal from the aircraft is more prevalent at lower frequencies. This is consistent with the knowledge that higher frequencies are attenuated more effectively by atmospheric attenuation.

Band 1 (100-1000 Hz) performs the best out of all frequency bands considered, yielding the smallest interval width, and localization on the rest of the acoustic data is performed considering the frequency range 100-1000 Hz defining this band. Thus, the criterion for successful localization for the rest of the



(a) Day 1, flight 7 (B738 Takeoff).

(b) Day 1, flight 18 (B738 Takeoff).



(c) Day 3, flight 6 (A21N Takeoff).

Figure 4.1: Comparison of ADS-B positional data (red) and Band 4 (100 - 250 Hz) localization result (green) of chosen flights.

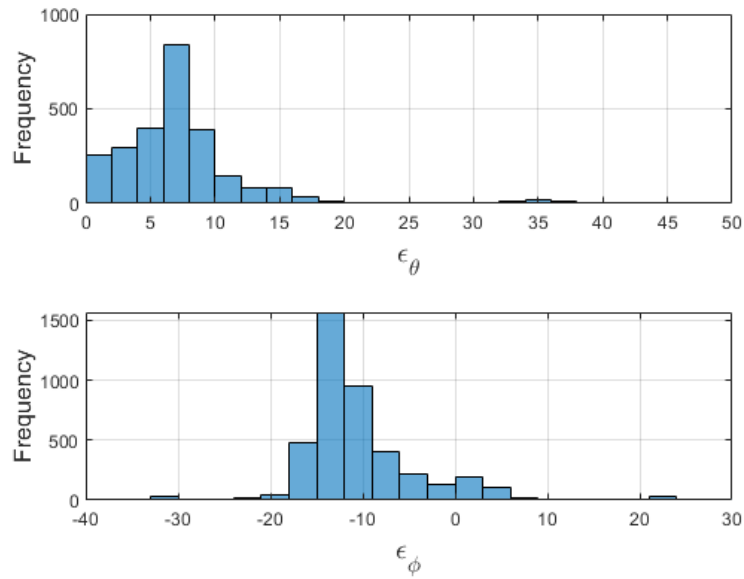


Figure 4.2: Distribution of elevation and azimuthal errors for selected flights.

Band	Median $\epsilon_\phi(^{\circ})$	2.5th Percentile $\epsilon_\phi(^{\circ})$	95th Percentile $\epsilon_\phi(^{\circ})$	Interval Width $(^{\circ})$
Band 1 (100-1000 Hz)	-11.9	-17.5	4.8	22.3
Band 2 (100-500 Hz)	-11.9	-18.4	4.4	22.8
Band 3 (500-1000 Hz)	-11.1	-20.3	88.3	108.7
Band 4 (100-250 Hz)	-11.7	-20.3	5.5	25.8
Band 5 (250-500 Hz)	-11.8	-19.7	24.3	43.9

Table 4.1: Comparison of localization azimuth error ϵ_ϕ distribution of selected flights for different frequency bands.

data set is also defined from the reference ϵ_ϕ distribution of the selected flights as:

$$-17.5^{\circ} \leq \epsilon_\phi \leq 4.8^{\circ} \quad (4.1)$$

4.2. Maximum detection range based on localization success rates

With the criterion defined in section 4.1, this section answers the first research question by assessing how detectability, quantified by localization success rate, changes with distance. For a measurement recording, each time step of 0.1 s produces a localization result, associated with a slant distance to the aircraft. The success rate is the percentage of successful localizations, classified by the established criterion, of the total number of localizations in each distance bin of 200 m. By examining this relationship, a detection range for each aircraft type and operational procedure can be determined. For this research, the success rate threshold that represents reliable detection is assumed to be 70%.

Figures 4.3 and 4.4 shows the localization success rate as a function of distance for takeoff and landing respectively. The orange line shows the total number of localizations in each distance bin. Each graph in Fig. 4.3 and 4.4 is labeled with an aircraft type.

Before interpreting these results, two characteristics resulting from the measurement geometry are worth noting. First, the total number of localizations for 3300 m bin is the highest for all aircraft types, while the success rate dips for most aircraft types at this distance. This bin corresponds to the ground distance between the array position and the runway, where the aircraft is in either takeoff or landing roll, so the low success rate here does not reflect the detectability of an aircraft at higher elevation and similar distance. Secondly, at distances below this bin, the total number of localizations is low, while the success rate is 100%, seen for the B738 and A21N. These points correspond to the selected flights, described in section 3.3 and discussed in section 4.1, that provide some measurements at lower distances and higher elevation angles, which resulted in high localization success rate and detectability.

For takeoff operations, a clear relationship between distance and localization success rate is observed, especially for the B738, for which significantly more flights were recorded. Success rate declines gradually with distance for the B738 takeoff, as expected from the noise signal being attenuated over larger distances by geometrical spreading, and at 6600 m drops below the 70% threshold. A higher success rate between 9500-10000 m was observed, beyond which the success rate drops, but is still significant. This may indicate that the aircraft is still detectable, but less reliably.

For the A320 takeoff, success rate is above the threshold for distances up to 5800 m. However, measurements at higher distances are not available, so the maximum detection range could not be determined. The E190, A21N, B38M and A359 have an abrupt drop in success rate at 7500 m, 5400 m, 6500 m and 6700 m, respectively. E190 has significant fluctuations in success rate before the drop, because one of its takeoff recordings captured a simultaneous flyover of a BAE Hawk T1A, visible in the localization result in Appendix A Figure A.1. B38M also exhibits fluctuations around the 70% threshold, and this can be attributed to this aircraft type being newer and quieter.

For landing operations, success rate is lower for all aircraft types, although a detection success rate of around 50% is observed for B738 at a distance of 3700-4100 m, and beyond which there is a gradual decline in detectability. Similarly, significant detection at the 3500 m bin for A320 and bins between 3500 to 4700 m for A21N can also be observed. The localization results of these recordings are further inspected and can be seen in Appendix A. For the A320 (Figures A.2 and Figure A.3), the detection

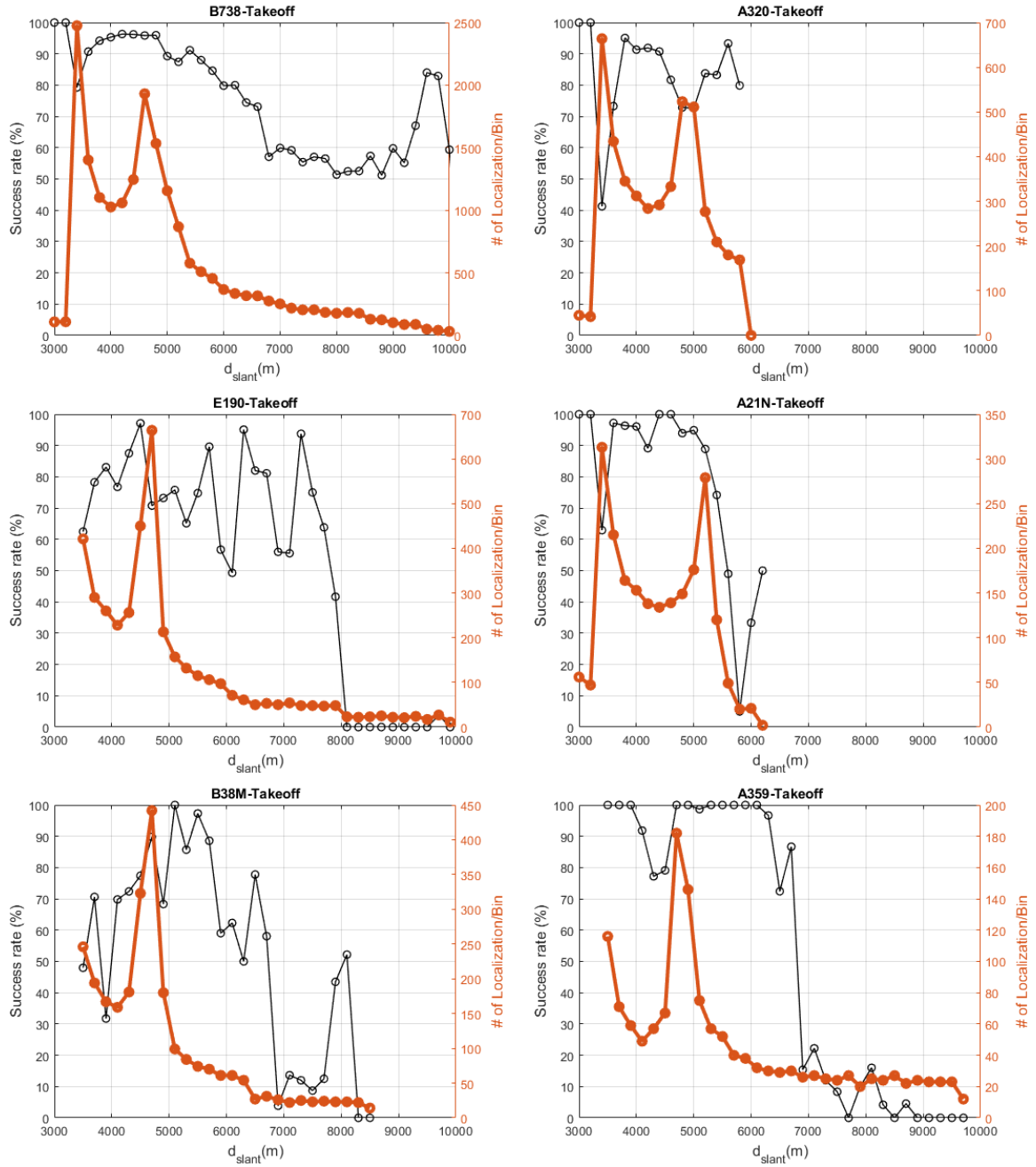


Figure 4.3: Localization success rate as a function of distance for different aircraft type in takeoffs.

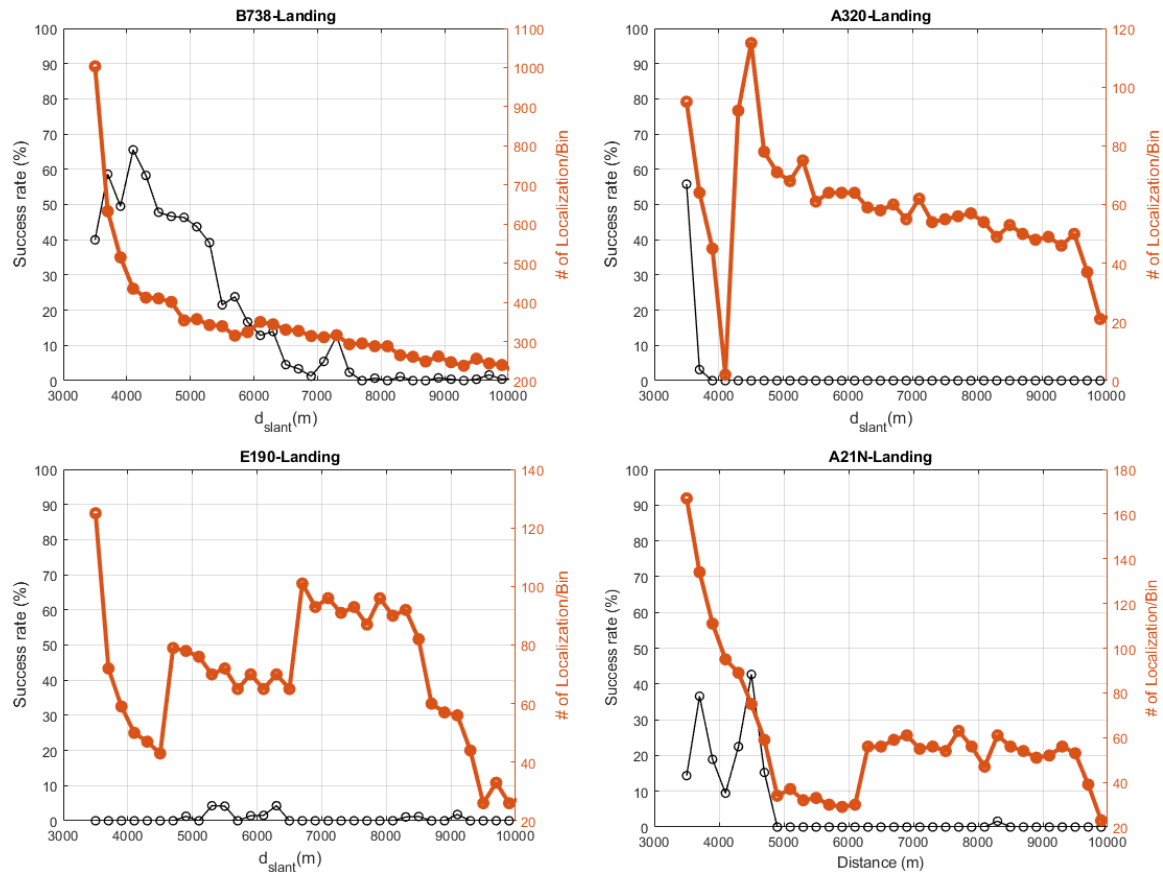


Figure 4.4: Localization success rate as a function of distance for different aircraft type in landings.

is a result of false detection, where the ADS-B reference track approaches the localization results of a fixed background noise source towards the end of the recording. For the A21N (Figure A.4), the recording includes 3 aircraft flyovers (2 takeoffs and the A21N landing). There are signs of localization towards the end of the landing when the localization results alternate between the previous takeoff and the landing. This indicates that these landings of B738 and A21N might also be detectable at distances smaller than recorded for this research, with the criterion and threshold defined.

The detection range, assuming the success rate threshold for detection is 70%, was determined for each aircraft type and operation type and shown in Table 4.2. The tabulated values show that during takeoff operations, newer and quieter aircraft types such as the B38M and A21N are less detectable in low-noise regions than older aircraft types B738 and A320. This aligns with findings in previous studies [25, 31]. The lower detectability of landing operations is expected, as takeoff operations generally produces higher noise levels from higher engine power settings required.

Aircraft type	Departure	Arrival
B738	6600 m	N/A
A320	≥ 5800 m	N/A
E190	7500 m	N/A
B38M	5700 m	
A21N	5400 m	N/A
A359	6700 m	N/A

Table 4.2: Maximum detection range based on aircraft type and operating procedures

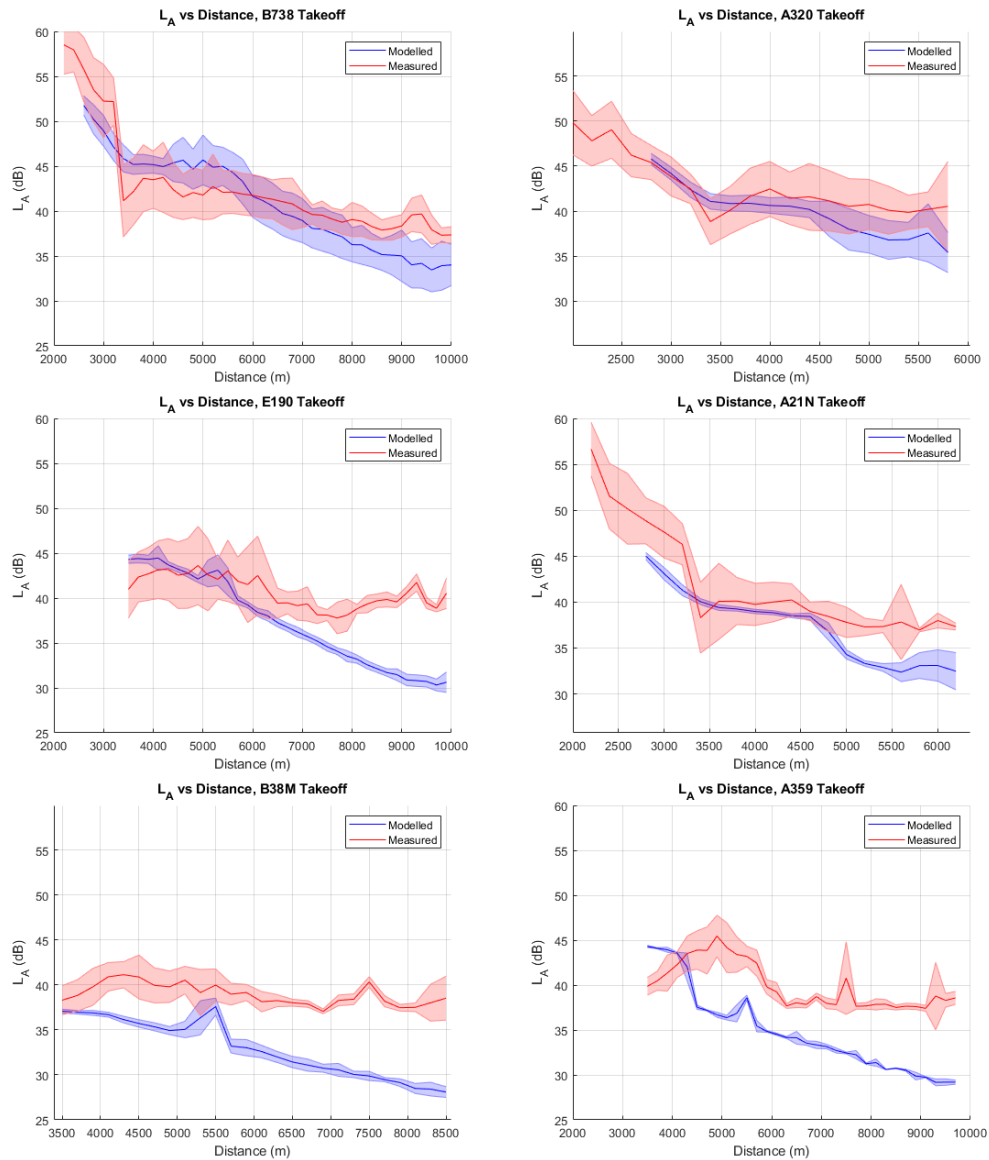


Figure 4.5: Measured and modelled noise levels as a function of distance for different aircraft type in takeoffs.

4.3. Measured and Modelled noise levels

This section addresses the second research question by comparing the measured noise levels at these distances to predictions by the ECAC Doc.29 model. The aim is to assess the behavior of the model relative to measurements at these distances.

Figures 4.5 and 4.6 shows the measured and modelled noise levels as a function of distance, for takeoff and landing respectively. The line represents the mean noise level at each distance bin, while the shaded region represents the ± 1 standard deviation. For takeoff operations, noise level jumps sharply at 3300 m for B738 and A21N, corresponding to measurements when the aircraft passes the measurement location at a high elevation angle and short slant distance, providing favorable conditions to capture the aircraft noise signal. Beyond and below 3300 m, the measured noise level decreases slowly with distance. Beyond 3300 m, the measured noise levels eventually approach a near constant level of approximately 37-40 dB, while the standard deviation of the measured noise level narrows. This is not observed for the A320 takeoff due to lack of measurements, but is visible for the other aircraft types. This suggests that, at large distances, the recorded sound levels become increasingly dominated by background noise, and differences between individual flights become less significant.

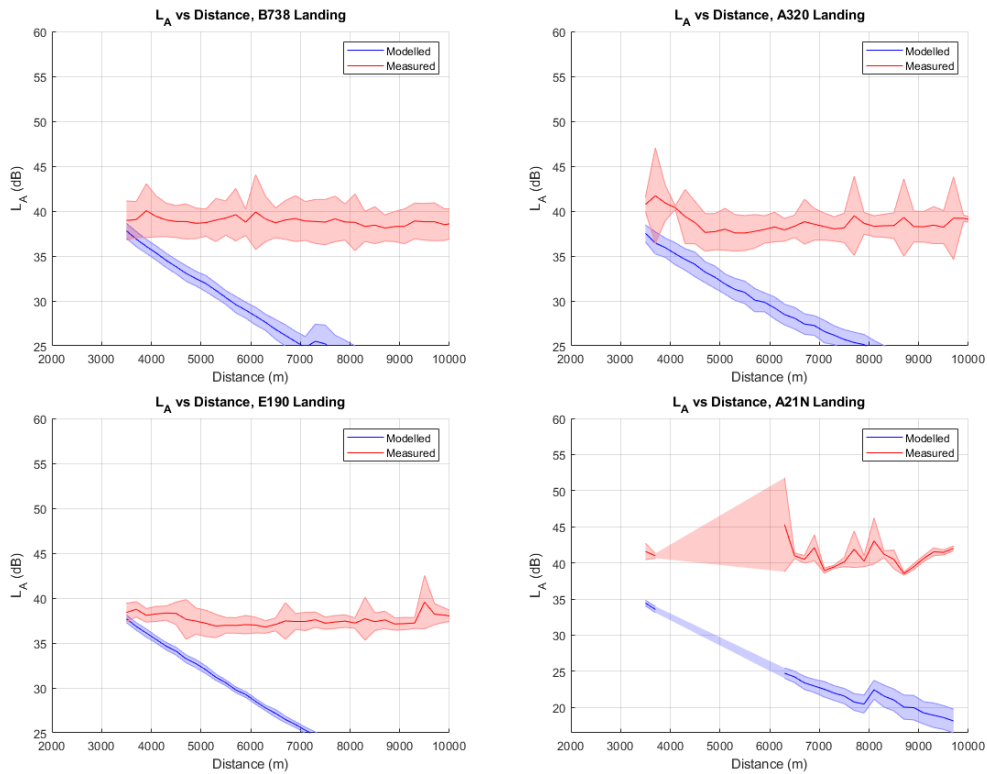


Figure 4.6: Measured and modelled noise levels as a function of distance for different aircraft type in landings.

Between 3500-5000 m, the model and measurements agree well for the A320, E190 and A21N takeoffs. For the B738, the model overpredicts by approximately 3 dB in this range. No agreement is seen for B38M or A359, the former can be explained by the large modelling uncertainty resulting from the proxy profile assumed, described in section 3.4, while the latter, despite being a larger aircraft type and providing elevated measured noise level, is significantly underpredicted. Beyond 6000 m, the model consistently predicts lower noise levels than measured in every case. This difference occurs because the model predicts the aircraft sound emission and propagation, whereas the measurements include background noise. As the aircraft contribution becomes dominated by background noise at larger distances, the measured sound levels approach ambient noise, while the modelled sound levels continue to decrease.

For landing operations of all aircraft types, the measured noise level is nearly constant with distance, while the model predicts a steady decrease with increasing distance. This again indicates that the background noise at the measurement location dominates the noise signal from the aircraft landings across the recorded distances. Consequently, the comparison offers no information about the model's behavior.

Chapter 5

Conclusions and recommendations

5.1. Conclusions

The objective of this research was to assess the detectability of aircraft in low-noise regions and its relationship with distance, aircraft type and operational procedure, using GO to perform localization on acoustic experimental data. It was found that detection range varies with aircraft type and operation. For takeoff, older and larger aircraft remain detectable at larger distances (B738: 6600 m, E190: 7500 m, A359: 6700 m), while newer aircraft types are detected at shorter distances (A21N: 5400 m, B38M: 5700 m). Landing operations were not reliably detected across all aircraft types at distances recorded, reflecting that the possible detection range is much shorter than the ones that were recorded in this work, which is due to lower power settings that are inherent to this operation mode.

Comparison of measured and modelled noise levels shows that ECAC Doc. 29 aligns with measurements within 3500-5000 m for A320, E190 and A21N takeoffs. For the B738, B38M and A359 takeoffs, the model does not fully align with the measurements in this range with the inputs and assumptions considered in this study, due to extra assumptions (for B38M) or inaccuracy from the model (B738 and A359). Beyond 6000 m, the model underpredicts for every case, likely because it only captures noise radiated by the aircraft, while measurements include background noise. For landings, there is no agreement between measurement and model at any distance. The measured noise levels also indicate that detection is possible at distances where the noise level is similar to background noise level, and GO can improve detection where aircraft might go undetected by current noise monitoring stations.

5.2. Recommendations

Recommendations for future work is as followed:

- **Obtaining background noise level directly:** Since the effect of different types and levels of background noise on detectability of aircraft is unknown, future work should consider acquiring measurements capturing background noise to improve our understanding of this variable.
- **Improve elevation angle estimation:** Since elevation angle localization results were found to be unreliable at low elevation angles, future work should investigate ways to improve elevation localization accuracy.
- **Validation against a broader set of measurements:** This study was conducted at a single measurement location over four measurement days. Findings from this study need to be validated in other background noise conditions and different airports.
- **Improve modelling input:** ECAC Doc. 29 modelling for this research was done using assumed weight and thrust settings based on standard thrust profiles. Using actual weight and thrust values or implementing better estimation methods will reduce uncertainty from these assumptions and provide a better comparison with measured noise levels.

References

- [1] M. Basner et al. “Auditory and non-auditory effects of noise on health”. In: *The lancet* 383.9925 (2014), pp. 1325–1332.
- [2] A. Behere et al. “Sensitivity Analysis of Airport level Environmental Impacts to Aircraft thrust, weight, and departure procedures”. In: *AIAA Scitech 2020 Forum*. DOI: 10.2514/6.2020-1731. eprint: <https://arc.aiaa.org/doi/pdf/10.2514/6.2020-1731>. URL: <https://arc.aiaa.org/doi/abs/10.2514/6.2020-1731>.
- [3] DCMR Milieudienst Rijnmond. *Jaarrapport Meldingen Rotterdam The Hague Airport 2025*. Annual report. DCMR Milieudienst Rijnmond, 2026. URL: https://www.cro-rotterdam.nl/wp-content/uploads/2026/02/Jaarrapport-meldingen-RTHA-2025_definitief.pdf.
- [4] EASA. *European Aviation Environmental Report 2025 - EASA*. URL: https://www.easa.europa.eu/sites/default/files/eaer-downloads/EASA_EAER_2025_Book_v5.pdf.
- [5] European Civil Aviation Conference (ECAC). *ECAC.CEAC Doc 29: Report on Standard Method of Computing Noise Contours around Civil Airports, Volume 2: Technical Guide*. Tech. rep. Paris, France, 2026.
- [6] M. Genescà. “Directional monitoring terminal for aircraft noise”. In: *Journal of Sound and Vibration* 374 (2016), pp. 77–91. ISSN: 0022-460X. DOI: <https://doi.org/10.1016/j.jsv.2016.04.004>. URL: <https://www.sciencedirect.com/science/article/pii/S0022460X16300219>.
- [7] M. Genescà et al. “Real time aircraft fly-over noise discrimination”. In: *Journal of Sound and Vibration* 323.1 (2009), pp. 112–129. ISSN: 0022-460X. DOI: <https://doi.org/10.1016/j.jsv.2008.12.030>. URL: <https://www.sciencedirect.com/science/article/pii/S0022460X09000078>.
- [8] gfaitech GmbH. *Point Spread Function in Acoustic Analysis — gfaitech.com*. <https://www.gfaitech.com/knowledge/faq/point-spread-function>. [Accessed 29-07-2026].
- [9] R. C. van der Grift, M. Snellen, and A. Amiri-Simkooei. “Aircraft noise model improvement by calibration of noise–power–distance values using acoustic measurements”. In: *CEAS Aeronautical Journal* 17.3 (2025), pp. 1101–1115. DOI: 10.1007/s13272-025-00902-6.
- [10] R. Guski, U. Felscher-Suhr, and R. Schuemer. “THE CONCEPT OF NOISE ANNOYANCE: HOW INTERNATIONAL EXPERTS SEE IT”. In: *Journal of Sound and Vibration* 223.4 (1999), pp. 513–527. ISSN: 0022-460X. DOI: <https://doi.org/10.1006/jsvi.1998.2173>. URL: <https://www.sciencedirect.com/science/article/pii/S0022460X98921733>.
- [11] B. von den Hoff. *Assessment of the use of global optimisation techniques for aircraft noise source identification*. URL: <https://resolver.tudelft.nl/uuid:1c88c4ec-3b84-403c-95db-a9b8a869c3ad>.
- [12] International Civil Aviation Organization. *Procedures for Air Navigation Services (PANS) – Aircraft Operations*. 6th. Doc 8168. Volume I: Flight Procedures. ICAO. Montréal, Quebec, Canada, 2018.
- [13] A.M.N. Malgoezar et al. “On the use of global optimization methods for acoustic source mapping”. In: *The Journal of the Acoustical Society of America* 141.1 (2017), pp. 453–465. DOI: 10.1121/1.4973915.

- [14] R. Merino-Martínez et al. "Improving Aircraft Noise Predictions Considering Fan Rotational Speed". In: *Journal of Aircraft* 56.1 (2019), pp. 284–294. DOI: 10.2514/1.C034849. eprint: <https://doi.org/10.2514/1.C034849>. URL: <https://doi.org/10.2514/1.C034849>.
- [15] H.M. Miedema and C.G. Oudshoorn. "Annoyance from transportation noise: relationships with exposure metrics DNL and DENL and their confidence intervals." In: *Environmental Health Perspectives* 109.4 (2001), pp. 409–416. DOI: 10.1289/ehp.01109409.
- [16] D. Nijhof. *Assessing the performance of two new acoustic imaging techniques*. URL: <https://resolver.tudelft.nl/uuid:1dd957fb-6ad4-4804-b903-cae9218661ed>.
- [17] X. Olive et al. "Filtering Techniques for ADS-B Trajectory Preprocessing". In: *Journal of Open Aviation Science* 2.2 (2025). DOI: 10.59490/joas.2024.7882.
- [18] International Civil Aviation Organization. "STATE OF THE INDUSTRY AND OUTLOOK FOR AIRPORT TRAFFIC". In: (2025), p. 2.
- [19] World Health Organization. "Environmental noise guidelines for the European region". In: (2018).
- [20] Z. Prime and C. Doolan. "A comparison of popular beamforming arrays". In: *Proceedings of the Australian Acoustical Society AAS2013 Victor Harbor 1* (2013), p. 5.
- [21] Rotterdam The Hague Airport. *Milieu-effectrapport LHB RTHA*. Environmental Impact Assessment Report. Sept. 2025. URL: <https://www.rotterdamthehagueairport.nl/wp-content/uploads/Bijlage-4-Deelrapport-Geluid.pdf>.
- [22] A Sahai et al. *Programmatiese Aanpak Meten Vliegtuiggeluid (PAMV): Validatie Doc.29-model voor Schiphol*. 2024.
- [23] M. Schäfer et al. "Bringing up OpenSky: A large-scale ADS-B sensor network for research". In: *IPSN-14 Proceedings of the 13th International Symposium on Information Processing in Sensor Networks*. 2014, pp. 83–94. DOI: 10.1109/IPSN.2014.6846743.
- [24] D.G. Simons and M. Snellen. *An introduction to general acoustics and aircraft noise*. 8th ed. 2023.
- [25] D.G. Simons et al. "Contribution of aircraft types to noise levels across the NOMOS network of Amsterdam Airport Schiphol". In: *Journal of Air Transport Management* 131 (2026), p. 102910. ISSN: 0969-6997. DOI: <https://doi.org/10.1016/j.jairtraman.2025.102910>.
- [26] Society of Automotive Engineers. *AIR1751 - Prediction method for lateral attenuation of airplane noise during takeoff and landing*. Tech. rep. SAE International, 2017.
- [27] Society of Automotive Engineers. *AIR5662 - Method for predicting lateral attenuation of airplane noise*. Tech. rep. SAE International, 2017.
- [28] R. Storn and K. Price. "Differential Evolution – A Simple and Efficient Heuristic for global Optimization over Continuous Spaces". In: *Journal of Global Optimization* 11.4 (1997), pp. 341–359. DOI: 10.1023/a:1008202821328.
- [29] M. Strohmeier et al. "Realities and challenges of nextgen air traffic management: the case of ADS-B". In: *IEEE Communications Magazine* 52.5 (May 2014), pp. 111–118. DOI: 10.1109/mcom.2014.6815901.
- [30] C. Struempfel and J. Hübner. "Aircraft Noise Modeling of Departure Flight Events based on Radar Tracks and Actual Aircraft Performance Parameters". In: Mar. 2020. URL: https://pub.dega-akustik.de/DAGA_2020/data/articles/000178.pdf.
- [31] R.C. Van der Grift et al. "Analysing the Effect of undetected flights in the comparison of measured and modelled aircraft noise". In: European Acoustics Association, EAA. 2025, pp. 5607–5614.
- [32] T.L. Verbraak et al. "Large-Scale ADS-B Data and Signal Quality Analysis". In: *12th Seminar Papers*. 12th USA/Europe Air Traffic Management Research and Development Seminar, ATM 2017 ; Conference date: 26-06-2017 Through 30-06-2017. 2017. URL: <http://www.atmseminar.org/12th-seminar/papers/>.
- [33] A. Vieira et al. "Comparison of semi-empirical noise models with flyover measurements of operating aircraft". In: *Journal of Aircraft* 59.6 (2022), pp. 1574–1587.

Appendix A

Localization Results of Individual Recordings

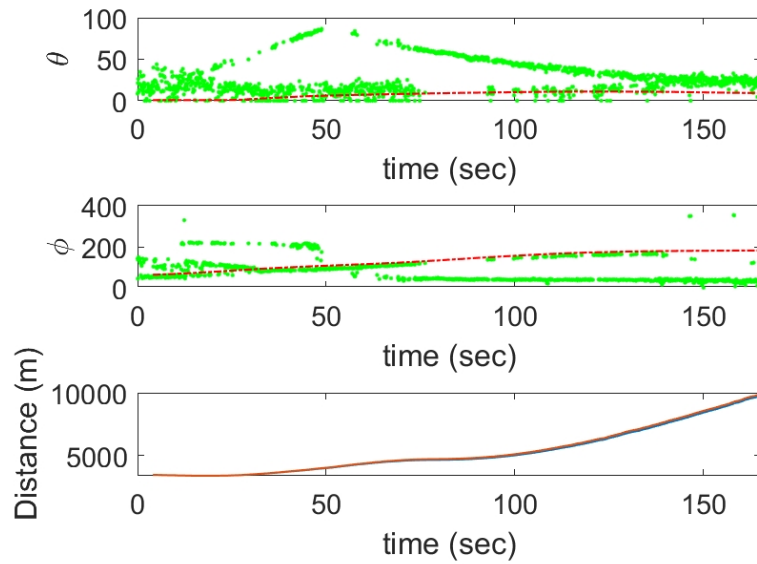


Figure A.1: Comparison of ADS-B positional data (red) and localization result (green) for a contaminated E190 takeoff measurement. Detection of the BAE Hawk T1A flying directly overhead can be seen as the source direction estimation approaches $\theta = 90^\circ$, and the azimuthal angle changes by 180 degrees at the same time around 50 s.

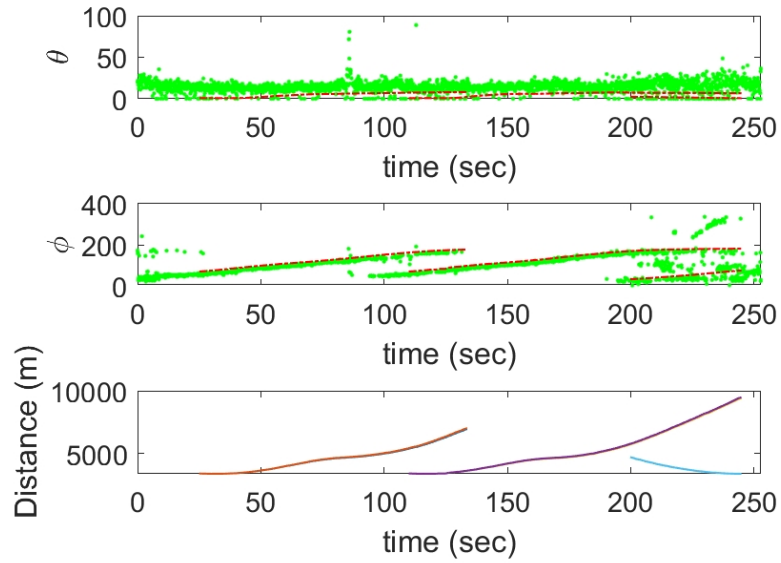


Figure A.3: Comparison of ADS-B positional data (red) and localization result (green) for a contaminated A21N landing measurement. The aircraft of interest is detected between 200 and 250 s, where localization result fluctuates between the landing and a takeoff from RTHA prior to it.

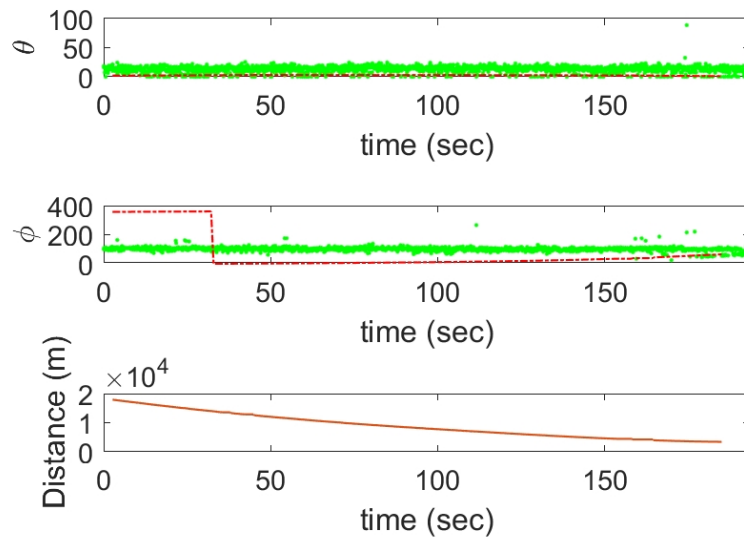


Figure A.2: Comparison of ADS-B positional data (red) and localization result (green) for a false successful detection of an A320 landing. False detection is seen at the end of the recording where the direction of the aircraft approaches the direction of the source of background noise.

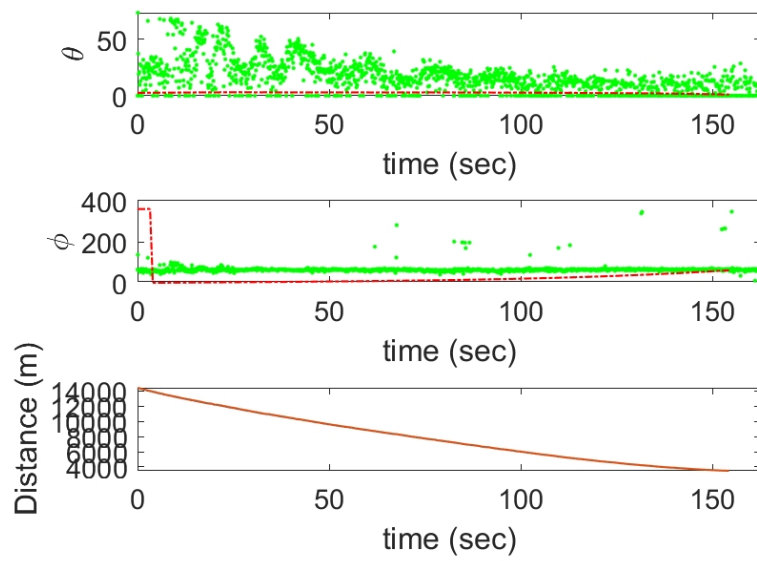


Figure A.4: Comparison of ADS-B positional data (red) and localization result (green) for a false successful detection of an A21N landing. False detection is seen at the end of the recording where the direction of the aircraft approaches the direction of the source of background noise.

Appendix B

Literature Study

A literature study is done to establish the foundational knowledge and the research gap to be addressed in this project. This appendix provides additional information found during the literature study that was not included in other sections of the main text. Section B.1 discusses the propagation of sound in air. Section B.2 provides an overview of current noise monitoring system and propose microphone arrays as an alternative measurement method. Section B.3 describes localization methods enabled by microphone arrays. Section B.4 introduces aircraft noise modelling and the ECAC Doc. 29 model. Finally, section B.5 identifies the research gap to be addressed by this project.

B.1. Propagation of sound

The sound generated by an aircraft is affected by several effects before it reaches the observer on the ground. These effects alter both the sound pressure level and spectral content of the measured signal.

B.1.1. Atmospheric attenuation

Sound waves travelling through a fluid result in loss of energy due to friction and interaction with molecules. This attenuation is not uniform over the frequency domain. For high frequencies the absorption is stronger, and these higher frequencies damp out faster. Factors contributing to the absorption coefficient are relative humidity and temperature [24]. The relationship between the absorption coefficient and these factors is illustrated in Figure B.1.

B.1.2. Geometrical spreading

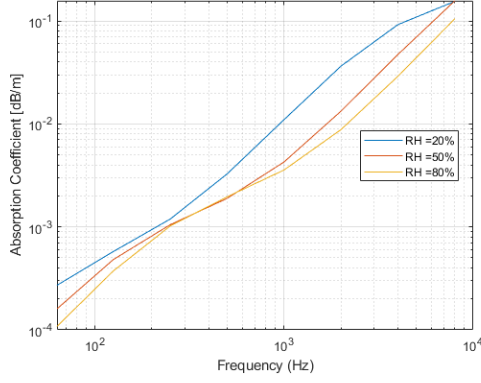
Geometrical spreading accounts for the reduction in sound level as acoustic energy spreads out from the source. For an aircraft treated as a point source, sound pressure level decreases with increasing distance due to the expanding wavefront. The loss in sound pressure level [dB] is given by Equation B.1, where r is the distance and r_{ref} is the distance at which the sound level is known.

$$\Delta = 20 \log \left(\frac{r}{r_{ref}} \right) \quad (\text{B.1})$$

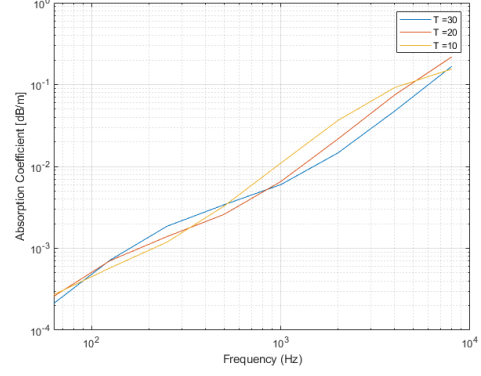
For the aircraft to be considered as a point source, the distance between the different the noise sources of the aircraft (engines, flaps, ...) must be small with respect to the distance between the aircraft and the observer. The sources also must be incoherent so that there is no destructive interference.

B.1.3. Doppler effect

The Doppler effect is caused by the relative motion between the aircraft and the observer. As an aircraft approaches, sound waves are compressed, resulting in an increase in observed frequency, while receding motion leads to a decrease in frequency. This relation is given by Equation B.2 where f



(a) Absorption coefficient of air (in dB/m) as a function of frequency (in Hz) for a temperature of 10° C and three values of the relative humidity.



(b) Absorption coefficient of air (in dB/m) as a function of frequency (in Hz) for a relative humidity of 20% and three values of the temperature.

Figure B.1: Absorption coefficient dependency on relative humidity and temperature across the frequency spectrum.

and f_0 are the observed and emitted frequencies respectively, M the relative Mach number and θ the angle between the observer and the aircraft.

$$\frac{f}{f_0} = \frac{1}{1 - M \cos(\theta)} \quad (\text{B.2})$$

Furthermore, because sound requires a finite time to travel from the aircraft to the observer, the received sound corresponds to an earlier aircraft position rather than its instantaneous location. This propagation delay is particularly important for source localization and time-domain comparisons between measured and modelled aircraft noise.

B.1.4. Ground reflection

Sound waves can reflect on surfaces. One of such surfaces is the ground, which can cause the sound wave to reflect into the microphone, resulting in two waves being measured, the direct wave and reflected wave. This can lead to a doubling or cancelling of sound pressure. Since the path length difference varies as an aircraft moves, the interference also changes throughout the flyover. Microphone placement for aircraft noise measurements is thus important to consider to ensure validity of measurement.

B.2. Noise measurement

The Noise Monitoring System (NOMOS) around Schiphol airport consists of 41 unattended noise monitoring towers, equipped with class 1 microphones with an uncertainty of 0.7-0.9dB¹. The microphones are placed on poles 6-10m above ground. NOMOS measurements are meant to monitor aircraft noise in communities, which increases the background noise and reflections from its surroundings. Before 2022, the event detection is based on a set threshold, which means that noise events are only registered when the noise exceeds it, allowing for under-reporting of noise events [22]. Since 2022, an improved detection algorithm which links the recorded noise to flights via RADAR data is implemented². However, newer and quieter aircraft still go undetected at distances over 10,000 ft, or 3 km, and for newer and quieter aircraft, 40% of flights are not measured below this distance [31].

Unlike conventional NMTs which consists of a single microphone, a microphone array comprises of multiple microphones which allows for localization of noise sources coming from different directions. The sound wave from a source will not reach all microphones simultaneously, and the delay is related to the direction of the source. This is the principle behind source localization using Beamforming and

¹<https://noiselab.casper.aero/ams/>

²<https://news.schiphol.com/improved-noise-measurements-in-the-area-around-schiphol/>

Global Optimization, described in section B.3. Because localization is based on the spatial coherence of the received signals instead of only sound pressure level, it is theorized that GO, similar to beamforming, can detect aircraft at greater distances than threshold-based methods, while eliminating the need to predefine a scan grid, therefore reducing computation time.

B.3. Source localization methods

Beamforming is a widely used method that uses measurements from a phased microphone array to identify noise sources. A 2D scan grid covering the potential source locations is defined. Because of the different relative position of the microphones to a scan grid point, they will receive the sound signal with different time delay. This time delay depends on the travel distances to each microphone. By delaying the measured signal by the microphone to account for the travel time and summing the delayed signal, the beamforming output is obtained. This method is called Conventional Beamforming. The beamforming output is calculated for all points on the scan grid, and is maximized when the actual source location overlaps with a point on the scan grid.

Beamforming can also be done in the frequency domain, which is called Conventional Frequency Domain Beamforming. The Fourier transform of the pressure measurement is considered.

$$\vec{P}(f) = \begin{pmatrix} P_1(f) \\ \vdots \\ P_N(f) \end{pmatrix} \quad (\text{B.3})$$

For a sound source ξ_j at the position of the scan point, the steering vector, describes the relative amplitude and phase at each microphone, assuming the sound had originated from ξ_j .

$$\vec{g}_{j,n} = \frac{\exp(-2\pi i f_k \Delta t_{j,n})}{4\pi |\xi_j - x_n|} = \frac{\exp\left[\frac{-2\pi i f_k |\xi_j - x_n|}{c}\right]}{4\pi |\xi_j - x_n|} \quad (\text{B.4})$$

x_n are the locations of N microphones, f_k the considered frequency, and $\Delta t_{j,n}$ is the time delay between emission time at ξ_j and reception time at x_n . The steering vector can be applied to the pressure measurement and summed for all microphones to obtain the beamforming output for the k-th frequency f_k .

$$B_{j,k} = \sum_n P_n(f_k) g_{j,n} \quad (\text{B.5})$$

This function is maximized when the candidate position ξ_j coincides with the true source position. An example of a map of beamforming output is shown in Figure B.2. The maxima of the beamform map coincides with the aircraft main and nose landing gears, which are known sources of airframe noise [24].

Rather than exhaustively evaluating a predefined scan grid, Global Optimization (GO) treats source localization as an optimization problem [13]. GO searches within a bounded parameter space for the source position that minimizes a cost function derived from the beamforming output. The algorithm for GO is described in detail in section 3.2.

B.4. Noise modelling

Aircraft noise models are widely used for environmental impact assessment, operational procedures assessment and evaluating legal compliance. These models can be classified into non-empirical and empirical models. Non-empirical models, such as ANOPP or PANAM, require very detailed geometry or flight parameters input that are difficult to obtain [33]. Empirical models are based on analysis of historical data.

A commonly used approach, described by ECAC Doc.29, utilizes the Noise-Power-Distance (NPD) tables. The model, developed by the European Civil Aviation Conference (ECAC) is widely used by airports, regulators and researchers to assess environmental noise exposure. The ECAC Doc.29 model makes use of ICAO's Aircraft Noise and Performance Database (ANP) Noise-Power-Distance (NPD) tables, and for a given combination of power and distance, it calculates the noise level based on the

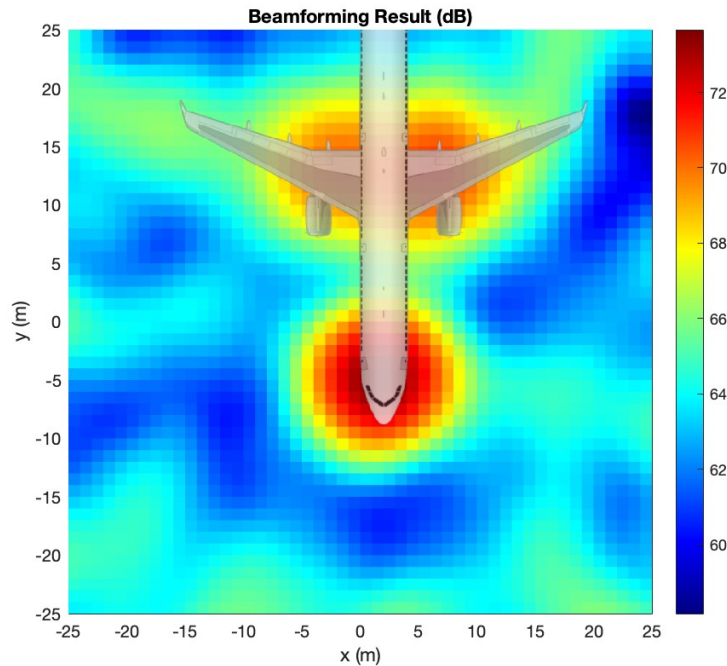


Figure B.2: Example of beamforming result of a Airbus A321 flyover, incoherently averaged between 1500-4500 Hz.

methodologies described by ECAC Doc.29. These tables provide noise value for an aircraft based on the distance and power setting inputs. These models are simple to use but have many shortcomings. For example, aircraft configuration is not accounted for, and different aircraft types are generalized to spectral classes, which increases the uncertainty for comparison with individual flyovers. Furthermore, the model's accuracy is questionable in low-noise regions, since validation is difficult due to measurement stations registering fewer aircraft events [22]. Details on the ECAC Doc. 29 model is discussed in section 3.4.

B.5. Research gap

The literature study on available research papers suggest that current NMTs, which rely on a threshold-based event detection method, are insufficient to monitor aircraft noise, as aircraft often go undetected at distances beyond 3 km [31]. Global Optimization (GO) applied to microphone array measurements offers an alternative method to detect low level aircraft events. However, this capability has not been experimentally quantified. Therefore, the objective of this project is to quantify the detection range of aircraft using GO and identify the trends in detectability based on distance, aircraft type and operational procedures. Furthermore, in existing literature, comparison between aircraft noise measurements and model predictions is mainly done for regions close to the airport [9, 22]. The focus on low noise regions combined with acoustic array measurements, to the author's knowledge, has not been described in the literature. Thus, the measured noise level at large distances are compared to ECAC Doc. 29 prediction to assess the behavior of the model under these conditions in this project.