

# Using a hemisphere noise model to obtain a single event based ground noise prediction for the Apache helicopter

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by

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# Preface

*"If I had to study the most beautiful sound and the most annoying one, it would probably both be a helicopter"*

— Julia Radius, DHC Gilze Rijen

From early ideas on graduation, I knew I had an interest to study noise. I wanted to understand it not just as a physical phenomenon, but also for its societal impact. Talking to C-DHC Robert Adang showed me the willingness of the Dutch military to work on this topic and subsequently, Robert Adang and DHC welcomed me with open arms. He and his colleagues gave me *carte blanche*, always allowed me to freely explore the air force and understand the working of the base and the military. Openly discussing the topic has inspired me. For all this, I'm grateful to Esther Broekman, Major Guusje van Vuuren, C-DHC Robert Adang and all other personnel.

Working to define my thesis subject more precisely and conducting my research, two other organisations came into focus. Casper, which involvement allowed me to source noise measurement data. A special thanks to Heleen Eerkamp for sharing the Casper data with me and thanks to David Heesbeen and Hendrik Hijzen for the support.

Soon as it became clear that the knowledge of noise modelling for the RNLAf is embedded within NLR, a second organisation came on board. Across three departments, I found people enthusiastic and willing to help. Especially due some very peculiar questions, I encountered a large span of people across the helicopter, noise annoyance and defence operations departments. Although various people have helped me, a special thanks goes out to ir. Kylie Knepper, who has been my supervisor for NLR.

This project has been the highlight of my Master of Science in aerospace acoustics -a programme that I have recommended to many people. Education is people, an acknowledgement to prof. dr. Dick Simons for his knowledge, input and enthusiasm over the course of my research. The personal guidance, tailored education and open conversations have shown the best of education. Prof. dr. ir. Mirjam Snellen: you have been great.

Writing these words and finalising my thesis also ends my student days. I'll remember dearly all the amazing people I've met – during courses, projects, and in extracurricular activities – and who've supported me through thick and thin. That gratitude, of course, also goes out to my family and parents especially. You have been the backbone of my support.

*Julia (J.S.M.) Radius  
Delft, May 16*

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# Introduction

Noise annoyance hinders people in their everyday life. This may have adverse health effects, such as stress and sleep disturbance. Aviation also contributes to noise exposure and resulting annoyance, especially when flights pass by noise-sensitive areas such as residential communities. Contrary to for example road or rail noise, aircraft noise does not originate from a fixed location (such as a road or railway), and therefore can also expose quieter areas to noise. Predicting where the noise generated by aircraft is observed is difficult. For example, weather effects can affect the noise propagation path.

Noise annoyance by aviation also extends to defence operations. In order to ensure deployability, constant exercise is required. Some exercises take place at the base, whereas others take place in designated low level flying training areas. The practice itself, transit and the base result in noise production in several areas. The noise caused by military exercises affects more people than just the neighbours.

The RNLAf is working towards reducing noise annoyance. Previously, the impacts of changes in transit flight routes were evaluated using a community survey. However, this evaluates annoyance rather than noise exposure. Also, it is only possible to do this after making such a change.

Predicted noise exposure from a single flight event would make it possible to compare noise exposure from different flight route options. This can help in assessing new routes for lower noise exposure.

More progress in noise reduction for helicopters has been made on the civil side. Design alteration have reduced noise, e.g. casing around the tail fan. Also in noise modelling progress has been made. A model HELENA was developed and tested for the EC135 and showed improvement over NPD tables. In thesis it is assessed whether this model could also be used for military helicopters. Formally, the research objective is defined as follows:

How can HELENA be used to predict ground noise exposure for helicopters of the RNLAf on a single event basis?

In this research, a literature study is performed to understand the origins of the helicopter sound and what is the dominant source behind what is heard by a receiver. Several metrics are assessed in the literature study.

In the thesis part, noise levels from single events (helicopter fly-bys during transit) as recorded by the noise measurement system Casper are compared to values modelled using HELENA. Part I is the paper, a standalone document. Part II contains the literature study which has been previously graded. Lastly, Part III contains information on a test flight that was measured for the Chinook.

**I**

Paper

# Evaluating the suitability of a hemisphere noise model to obtain a single event based ground noise prediction for the Apache helicopter

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Noise quantification methods for helicopters are limited, this especially holds for military helicopters. This research assesses the suitability of an existing civil helicopter noise model for the military helicopters of the RNLAf. In order to achieve this, the noise modelling platform HELENA, which uses hemispheres created for the Apache in a previous project, has been integrated as input data in this research. HELENA has previously been used for civil helicopters. Surrounding the Gilze Rijen Airport, the noise measuring network Casper is installed. From Caspers Noise Measuring Terminals (NMT), noise levels  $L_{A,max}$  and  $SEL$  are extracted for every helicopter that passes by. These values are compared with the calculations from HELENA.

For this research a set of flights has been selected, carefully keeping the limitations of both HELENA as well as Casper in mind. The most ideal flights would be steady, straight, symmetric and repeatable flights. Transit flights departing to or returning from a northeast positioned low-level flying area, encompass most of these requirements. These flights pass three NMTs. For a full year, all Apache flights passing these three NMTs were collected. The formation flights and flights with a maximum  $L_{A,max}$   $dB$ A relatively close to the background  $L_{A,max} \leq 70$   $dB$ A were removed. In total, 108 noise events were selected for the model-calculation comparison. In general, the noise events were underestimated by HELENA. The error, measurement minus calculation, showed a large difference with a mean of  $\mu = 4.9$   $dB$ A and variance of  $\sigma = 2.9$   $dB$ A. Upon closer inspection, the performance varied amongst the NMTs. One NMT (58) had the least noise events after selection but produced the largest difference between measurement and calculation ( $\mu = 8.8$   $dB$ A and variance  $\sigma = 3.3$   $dB$ A). The NMT with the most (70) noise events produced the smallest error with a mean ( $\mu = 4.2$   $dB$ A) and variance ( $\sigma = 2.4$   $dB$ A). The underestimation could be due to certain circumstances that influence the measurement but are not included in the calculation. No correlation could be found for the presence of wind, deviation in speed relative to the speed of the corresponding hemisphere, distance or addition of ground effect.

## Nomenclature

### *Abbreviations*

BVI	=	Blade Vortex Interaction
FANOMOS	=	Flight Track and Aircraft Noise Monitoring System
HELENA	=	Helicopter Environmental Noise Analysis
HIS	=	High Speed Interaction
IP	=	Initial Point
NLR	=	Royal Netherlands Aerospace Centre
NMT	=	Noise Measuring Terminal
NORAH	=	Noise of Rotorcraft Assessed by a Hemisphere-approach
NPD	=	Noise Power Distance
OASPL	=	Overall A-weighted Sound Pressure Level
OSPL	=	Overall Sound Pressure Level
RNLAf	=	Royal Netherlands Air Force

### *Symbols*

$\alpha$	=	Absorption coefficient
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$\Delta$	=	Difference
$\mu$	=	Mean
$\phi$	=	Horizontal angle between helicopter flight path and observer
$\psi$	=	reflection angle
$\sigma$	=	Variance
$\sigma$	=	Ground flow resistivity
$\theta$	=	Vertical angle between helicopter and observer
$c$	=	speed of sound
$dObs$	=	Distance between helicopter and microphone
$f$	=	frequency
$h_m$	=	microphone height
$H0$	=	Origin of helicopter reference system
$H1$	=	Flight path axis of helicopter reference system
$H2$	=	Lateral axis of helicopter reference system
$H3$	=	Downward axis of helicopter reference system
$L_A$	=	A-weighted sound pressure level
$L_{A,max}$	=	Maximum A-weighted sound pressure level
$Q$	=	surface impedance
$r$	=	Distance between source and observer
$r_1$	=	r, direct path
$r_2$	=	r, indirect path
$SEL$	=	Sound Exposure Level
$SPL$	=	Sound Pressure Level
$t_1$	=	begin point in time of integration
$t_2$	=	end point in time of integration
<i>Units</i>		
dB	=	Decibel
dBA	=	dB, A-weighted
Hz	=	Hertz
kts	=	knots

## I. Introduction

LOUD or unwanted noise can be annoying and distract people from essential tasks (e.g. sleeping). If noise annoyance occurs regularly, it may reduce the quality of people's domestic life. In the Netherlands, aviation is the 3<sup>rd</sup> most listed source of noise pollution, following road noise and noise from neighbours [1]. Helicopters produce a strong tonal sound and fly at relatively low altitudes. These characteristics make the contribution of helicopters to noise annoyance caused by aviation, despite their relative to planes lesser movements, substantial [2, 3].

Part of the Royal Netherlands Air Force (RNLAf), the Defence Helicopter Command, has three types of helicopters stationed at the air force base Gilze Rijen. The Apache, Chinook and Cougar are deployed for (personnel) transport, reconnaissance, to attack and to assist in firefighting. To ensure readiness, a lot of training is required. These activities can be divided into three categories: circuit flying around the base to practise landing and take off on the airstrip, exercises with landing on (complicated) spots and team exercises in designated low-level flight zones. The last requires a transit from the air force base in Gilze Rijen towards the low-level flight zones. This transit means that en-route villages are exposed to noise of a helicopter flyover.

The dense population of the Netherlands is a complicating factor in finding noise-abating transit routes. In a recent noise nuisance diminishing project, an Initial Point (IP) was relocated. Aircraft flying from Gilze Rijen to low-level flight zone Oirschot now evade the centre of the village Haghorst relieving the inhabitants of noise. A year after the implementation of the new route, the new routes were evaluated by questioning the inhabitants. The relocation of the IP has effectively reduced noise annoyance experienced by the inhabitants of Haghorst [4].

However, evaluating a noise-reducing measure by questioning is extensive and imposes a risk: noise annoyance is not directly in line with the level of sound [5, 6]. Next to that, it should not be omitted to mention that in the case of Haghorst the alternative route was already clear. However, this may not always be the case. In some scenarios, an alternative route is not yet found or several options exist. To evaluate a potential noise abatement measure, better insight

can be obtained by separating the evaluation of the noise levels and annoyance due to those noise levels experienced. A methodology to calculate the noise level of a single event received at the ground (ground noise exposure) does not yet exist for the helicopters of the RNLAf. If such a methodology were to exist, it could support the RNLAf in decision making or investigating new proposals concerning noise abatement.

What does exist is HELicopter Environmental Noise Analysis (HELENA), a rotorcraft environmental noise analysis tool. HELENA uses acoustic hemispheres to compute noise footprints on the ground. This methodology worked for the EC130 and EC135 [7] and showed an improvement over using NPD (Noise Power Distance) tables. Currently, HELENA is being further developed into NORAH (NOise of Rotorcraft Assessed by a Hemisphere-approach), a newer helicopter noise model for a set of eight civil helicopters [8].

The objective of this study is to research the opportunity of a ground noise helicopter model based on HELENA for the helicopters of the RNLAf. The first section describes the noise produced by a helicopter flyby. Then the model HELENA is described and the measuring network is reported. The setup of the comparison is described in methodology. Finally, the results are discussed and recommendations are made.

## II. Modelling noise of a helicopter

In this chapter it is explained how the general noise theory is applied to the passage of a helicopter. Then it is described how HELENA models this.

### A. Noise Theory

As a helicopter approaches, a receiver will experience an increase in sound level followed by a decrease in sound level. The total sound level received by an observer is the summation of different sound waves that arrive at the receiver at one instant. Each of those sound waves has a different strength and frequency and is emitted at a certain time, from a certain location and in a certain direction. As sound waves propagate through the medium between the source and the observer, energy is lost. Furthermore, waves might be reflected by the ground or other surfaces. What is heard by a receiver is thus a summation of waves arriving directly from the source and waves having travelled an indirect path. The expression below, shows how these three parts make up the sound level, known as the Sound Pressure Level ( $SPL_{r=1m}(\theta, \phi, f)$ ).

#### Sound Pressure Level = Source + Propagation Loss + Ground Effect

This Sound Pressure Level contains the energy for a certain frequency or a range of frequencies. A frequency band analysis sorts the energy per band, a range of, frequencies. In this research the 1/3<sup>rd</sup> octave band analysis is used, where 24 frequency bands are used. The frequency bands can be found in the appendix. Most noise energy of the helicopter is present in the lower frequencies. Sound that has a large presence of energy on a certain frequency is described as tonal, if the energy is more spread the term broadband is used.

To get to one value for the sound, the  $SPL_{r=1m}(\theta, \phi, f)$  levels of each band can be added. This can be done counting each  $SPL_{r=1m}(\theta, \phi, f)$  equally, the Overall Sound Pressure Level (OSPL) is then unweighted. If the A-weighting is used, the frequencies are added according to the equal loudness to the human ear. Then the Overall A-weighted Sound Pressure Level (OASPL) is calculated. Noise levels are often expressed as  $L$  or  $L_A$  depending on the weighting. The maximum noise level of a noise level is expressed as  $L_{max}$  or  $L_{A,max}$ . This is the loudest Overall (A-weighted) Sound Pressure Level perceived in a noise event, usually at the closest distance between source and receiver.

For the flybys discussed in this paper, the only source of the sound waves is a helicopter. The following sections each explain one part of the expression.

#### 1. Helicopter as a noise source

The main rotor causes the majority of the sound of a helicopter [9]. The sound created is a result of the interaction with the surrounding air and varies per flight condition. This is due to the presence of aerodynamic phenomena that occur in certain flight conditions. The ones always present are thickness noise and loading noise. When a rotor blade passes through air, mass is displaced. The noise that this gives is described as thickness noise [10]. The blade has a loading (it is keeping the helicopter in the air) and gives momentum to the air it passes. This results in loading noise.

Some phenomena occur only in certain flight conditions. Two phenomena that become the dominant source of noise when they occur are BVI (Blade Vortex Interaction) and HSI (High Speed Interaction). These much researched (for example: BVI: [11–14] and HSI: [15–17]) phenomena occur when the main rotor blades fly through the vortex (BVI)

created by a previously passed blade or when the tip speeds of the blade reach transonic speeds (HSI). A helicopter in slow descent is likely to have BVI. This interaction with a vortex also often occurs in turns, depending on the acceleration [18]. HSI only occurs when tips of the blades reach transonic speeds, which only happens if the helicopter has a very high speed. These velocities are outside the normal operating range for the RNLAf helicopters.

A helicopter emits sounds in all directions. However, for a helicopter, the frequencies present and the amount of energy in those frequencies of the sound emitted varies over the angles  $\theta$  (inclination angle) and  $\phi$  (angle between the direction of the helicopter's nose and projection of distance between observer and helicopter), see Figure 1. This means that for every angle ( $\theta$  and  $\phi$ ) between the receiver and helicopter there is a specific source level. The source level of the helicopter is expressed per angle and noted as  $SPL_{r=1m}(\theta, \phi, f)$ . The source level in the hemispheres used for HELENA is expressed as a  $1/3^{\text{rd}}$  octave band analysis.

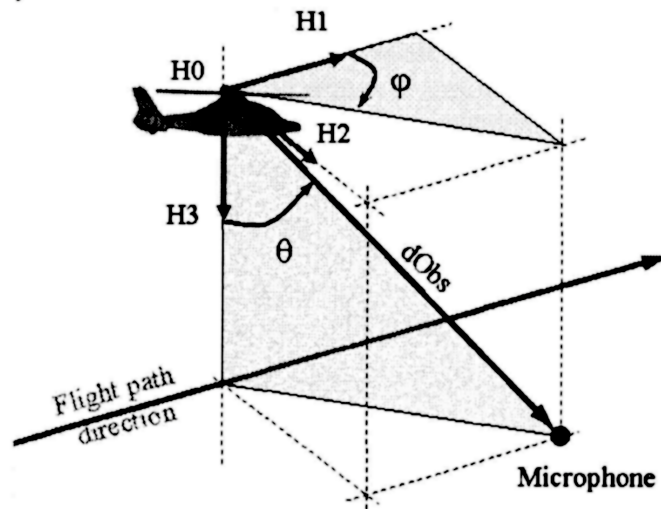
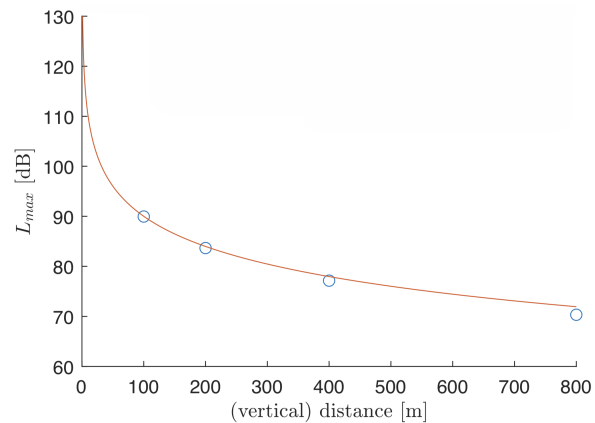


Fig. 1 Coordinate system used in HELENA [7].

## 2. Propagation

After the helicopter produces the sound energy, the energy is propagated toward the receiver. Some energy is lost in this process. The loss of energy is expressed in two terms:  $20\log(r)$  and  $-ar$ . These two terms determine the loss of sound level due to propagation over a distance. The helicopter is modelled as a point source and the (sound) energy thus spreads over a larger and larger sphere. This means energy reduces over distance ( $r$ ) with  $20\log(r)$ . For the helicopter passages in this study, the distance between Noise Measuring Tower and the helicopter at the closest point ranges between 150 metre and 2000 metre. For these (relatively) short ranges combined with the presence of mostly lower frequencies, the loss due to spreading is typically in the range of 25 – 10 dB.

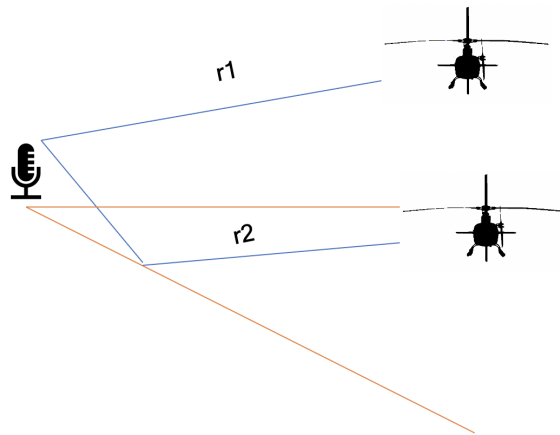
In Figure 2, four measurements of a directly overhead Apache Longbow (H64) helicopter are plotted against an analytical approach. For the analytical approach, the ( $1/3^{\text{rd}}$  octave) frequency band analysis of an overhead Apache is used. The calculated Sound Pressure Level (at 1 metre distance) is then propagated by only regarding the loss due to spherical spreading. The  $L_{max}$  measurements include all effects and thus show the effect of including the atmospheric absorption. The differences are minimal for ranges below 800 metres for sound sources with mostly low frequencies.



**Fig. 2** Unweighted sound pressure level for different ranges comparing four measurements with  $OSPL - 20 \log(r)$ .

### 3. Ground Effect

Sound is the result of all sound waves arriving at one instant at a receiver. In this research, it is assumed that all sound waves considered originate from an Apache helicopter. The sound waves arriving at one instance may all have travelled a different path. Amongst these waves is a direct path and a path that has reflected on the ground. The reflected sound may complicate the interpretation of sound measurement [19]. This is the so-called ground effect. The microphone is placed at an altitude above the ground (in this case 1.2 metres), and thus sound waves may reflect on the ground and then travel to the microphone.



**Fig. 3** Sketch of geometry of a helicopter flyby. Apache seen from behind with  $r_1$  the direct path and  $r_2$  reflected via the ground.

This reflected path adds to the Sound Pressure Level. The maximum addition due to the presence of a (single) reflected path (on top of a direct one) is 6 dB. To calculate the  $\Delta SPL(r, \theta, \phi, f)$  due to reflection with the ground the following needs to be known:

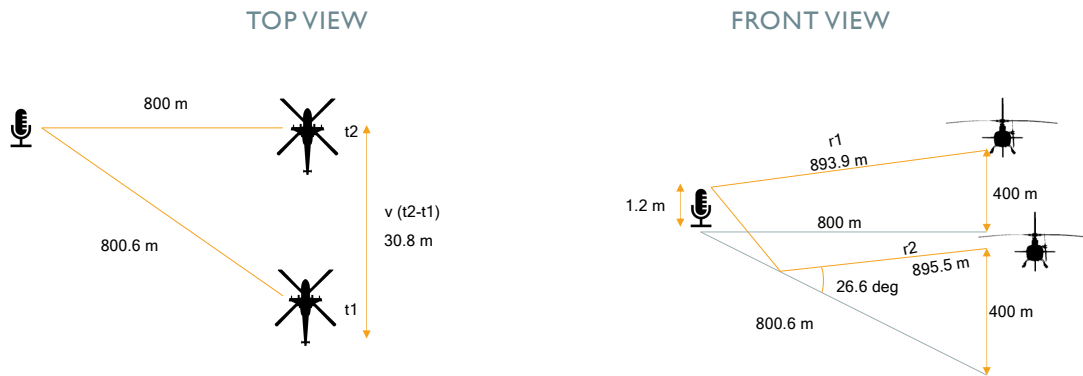
- $r_1$  length of direct path
- $r_2$  length of the reflected path
- $Q$  surface (impedance) of ground where wave reflects
- $f$  frequencies present in sound wave
- $c$  speed of sound
- $h_m$  height of the microphone (1.2 metres)

- $\psi$  angle of reflection
- $\phi$  phase change of sound wave

$$\Delta \text{SPL}(r, \theta, \phi, f) = 10 \log \left[ 1 + \left( \frac{r_1}{r_2} \right)^2 |Q|^2 + 2 \left( \frac{r_1}{r_2} \right) |Q| \cos \left( \frac{4\pi f}{c} h_m \sin \psi + \phi \right) \right] \quad (1)$$

When the position of the helicopter at the time of emission of the direct path and indirect path is established, the path lengths and angles can be calculated. However, the surface properties of the ground at the wave reflection may remain unknown. For direct flyovers, this is the surface on which the microphone is located. However, for more (horizontally) distanced helicopters, the location of the reflection may be several metres away.

For the following situation, Figure 4, the ground effect is calculated. A helicopter flies at an altitude of 400 metres and an 800 metre offset along a microphone at 1.2 metres height. From geometry  $r_1$ ,  $r_2$  and the angle of the reflection ( $\psi$ ) can be obtained. The speed of sound is assumed to be  $340\text{m/s}$  and the phase change ( $\phi$ ) is neglected. The  $\Delta\text{SPL}$  is calculated for four frequencies, as these are the centre frequencies of  $1/3^{\text{rd}}$  octave bands with a high amount of sound energy. The last variable is the impedance of the surface where the indirect wave reflects. The surface properties of this location are unknown. The impedance can be estimated with the Delaney and Bazley model [20] or [19, ch. 3.5]. This model is valid for fibrous absorbent materials [19] and only uses the parameter for flow resistivity  $\sigma$  in  $\text{kPasm}^{-2}$ . The Apache helicopter has more sound energy in the lower frequencies\*. The following graphs show the  $\Delta\text{SPL}$  for grass ( $\sigma = 250\text{kPasm}^{-2}$ ) and concrete ( $\sigma = 750\text{kPasm}^{-2}$ ). As can be seen in Figure 5, the  $\Delta\text{SPL}$  values for a reflection on grass and concrete for the same frequency and angle are very similar.



**Fig. 4 Sketch of geometry of the helicopter flyby in the example discussed. Apache seen from behind with  $r_1$  the direct path and  $r_2$  reflected via the ground.**

For the example in Figure 4,  $Q = 1$  is assumed. The values are then calculated for 50Hz, 63Hz, 80Hz and 100Hz. The values here are compared to the method used by the model which is explained in the next section.

**Table 1  $\Delta\text{SPL}$  calculated with theoretical method from [19] and the NAU soroka method.**

Method	Frequency			
	50 Hz	63 Hz	80 Hz	100 Hz
Equation 1	4.8	4.0	2.6	0.2
NAU Soroka	3.6	2.4	0.4	-2.9

\*For details or source, contact author.

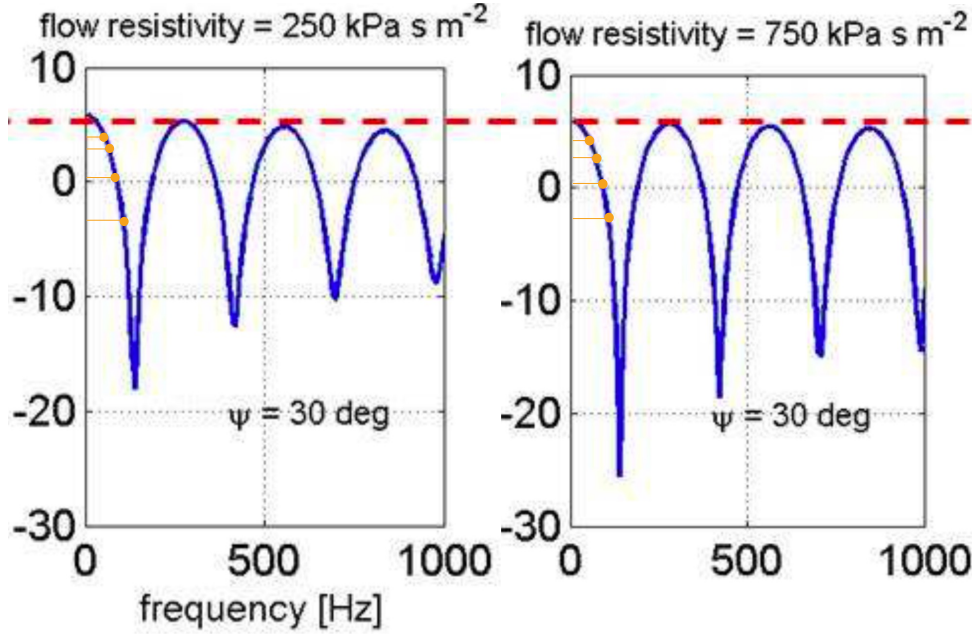


Fig. 5 Ground effect calculated for a  $\psi$  of 30 deg. The difference for the two surfaces is minimal [19].

Previous sections have explained the three parts of Equation 2, the noise theory equation from [19]. The next part will explain how a model calculates the  $SPL(r, \theta, \phi, f)$  values.

$$SPL(r, \theta, \phi, f) = \underbrace{SPL_{r=1m}(\theta, \phi, f)}_{\text{source}} - \underbrace{20\log(r) - \alpha r}_{\text{propagation}} + \underbrace{\Delta SPL(r, \theta, \phi, f)}_{\text{ground effect}} \quad (2)$$

## B. Modelling with HELENA

Part of the Friendcopter European research project, a software platform called HELENA, was designed to provide high accuracy rotorcraft noise predictions [7]. To include directivity, for each flight condition a hemisphere is used. This means that the usability of HELENA is directly linked to the available hemispheres. HELENA has two versions, a research and a public version. For this study, the research version is used. This research version contains a platform in which different modules can be added. HELENA is run in Fortran.

HELENA calculates for a chosen frequency the sound pressure level for every microphone of a fictive microphone grid. This sound pressure level can then be further calculated into a metric. In this project, the goal is to compare these values with measurements.  $L_{A,max}$  and  $SEL$  are metrics both available for HELENA as well as Casper. The following sections will explain what these metrics are and how HELENA calculates these values.

### 1. Metrics

The purpose of developing a method to determine ground noise is to compare flown tracks and see which one creates the least amount of noise at a certain location. In order to perform a comparison, noise events need to be quantified. Many metrics have been developed, see literature study chapter 3.2, but generally, the duration and the maximum level are often used to compute how “intense” or “heavy” the noise event was [21]. The maximum noise level of an event can help classify how loud an event was. For it to be heard, the maximum level needs to be above the background noise level. For an awakening or even a highly disturbed sleep, much higher levels are required.

However, the sound energy is spread over several frequencies. To establish the Overall Sound Pressure Level some options are available on how to add the  $SPL(r, \theta, \phi, f)$ . As humans have selective hearing, some frequencies will be experienced as louder even though in  $dB$  there is no difference. Thus, to account for the frequency dependent sensitivity of the human ear the A-weighting [19] is applied. This metric is fairly easy to model and process as each noise event can be brought down to one value. However, as just one value is selected to represent the whole noise event, this metric

is sensitive to errors. An error in the position of the helicopter at the moment where the helicopter is the nearest to the microphone for example could give a wrong  $L_{A,max}$ . The A-weighting corrects more strongly for lower frequencies (20-100 Hz) than for the centre (500-2000 Hz) frequencies. It is in these lower frequencies that the helicopter holds more (noise) energy. The combination of a strong tonality and a very typical sound (hard to ignore) raises the question if this A-weighting does not detract from the (experienced) loudness of the helicopter. More inclusive metrics and methodologies exist [22], however, these are not yet implementable for HELENA and will not be considered for this research.

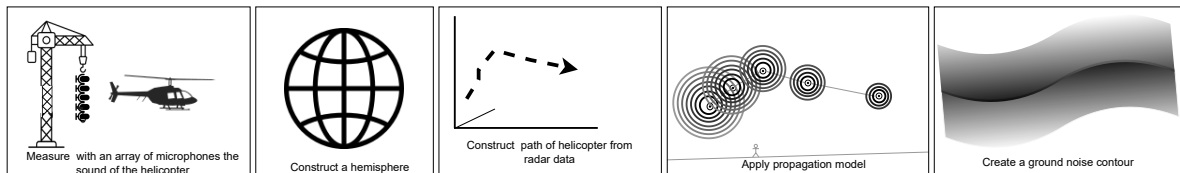
The  $SEL$  is obtained by integration of the A-weighted sound level ( $L_A$ ). HELENA starts the integration at the “10 dBA downtime”. The moment in time where the integration starts is denoted as  $t_1$ . This is the point in time where the  $L_A$  is 10 dBA lower than the maximum measured  $L_{A,max}$ . Then, the first point after  $L_{A,max}$  where the  $L_A$  is 10 dBA lower again is taken as  $t_2$  of the integration. The integration of a noise event makes it possible to compare events of different duration. It also provides a more robust metric: small deviations (wrong position, variation in speed) will not influence the  $SEL$  easily.

## 2. How does HELENA work?

In short: HELENA attaches a hemisphere to a position from a flown track and propagates the sound to a (fictive) microphone grid on the ground. In order to obtain  $L_{A,max}$  and  $SEL$  for a (fictive) microphone at a certain location the user has to:

- 1) Obtain acoustic hemispheres of the noise source
- 2) Define the surroundings and create a grid
- 3) Reconstruct the flight path in an input file
- 4) Run HELENA and calculate noise levels for each microphone
- 5) Retrieve metrics from calculations

The first step has already been done in a previous project. The hemispheres originate from a project that was finalised in 2008<sup>†</sup>. For the measurements, a 100-metre array was used to capture the acoustics of the RNLAf helicopters [23]. Due to the different nature of the project for which the hemispheres were recorded, more side angles were measured than conventional. The weather conditions were non-ideal for measuring, which may have influenced the hemispheres. During the measuring of the hemispheres, the non-ideal weather led to a small concern with reproducibility as differences up to 3 dB were in between measurements seen.



**Fig. 6 Overview of helicopter noise modelling using hemispheres.**

The second step is to define the surroundings of the location where the helicopter has flown. This is done by describing the medium through which the sound propagates, choosing methodologies on how to calculate the propagation and ground effect and defining a grid where the (fictive) microphones are located. In a parameter definition file (pdf) the user defines parameters and choices that are required for the calculations, e.g. height of the microphone. Then from an available set, methodologies can be chosen. In this study, methods were chosen for

- Atmospheric Propagation/Attenuation
- Ground Reflection
- Hemisphere method
- Format of output files (which metrics are calculated for the microphones)

The atmospheric input file (atm.txt) requires the user to insert values of parameters that describe the surroundings (atmospheric temperature, ambient pressure etc). For atmospheric attenuation, hemisphere method and output files, the default settings were used. In the default mode, no ground reflection is calculated. In this study, the NAU\_Soroka

<sup>†</sup>Contact author for source

ground reflection model [24] was chosen because it was the only one for which documentation was found. This module is added to HELENA and calculates the  $\Delta SPL(r, \theta, \phi, f)$  for each frequency band. In a later stage, the calculated values will be compared with measurements from microphones. The location of these (real) microphones is fixed. In order to accurately compare fictive microphones need to be placed as close as possible to the location of the real microphones. For this study, a grid was defined that encompasses Gilze Rijen airport and all microphones surrounding it. The grid is a 6 by 7 kilometre grid with a microphone every 100 metres. This means that the grid has in total 5751 (fictional) microphones.

### 3. Input file

To recreate the flown track in the input file the positions need to be listed. For every position, a hemisphere should be selected. Ideally, this hemisphere represents the flight condition at that position point.

The position points are retrieved from FANOMOS (Flight Track and Aircraft Noise Monitoring System), a program developed by NLR. The radar position points have a four-second interval, which is an industry standard. The radar data is assembled from three radar towers as the airport of Gilze Rijen does not have one. This comes with a disadvantage: radar height. Due to the curvature of the Earth's surface and the distance of the radar towers (Eindhoven, Woensdrecht and Rotterdam), flights below 300ft are technically not seen. The altitude of the aircraft is not measured by the tower but is derived from pressure data measured on board of the aircraft. However, due to the radar height this information does not arrive. This means that technically aircraft flying at a height lower than 300ft are flying below radar and miss position points in tracks recorded by FANOMOS.

As a consequence of this radar height, flights flying below 300ft are likely to have inaccuracies. Flights such as landing exercises on the base, take-offs and landing are thus not suitable for this noise modelling research as part of their FANOMOS tracks are missing. The transit flights are not likely to fly below 300ft.

To each position point a hemisphere should be connected. The available hemispheres are:

**Table 2 Overview of hemispheres available for RNLAf.**

	Forward				Descending		Climb
	20 kts	60 kts	100 kts	120 kts	80 kts	120 kts	120 kts
Apache	✓	✓	✓	✓	✓	✓	✓
Cougar	✓	✓	✓	✓			
Chinook	✓	✓	✓	✓	✓	✓	✓

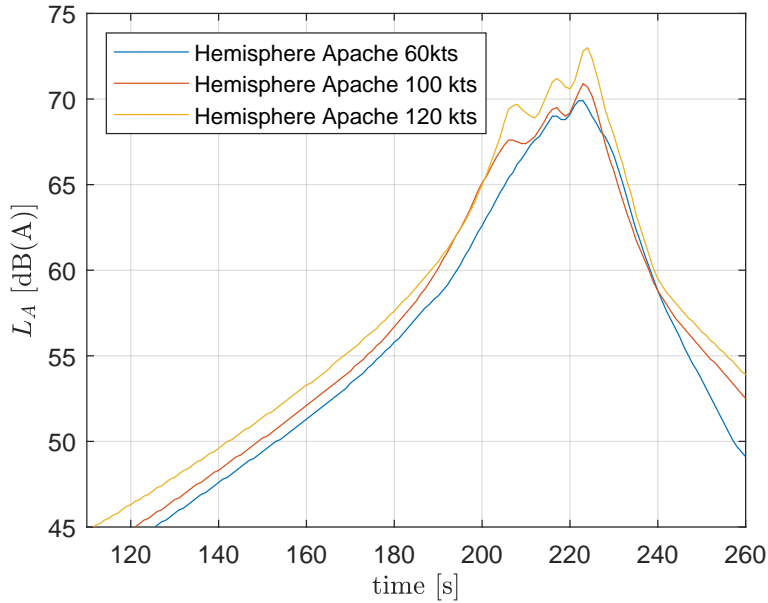
To choose the right hemisphere the velocity at every position should be known in direction of the flight path and in the vertical direction. For the transit flights it is assumed that the altitude remains the same and thus the vertical velocity is assumed to be negligible. Then four hemispheres remain. In order to choose between them two questions are relevant:

- Can the speed of the helicopter be accurately obtained?
- Are the differences in sound energy amongst the hemispheres significant?

FANOMOS provides a speed for every measured point. However, considering that this speed is derived from positions with a 4 second interval, this speed is not of high accuracy. For a transit flight, the speed is expected to be between 60 and 120 kts. In practice, flights with 140 kts speed exist. The measurement system Casper also gives the speed at the nearest position. This speed showed disagreements with FANOMOS. For now, it was chosen to not use the speed to select a hemisphere, but to assume one constant speed for all flights. It is then to be researched if an error can be correlated to this assumption.

If one hemisphere is selected to model all flights, the differences amongst these hemispheres should be known. To see the difference between a 60 kts, 100 kts and 120 kts hemisphere, the noise for an 80 kts straight steady flight was calculated with all hemispheres. The result shows that for the Apache, the  $L_{A,max}$  and the  $SEL$  are very similar for the 60 kts and 100 kts hemisphere. The 120 kts hemisphere shows a nearly  $2dBA$  difference for the  $L_{A,max}$ . This raises a concern for flights with a velocity higher than 120 kts, as there are no hemispheres available for these velocities. For these speeds, no information on the noise is known. Looking at Figure 7 it is clear that the relation between noise produced and speed is not linear. There is no standard velocity prescribed for the transit route. A variety of speeds (60

kts-140 kts) was seen in the data. For now, it was thus decided to model all flights with the 60 kts hemisphere. Part of this research will be to see if this underestimation of velocity contributes to an underestimation of noise.



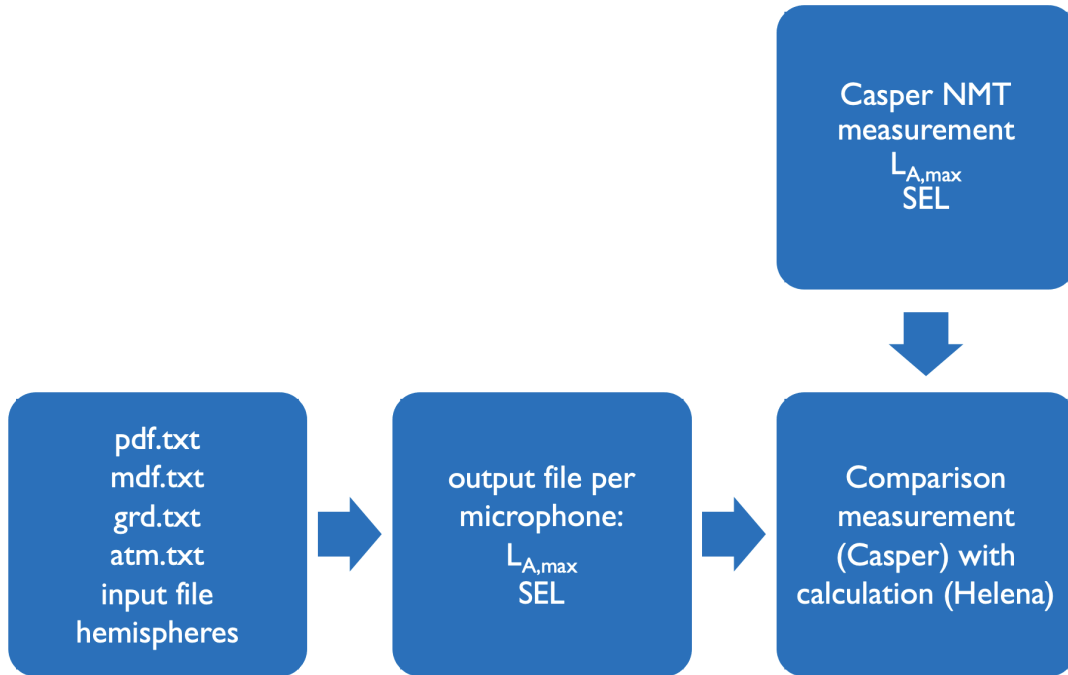
**Fig. 7 Modelling a 80 kts flight with a 60 kts, 100 kts and 120 kts hemisphere.**

#### 4. HELENA calculation

After the environmental conditions have been defined and the track is reconstructed, HELENA calculates the noise level for each moment in time for each microphone on the grid. This requires HELENA to establish the distance and angles between each microphone and the helicopter for each moment in time. HELENA needs to find the  $dObs$ , the distance between the helicopter and microphone, and the angles  $\theta$  and  $\phi$ .

The helicopter has a fixed orthogonal system with H0 as origin, H1 in line with the flight path, H2 pointing orthogonal to H1 in the lateral direction and H3 pointing downwards, see Figure 1. Between the H0 of the helicopter and the microphone, the vector  $dObs$  is drawn.  $\theta$  is the angle between H3 (pointing down) and the  $dObs$ . The angle  $\phi$  corresponds to the angle between the H1, in line with the flight direction, and the projection of  $dObs$  on the ground.

When the angles  $\theta$  and  $\phi$  have been established, HELENA will read the hemisphere and find the corresponding (1/3<sup>rd</sup> octave) band level. HELENA does not interpolate between angles, in order to minimise the chance of non-physical behaviour [7]. After the source level is established, the propagation loss is calculated with the default methodology SAE\_ARP866A\_R [25]. Then the NAU\_Soroka methodology [24] is used to calculate the ground effect.



**Fig. 8 Overview input and output files to obtain comparison.**

### III. Measurements

The goal of this study is to see if a methodology can be found to predict ground noise levels for a single flight with a military helicopter. Provided is the helicopter noise model HELENA which has been used before for the noise modelling of civil helicopters. For the helicopters of the RNLAf, there is no set of measurements or previous model available to validate. However, surrounding the base, a noise monitoring network is installed. The measurements of these installed Noise Monitoring Towers (NMTs) are used to compare the calculations to.

This section will elaborate on Casper, the noise measuring network and will go into depth on the measurements used in this research.

#### A. Casper

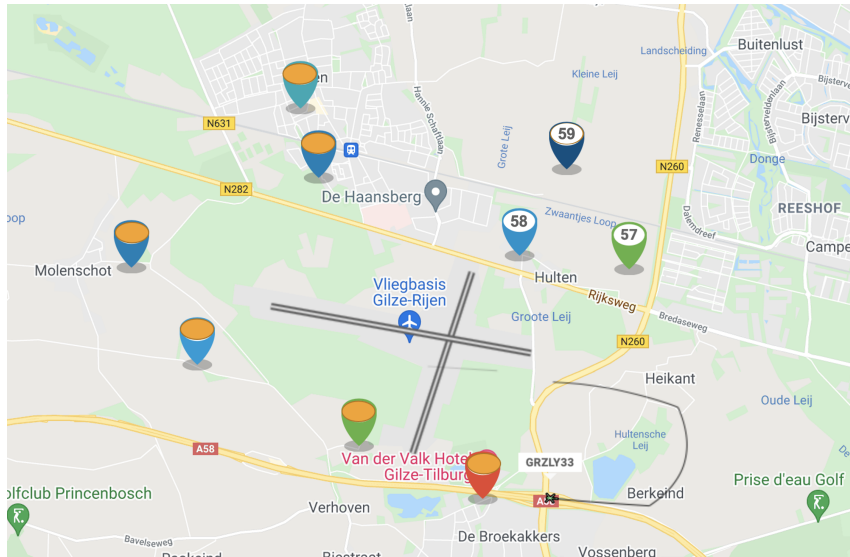
Casper is a company that delivers an airport noise monitoring system. This system provides continuous measurements of noise caused by aircraft. The resulting noise levels are published on the (publicly available) website<sup>‡</sup>. On this website, inhabitants of nearby communities can watch real-time noise levels at every NMT. The noise measuring networks have been installed at several airports, both civil as well as military. The platform aims to inform residents and has not yet been used for scientific research.

Around the airport of Gilze Rijen, nine Noise Monitor Terminals (NMT) are installed. The microphones are class 1 and have an accuracy of 0.7-0.9 dB [26]. Keeping background noise and reflection in mind, NLR advised on the location and installation for seven of the NMTs [27]. The other two NMTs (59 and 51) were put in a location that was perceived as very noisy by the residents. The locations of the NMTs can be seen in Figure 9. NMT 59 has been located north of Rijen since February 2021.

Compared to civil airports, Gilze Rijen airport has much more functionalities. The helicopters do not just depart or land but also circle around the airport or perform landing exercises. This makes the process of determining whether a noise event is connected to a helicopter different than for a regular airport.

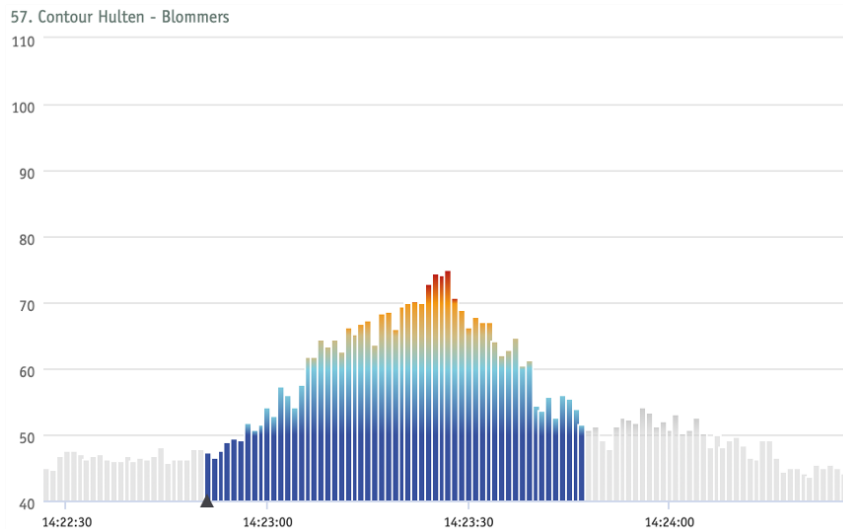
The microphone of the NMT is constantly on. For a noise event to be created a number of conditions have to be met: the noise event must be longer than the selected minimum duration, the value of  $SEL$  must be higher than the  $L_{A,max}$  set by the minimum threshold, and the  $SEL$  must not exceed the value of  $L_{A,max}$  set by the maximum threshold. This

<sup>‡</sup><https://glz.flighttracking.casper.aero>



**Fig. 9 NMT network surrounding Gilze Rijen airport.**

range of how much the  $SEL$  should exceed the  $L_{A,max}$  differs for each NMT. An example is provided in Figure 10. Here the  $L_{A,max}$  is  $75.4 \text{ dBA}$  and the  $SEL$  is in the range of  $78.4 (75.4 + 3) \text{ dBA}$  (minimum threshold) and  $88.4 (75.4 + 13) \text{ dBA}$  (maximum threshold).



**Fig. 10 Example of the resulting  $L_A$  derived from a Casper measurement.**

When a noise event is created, the time interval in which the noise was measured is saved. This is then used to search for nearby helicopters on the radar track. If multiple tracks are found, the most nearby one is chosen. However, this primary matching method does not catch all helicopters. Thus for any approaching or departing helicopter, it is checked if they are already linked to noise events. When they are not, noise events in the corresponding time range are checked for helicopter characteristics and matched if positive. If a noise event exists for which no helicopter can be found and the  $L_A$  level exceeds  $50 \text{ dBA}$  then the noise event is saved.

Each NMT is placed in a different location. This implies that their local surroundings are different. Locations are chosen with noise monitoring in mind. But, measuring noise in a community risks measuring noise from the community.

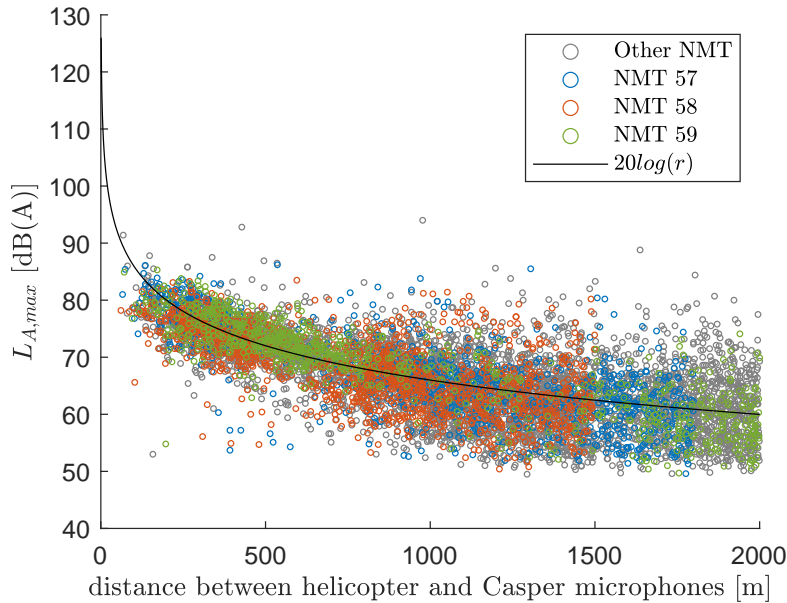
The NMTs are calibrated to capture helicopter noise events. This means that each NMT has their own settings, see Table 3.

**Table 3 Overview of noise event settings per NMT.**

NMT	Range $SEL > L_{A,max}$ [dBA]	Minimum duration [s]
57	[+3 +13 ]	5
58	[+3 +13 ]	10
59	[+10 +13 ]	5

### B. Measurement obtained with Casper

The figure below shows all noise events obtained with NMT 57, 58 and 59 separated from other noise events obtained by other NMTs. Noise events with no distance measured were removed. The  $OASPL(r, \theta, \phi) - 20\log(r)$  is plotted to show how much the results of Casper correspond with the (simplified version of) noise theory. Other aspects, atmospheric attenuation, ground effect or measurement inaccuracies are not addressed by the  $20\log(r)$  line. Next to that, the distance provided by Casper may have inaccuracies. This could be due to the difference between the actual altitude of the helicopter and the pressure altitude, the 4-second interval, or a match with the wrong helicopter.

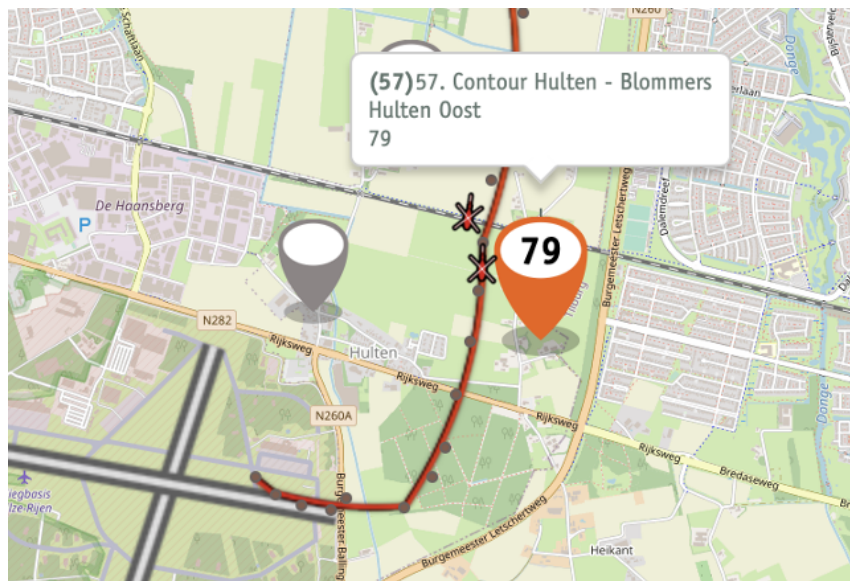


**Fig. 11 All measurements from NMTs in 2021 with the used NMTs highlighted.**

### IV. Choosing the right flights to compare

Previous sections explained how HELENA and Casper work. In order to get a fair comparison, a set of flights need to be selected. The set must respect the limitations set by HELENA and Casper. This does not mean that either of them does not function in expressing noise in the metrics  $L_{A,max}$  and  $SEL$  but since both the systems were not designed with this case study in mind, caution is required. In particular, the usage of a continuous measuring system for the measurement of single events asks for precaution. An unmanned monitoring system might not notice an invalid measuring situation. It cannot be known beforehand how many of these invalid situations are present in the selected flight set.

In some scenarios, the accuracy of noise quantification at a noisy location does not directly transfer to the accuracy of the quantification of noise that can be assigned to single contributors. In some situations, the noise events individually are influenced by the situation rather than the result of one helicopter passing. An example of this is formation flight. When two helicopters fly close to each other, often during a transit towards a low-level flying area, they cause a significant noise event. In a measurement, this appears as a very loud noise event followed by a smaller one. Casper will assign the first noise event to the most forward flying helicopter and the second one to the following helicopter. It might also happen that Casper assigns both noise events to the forward flying helicopter. This is not wrong for a monitoring system, as it expresses what noise was perceived at a certain location. However, it provides an incalculable scenario for HELENA (which cannot yet model multiple aircraft). As an example, in the situation depicted in Figure 12, the forward flying helicopter caused a noise event with  $L_{A,max}$  of 78.8dBA and a  $SEL$  of 89.8dBA. The helicopter flying behind did not create a noise event at NMT 57. From inspection, it can be seen that the noise event can not be associated to one helicopter.



**Fig. 12 Two Apache flying in formation next to NMT 57.**

Choosing transit flights comes with a number of advantages:

- all flight conditions are represented by the available hemispheres
- high likelihood of constant speed
- straight and symmetric flight
- they are (likely) above radar height
- above sea level
- less likely to carry additional loading
- more representation: more similar flights
- multiple NMTs measure noise events of the same flight (NMT are in line)
- transit of flights occur throughout the year, spread in seasonality (fire fighting only happens in one season), other exercises may be bound to educational programs

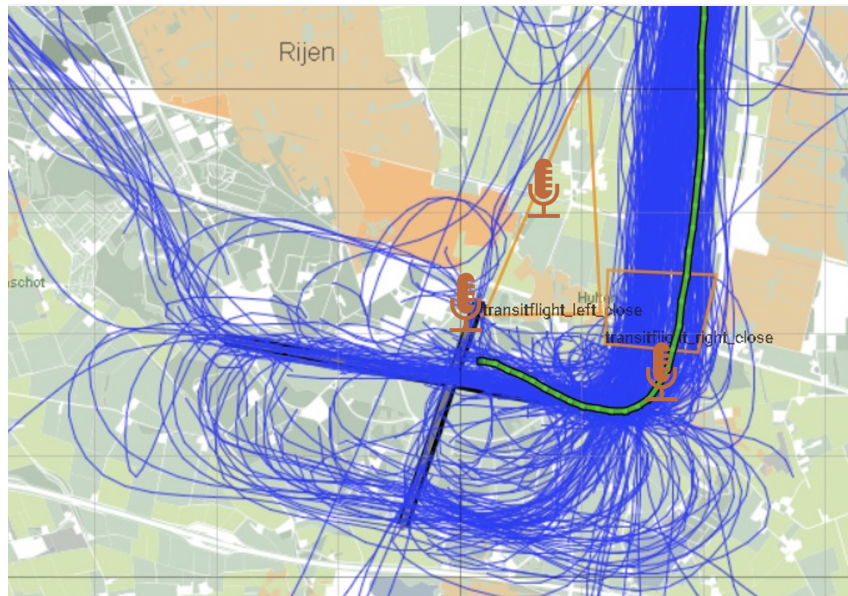
However, transit flights come with a major drawback: often formation flying is present. Thus in the selection process, it was required to build a filter to avoid measurements corresponding to formation flights. These requirements were made beforehand. In a later stage of the flight selection, it appeared that flights with an  $L_{A,max}$  lower than 70 dBA were often influenced by background noise. By manual inspection, it was often found that the helicopter, in such a case was further away and the background noise was relatively close to  $L_{A,max}$  (peak) of the event. For the NMT it then appears as if the helicopter caused a long noise event. This results in a high  $SEL$ . In reality, the helicopter either flew at a great distance or made a circular movement (e.g. a turn as part of the circuit flying) resulting in a short noise event. The cause of these misinterpretations is likely related to a relative noisy background (nearby roads, train transport and airport). Sometimes two noise events were linked to one flight. The NMT has then likely cut the noise event in two. These noise

events were also removed.

Lastly, each noise event was manually inspected. Some unfortunate situations were discovered. Mostly, another aircraft was nearby and thus also contributed. In some scenarios, multiple (military) helicopters were measured at the same time. The NMTs (especially 58) are close to the transit route as well as the circuit flying. It may occur that on both routes multiple helicopters are flying (and are heard) simultaneously. Finally, 108 noise events were selected caused by 75 flights.

### Selection and matching of flights

FANOMOS provides an application in which flights can be loaded. These are then displayed on a map. Before any filters were applied, all Apache flights from the year 2021 were loaded. To select only the transit flights, two spatial objects were constructed. These objects are shapes that can be two- or three-dimensional and can be used to create a filter. The goal is to select the transit flights departing towards or returning from the low-level flying area Maas en Waal and who passed NMT 57, 58 and 59. Two shapes are created, the first one (`transitflight_right_close`) the flights must have flown through and the second one (`transitflight_left_close`) the flight must not have flown through. After using this method of selection 230 flights were selected.



**Fig. 13** Two spatial objects in FANOMOS defining the MUST NOT and MUST fly through zone.

The first spatial object (`transitflight_right_close`) confines the space where a passing helicopter is very likely to have been observed by the (selected) NMTs. This means that the moment at which the helicopter crosses the border of the spatial object is likely to be close in time to the moment that the helicopter is observed by the microphone. This creates an opportunity to match the flight to the noise event based on these two moments in time.

After loading all (230) FANOMOS flights into Matlab, a script checked if the moment of entering the (first) spatial object matches with the moment the noise event started. If the noise event started more than 1 minute later or earlier than when the aircraft entered the spatial object, it was removed from the selection. For the final set of noise events, a HELENA input file was created for each corresponding flight. After running HELENA, the calculated  $L_{A,max}$  and  $SEL$  were assigned to the noise events. Running HELENA was performed with and without the ground effect. Then all formation flights were removed, resulting in 172 noise events. Removing all noise events below 70 dBA gave a final list of 108 noise events containing both measured as well as a calculated values.

## V. Results

In this chapter, the results from the modelling and measuring are presented. The agreement between the measurements and the modelled results are displayed in subsection V.A. Then, possible explanations for these differences are investigated

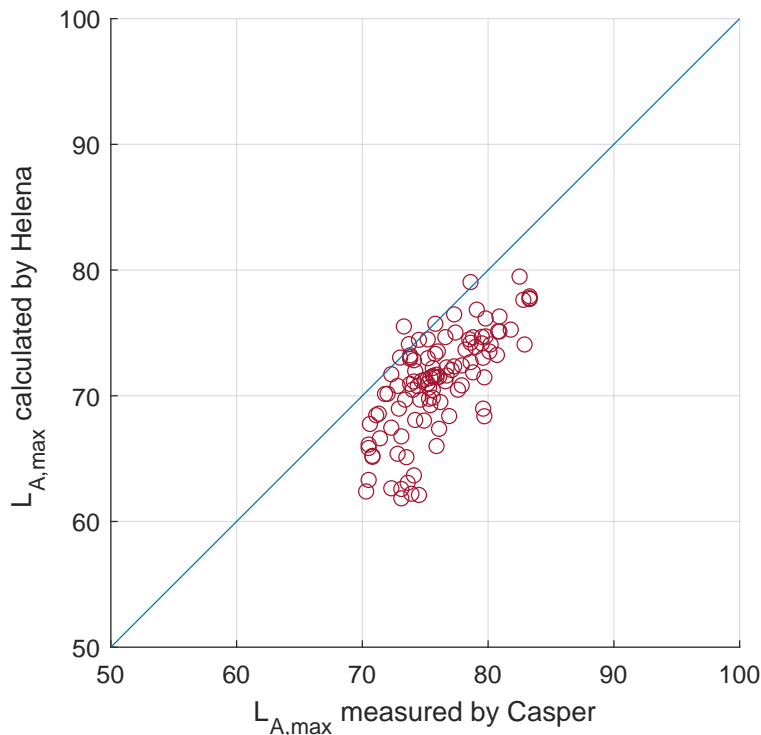
in subsection V.B, subsection V.C, and subsection V.D.

### A. Differences between measurement and calculation

The main objective of this study is to see if HELENA is suitable for the prediction of the noise caused by the Apache helicopter. As a primary metric  $L_{A,max}$  is used. The values of  $SEL$  have also been compared.

#### $L_{A,max}$

In Figure 14, the values of the measured  $L_{A,max}$  are displayed on the x-axis and the corresponding calculations are on the y-axis. The solid line represents perfect agreement. For the majority of the calculations an underestimation is prevailing. The mean difference (of the measurement minus calculations) is  $\mu = 4.9 \text{ dBA}$  and variance is  $\sigma = 2.9 \text{ dBA}$ .

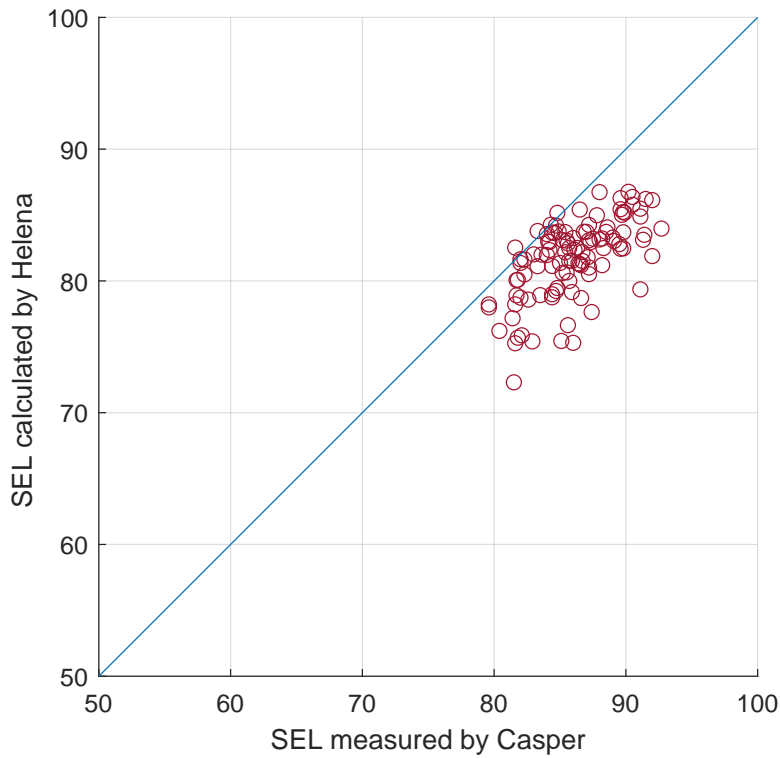


**Fig. 14**  $L_{A,max}$  obtained by measurement and calculation for all 108 flights (ground effect included in calculation).

#### $SEL$

$L_{A,max}$  was chosen as the primary metric because the value can be directly obtained from the measurement. To obtain  $SEL$ , Casper uses a calculation method. This method is different from HELENA as HELENA uses a 10 dB downtime method, whereas Casper keeps on integrating until the  $SEL$  exceeds the  $L_{A,max}$  by a set amount of dBA. However, the advantage of  $SEL$  is that by integrating over the whole event, the metric is more robust. The figure below compares the calculations from Casper measurements with the calculations from noise model HELENA. Despite the different methods, the difference (Casper  $SEL$  - HELENA  $SEL$ ) is smaller than for the  $L_{A,max}$  values. The mean of the difference is  $\mu = 4.3 \text{ dBA}$  and variance is  $\sigma = 2.6 \text{ dBA}$ .

For the next sections,  $L_{A,max}$  will be used as metric. In order to explore whether this deviation is a result of an error in methodology or circumstances, three courses of action were undertaken. First, it was investigated if the difference between measurement and calculation is constant for all the noise events. Perhaps any characteristic of the circumstances



**Fig. 15** *SEL* obtained from measurement and calculation for all 108 flights (ground effect included in calculation).

(e.g. wind) could be correlated. Second, the results were separated by NMT to see if the performance differed amongst NMT. Last, HELENA’s method of calculation was investigated for sensitivities with a focus on the ground effect.

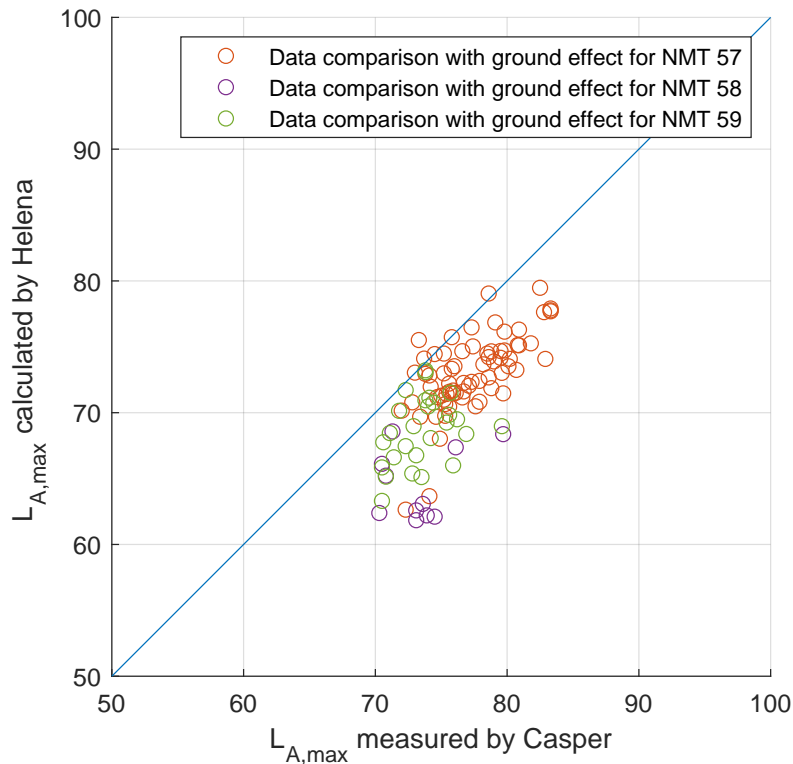
### B. Differences amongst NMTs

Throughout the process, the number of noise events of each NMT changed. In the selection of 237 flights, NMT 59 had the most noise events, followed by NMT 57 and NMT 58. After removing formation flights, NMT 59 lost most of its noise events. However, when all events with a measurement below 70 dBA were removed from NMT 58, only 10 noise events remained.

**Table 4** Amount of noise events per NMT during selection.

Amount of noise events	NMT 57	NMT 58	NMT 59
All transit flights	106	78	157
After removing formation flights	72	61	37
After removing flights with $L_{A,max} < 70$ dBA	70	10	26

The results amongst the NMTs show a much higher deviation for NMT 58. NMT 57 and 59 show similar  $\mu$  and  $\sigma$  where NMT 58 has a much higher variance. Note that NMT 57 has the most noise events, yet the lowest variance.



**Fig. 16 Measurement versus calculation for all 108 flights (ground effect included in calculation).**

**Table 5 Mean and variance of  $L_{A,max}$  error split per NMT.**

Metric	NMT 57	NMT 58	NMT 59
Mean $\mu$	4.2	8.8	4.9
Variance $\sigma$	2.4	3.3	2.7

### C. Testing error hypotheses

The underestimation of HELENA is quite ( $\sigma = 2.9$  *dB*A) constant. Yet, some noise events were not underestimated. NMT 57 scored the lowest mean ( $\mu = 4.2$  *dB*A) and variance ( $\sigma = 2.4$  *dB*A) whilst it had the most noise events. A subset of 26 events measured by NMT 57 was studied in detail by manual inspection in the Casper system. Four characteristics were tested for correlation. The Casper system keeps a record of wind strength and direction. Noise events with winds above 15 kts are noted as windy by the Casper system. No such noise events were found in the subset. The wind speed present at the moment the helicopter was near the microphone was compared with the difference (measurement - calculation). It is not likely that wind on this scale (short distance) has a significant impact on the propagation of sound. However, it could cause a more ‘bumpy’ flight for the helicopter which could be noisier than the recorded hemisphere. No significance was found in the relation between windspeed and underestimation in the calculated values for this subset.

Probably the strongest assumption in this research is modelling all helicopter flights with the 60 kts hemisphere. To see if a correlation could be found between the underestimation of speed by the model and the produced difference in  $L_{A,max}$ , the two were compared. For every noise event in the subset, the actual speed minus 60 kts was compared to the difference in  $L_{A,max}$  (measurement - calculation). Again, no significance was found.

If there would be an fault in the propagation then it might be that the error of the model increases with the distance.

Thus the distance at the nearest position of the helicopter w.r.t to the microphone was compared with the difference in  $L_{A,max}$  (measurement - calculation). No significance was found.

Lastly, the calculation of the ground effect came with some uncertainties, for example, which surface properties of the location should be chosen? Is this methodology the right one? For the noise events in the subset, the difference between the calculation with ground effect and the calculation without ground effect was compared with the difference in  $L_{A,max}$  (measurement - calculation). If the ground effect methodology adds too little  $\Delta SPL(r, \theta, \phi, f)$ , events with a large contribution to the noise level might have a smaller difference. However, for this subset, no significance was found.

**Table 6 Correlation and significance comparing various factors to the difference in modelling and measuring.**

	$R$	$R^2$	p-value
Wind	0.163	0.02668	0.456
Speed at closest point - 60 kts	-0.116	0.013	0.598
Distance	-0.109	0.0118	0.621
Calculation: with GF - without GF	-0.1502	0.0225	0.494

#### D. Possible sensitivity of unknown ground surface properties to method

An uncertainty in modelling is the location of the reflection of the sound wave that arrives simultaneously with the wave travelling the direct path. The location can be calculated with geometry (see Figure 4), but the surface properties remain unknown. The ground flow resistivity varies with the type of surface. Unfortunately, the ground flow resistivity could not be changed in the NAU\_Soroka method. For all calculations a value of  $\sigma = 400kPasm^{-2}$ . Using the theoretical approach, see also Table 1 from [19], several  $\Delta SPL(r, \theta, \phi, f)$  were calculated.

**Table 7  $\Delta SPL(r, \theta, \phi, f)$  for various ground flow resistivities calculated with method from [19].**

$\sigma$	Frequency					
	50 Hz	63 Hz	80 Hz	100 Hz	120 Hz	160 Hz
50	4.5	3.6	2.0	-0.8	-5.5	-11.1
500	5.0	4.4	3.3	1.4	-1.4	-17.2
20 000	5.1	4.5	3.5	1.8	-0.66	-12.5

## VI. Conclusion

The objective of this study was to research if a methodology to obtain ground noise values for the Apache helicopter for a single event could be found. No (publicly available) models exist to compute noise levels for the Apache helicopter. For this HELENA, a hemisphere noise modelling platform was researched. HELENA has been used for civil helicopters but not yet for military helicopters. The hemispheres required for modelling with HELENA for the RNLAf helicopters were obtained from a previous project. The hemispheres are suitable for HELENA, however, no previous studies have been performed to research the quality of this combination. As there is no other available model or set of measurements available to compare, it was chosen to compare the calculations with measurements from the Casper Noise Measuring Terminals (NMT) network. This network measures helicopter noise continuously at nine locations near the airport. It is designed to inform residents. For every flyby, a  $L_{A,max}$  and  $SEL$  value is obtained. These values obtained from the Casper measurements have been compared with calculations from HELENA.

Both systems were designed for a different purpose and thus in the comparison, their limitations must be taken into account. HELENA can model one helicopter for a flight condition for which a hemisphere has been recorded. This implies that the reach of HELENA is directly linked to the hemisphere available. The RNLAf hemispheres available are forward flight (20, 60, 100, and 120 kts), descent (80 and 120 kts, fixed descent rate) and climb (120 kts fixed climb rate). These hemispheres are suitable for straight, steady and symmetric flight, e.g. no turns. Next to that, the suitable flights for modelling with HELENA are also limited by a minimum altitude. Due to the lack of a radar tower present at the airport, the minimum altitude at which the helicopters are denoted by the radar (radar height) is 300 ft. This gives

inaccuracies for flights that fly lower than 300ft for a longer amount of time. Taking into account these limitations, it was chosen to model only transit flights departing to and arriving from low-level flying area Maas en Waal. Transit flights using the northeast route in between Rijen and Tilburg fly past NMT 57, 58 and 59. These flights were selected amongst all Apache flights in 2021.

A major drawback of using flights on a transit route is formation flying. Apaches often fly in formation towards a low-level flying area. This is incalculable for HELENA but also gives inaccurate measurements. Next to that, noise events with a  $L_{A,max} \leq 70dBA$  were often influenced by background noise. Contrary to HELENA, Casper does not use a 10dB downtime method. The effects of this different method are unknown and thus form a drawback of using the  $SEL$  value. Casper monitors the  $L_{A,max}$  values and integrates to see if a noise event with a  $SEL$  in a certain range can be found. This range for  $SEL$  differs per NMT. The result is that for  $L_{A,max} \leq 70dBA$  events often the background noise levels were close to the  $L_{A,max}$ . Consequently, for the  $SEL$  value to be in the predetermined range, the duration of the event became much longer than the helicopter passage. This means that part of the noise event assigned to the helicopter was in fact the background noise. These events were removed from the selection.

The comparison of measurement and calculation showed an underestimation of both the  $L_{A,max}$  as well as the  $SEL$  by HELENA. Values of  $\mu = 4.9dBA$  and variance  $\sigma = 2.9dBA$  show that the underestimation is substantial but consistent. The results varied per NMT: NMT 58 showed a much larger underestimation and delivered few reliable noise events in comparison to the others. Possibly this NMT is too far from the track to provide accurate measurements. Out of the three NMTs, NMT 57 gave the most noise events and had the smallest differences with the calculations. Using only noise events obtained from NMT 57 the  $\mu = 4.2dBA$  and variance  $\sigma = 2.4dBA$ .

The reason for this deviation could be the result of circumstances for which unknown phenomena create errors in calculation or measurement. Another reason might be a fault in the methodology of calculation. The presence of wind, deviation in flight condition with hemisphere, distance and addition of ground effect were investigated for a subselection of the flights. No significant values were found. In the method, the sensitivity of the ground effect was further researched. The unknown properties of the surface of the location where the sound waves reflect cause an uncertainty in the ground reflection. Asphalt or concrete has a higher ground flow resistivity  $\sigma$  than grass. The default setting of  $\sigma = 400kPas m^{-2}$  in the NAU\_Soroka methodology could not be changed. The theoretical approach ([19]) was thus used to calculate how much the  $\Delta SPL(r, \theta, \phi, f)$  changes for various values for the ground flow resistivity. The values show a similar result as the graphs in Figure 5. Even though the graph only experiences small changes for a different  $\sigma$ , the cancelled frequency changes. The asymptotic nature of the graph can cause a large change in  $\Delta SPL(r, \theta, \phi, f)$  for a small change in its input.

Thus, comparing the measurements from Casper with HELENA could not explain the differences. The subset was too small and the influencing variables too many to prove any significance. In modelling transit flights with HELENA, the propagation loss and ground effect are significant factors. Thus it is important to obtain the right distance and choose the right methodology for the ground effect. The NAU\_Soroka method was chosen for its documentation and even though a similar approach is used, results do not agree with the theoretical approach.

The Casper network is designed to continuously monitor the noise levels in the neighbourhoods surrounding the airport. To compare individual noise events with calculations where the helicopter is the single noise contributor, not all events are suitable. Noise events with a  $L_{A,max} > 70dBA$  are least likely to have contributions from background noise if they are not flying in formation flight.

HELENA has a constant underestimation of the  $L_{A,max}$  for the transit flight investigated. The low variance thus implies that HELENA would be suitable to compare flights amongst each other. As a decision aid tool, HELENA could be used to compare different heights and different offsets in planning new routes. If in the future the contribution of speed is clear and a valid determination of speed at every position point exists, the decision aid tool could be used to compare different transit routing options.

## VII. Recommendations

In this research, helicopter noise measurements were compared to calculations. For the Apache helicopter, modelled with HELENA, a constant underestimation was seen in the calculations. This underestimation ( $\mu = 5 dBA$ ) stirs up interest in what might be the cause of that. The answer is likely to be very elaborate and versatile. In an attempt to see if the presence of wind, high speed or distance could explain this underestimation, a small subset was researched. It is probably due to the fact that so many factors have been involved that no significance could be found. However, it would be interesting to conduct more research to find out if significance can be found for these or other factors. To do so, it would be recommended to perform a large number of measurements where the presence of potential influencing factors

is limited. For instance, start with measurements on a wind-free day, with a directive microphone, on a low background noise location, with a straight steady flight of a single Apache helicopter.

The results of these measurements could help identify which kind of factors are missing and should be taken into account in modelling. Equally interesting is to know which factors do not, or barely influence the noise. The results of modelling an 80 kts flight with a 60 kts and 100 kts hemisphere were so alike that it may not be necessary to create more hemispheres in this speed range. However, the difference between a 100 kts hemisphere in comparison with a 120 kts hemisphere showed that the noise rapidly increases with speed in the higher velocities. It should thus be researched what further increment of speed does to the noise. It is recommended to also record a 140 kts hemisphere.

Distance between the microphone and the helicopter influences the noise level perceived: This becomes evident looking at the propagation loss presented in theory and the measurements plotted against distance. It is thus important to reconstruct the flight as accurately as possible. No research has been performed yet to investigate the accuracy of reconstructing the flight with FANOMOS. Perhaps the FANOMOS reconstruction could be compared with on-board data. Not only the location but also the speed of the helicopter is of importance. By manual inspection, the speed provided by the radar data was sometimes different to what the NMT had noted. Only when an accurate method of speed determination at each location point is found, it makes sense to connect a hemisphere based on speed.

For more complete coverage of flight phases that can be modelled, a solution should be found for the radar height. This could be solved by performing landing exercises elsewhere, using a different source for the reconstruction of the flight (e.g. on-board data) or installing a (temporary) radar tower at Gilze-Rijen.

If it is desired to expand the coverage of the modelling, more flight conditions have to be modelled and compared. Especially, turns require investigation as the loading will increase in a sharp turn. In a comparable project, adjusting the attitude of the hemisphere was sufficient [7]. Yet, whether this holds for the (heavier) Apache helicopter and up to which bank angle this is accurate must be researched.

The above suggestions have the potential to further improve modelling. Nevertheless, a (societal) wish remains to compare modelling with measurements. In the end, a microphone in the neighbouring community seems a reliable method to capture what neighbours experience. Yet, a comparison study for the Casper network with a (manned) microphone has not yet been done. Of interest would be to research to what extent the microphone is influenced by reflections (on the ground or due to nearby walls etc.) and background noise. The reflections are a potential source of error in modelling noise. An in-depth study on the contribution of the ground effect on the measurement of a passing helicopter could enlighten the extent to which (local) geometry near the microphone has to be taken into account in the modelling process. Uncertainty on surface properties and ground effect does not only play a role in modelling, but also in the recording of a hemisphere. The current industry practice is to withdraw 6 dB from the measured values for the hemisphere to take this effect into account. However, considering helicopter hemispheres are likely to be recorded at (military) airports, the assumption of perfect reflection might be too large.

Lastly, if in the future this study is to be performed again, attention should be paid to the metrics used. For this study,  $L_{A,max}$  and  $SEL$  were chosen for their availability. However, both have their shortcomings.  $L_{A,max}$  reduces an entire noise event to one noise level measured at one moment in time. Any error in the nearest location to the microphone ( $DOBS$ ) can be detrimental to the outcome of the modelling. On the other hand, any second source of noise or disturbance at the moment when the helicopter is near the microphone can create an offset in measuring.  $SEL$  has the advantage of integrating the noise levels over the entire duration, providing stable representation of the noise event. However, the Casper network uses a different method to calculate  $SEL$  than is used in modelling. In order to compare the  $SEL$  values, it should therefore be investigated how the used methods to obtain  $SEL$  from the  $L_A$  over time affect the outcomes.

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# II

## Literature Study

# Using HELENA for military helicopters to obtain a noise prediction for a single event

## A literature review

J.S.M. Radius

April 25, 2022



# Using HELENA for military helicopters to obtain a noise prediction for a single event

## **A literature review**

by

J.S.M. Radius

in partial fulfilment of the requirements for the degree of

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in Aerospace Engineering

at Delft University of Technology

Student number    4381416

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# Introduction to helicopter noise

Sound plays an important role in life: it enables communication, helps us grasp an environment and alerts for danger. Despite the positive functionalities, sound can be a distraction leading to disruption of (essential) activities. Our ears are never “off”. Sound with a hindering effect is referred to as noise.

In the Netherlands, aviation is the 3rd most listed source of noise pollution, following road noise and noise from neighbours [36]. Within the category aviation, helicopter fly-overs play a large part [53] and [54]. Research shows a concentration of military aircraft noise annoyance around (military) airforce bases [53].

Helicopters have a strong tonal sound and fly at relatively low altitudes. Both civil and military helicopters are known to be noisy, however, the military helicopters are heavier and thus relatively noisier, [34].

The Royal Netherlands Air Force (RNLAf) has the task to be ready at all times to contribute to safety in and outside of the Netherlands. The Defensie Helikopter Commando houses all helicopters, apart from the maritime helicopter NH90, in Air Force Base Gilze Rijen. The airport Gilze Rijen is located in between Breda and Tilburg. The origins of the airport lie in early 1900s when factory director Sybrand Heerma van Voss invited Charles Lambert to perform the first flight of the Netherlands in his Wright Flyer. [22] Since then the field has been in use. After German occupation, the airforce base was used by the Dutch Army. Since 2005 all helicopters have been merged in to one Commando. The Apache, Chinook and Cougar are located in Gilze Rijen and the maritime helicopter NH90 in the Den Helder.

To ensure readiness, exercises have to be done regularly. Exercises are either done at the air force base itself or in low-level flight zones (‘laagvlieggebieden’). Tasks of the military helicopters consist mostly of transporting, observing, protecting or fire fighting. These tasks are executed in close proximity to the ground and thus all the exercises are at low altitudes as well.

At the base itself a lot of landing exercises take place. Similar to fixed-wing, most accidents occur in the first and last phase of the flight. To practice a safe landing and departure, the helicopters fly in circuits where they land and take off every circuit. A military helicopter airport in a peace setting has fixed circuits to avoid collision in dense traffic situations. In Gilze Rijen, up to eight helicopters can be handled simultaneously by the Air Traffic Management.

Deployment of the RNLAf is usually abroad, but most of the training takes place in the Netherlands. As a result, areas in the vicinity of the base or training area are exposed to helicopter noise. This effects communal areas near military airports.

Humans have different experiences with noise. As there are many other non-acoustical factors that influence the perception of the noise, the nuisance experienced by neighbours cannot be simplified to noise exposure. It is clear that a neighbour has a different experience with sound nuisance than a

test person is in a scientific set-up [2]. However, the first step in noise quantification is to establish what kind and what amount of sound has reached which location. The development of noise exposure quantification research methodologies could aid in the evaluation of efforts made in noise abatement. These research methodologies can be performed by extensive measuring, modelling or a combination of the two.

The aim of this literature research is to create an understanding of helicopter noise and its modelling options. Chapter 2 will dive into the different sources of noise of the helicopter and explain which source is dominant in which flight condition. Chapter 3 will discuss the options to capture the noise as perceived by humans. Chapter 4 explain approaches to reduce helicopter noise and chapter 5 will look at the different modelling approaches.

# 2

## Noise sources of the helicopter

When a rotor blade system passes through air, aerodynamic interactions occur. In this process, sound pressure waves are created. These sound pressure waves are the product of the rotor blade system, the medium in which it operates and the type of interaction it has. Five specifics that influence the sound are:

- The design of the blade
  - ◊ The thickness of the blade
  - ◊ The trailing edge of the blade
- The loading on the blade
- The speed of sound in the medium
- Turbulence present in the medium
- Speed of the rotating blades (sub or supersonic)

The thickness of the blade determines how much air is displaced during a blade passing. Depending on the design, the trailing edge may create a vortex. This vortex influences the medium for the upcoming blade. The design choices made in designing the helicopter blade thus influence the sound created by a passing of the blade, but also influence the medium and thus the sound that will be created by upcoming blades.

The specifics of the military helicopters are discussed first in this chapter. Then, this chapter will provide an introductory explanation to helicopter control and aerodynamics. Then it will go over the dominant noise sources and explain why the noise is not the same for different directions.

### 2.1. Characteristics of the RNLA military helicopters

A fixed-wing aircraft creates lift with its wings and forward propulsion with an engine. A helicopter has designated both these tasks to the main rotor. As a result, the blades of a helicopter rotor carry a heavy load. The weight of the helicopter also adds to the loading on the blades. The Chinook CH-47D, for example, has a maximum take off weight of 22 680 kilograms or 50 000 lbs.

Blades are long and rotate with a speed in the range of 200 - 600 rpm (rotations per minute). That is 289 rpm for the Apache [48] but a maximum of 420 rpm for the Alouette [1]. This is much lower than the rotational speed of an aircraft (turbofan) engine, which is e.g. in the range of 1000-3000 rpm (e.g. AE 2100 engine of a C-130 has a max rpm of 1100 rpm [12]). This rotational speed of the helicopter is limited by the maximum tip speed on the blades. It is avoided in design to reach a supersonic speed at the blade tips. On the advancing side the blade may reach transonic speeds at the tip, but supersonic (air) speeds are to be avoided to prevent stall and for structural durability ([26], page 57). To reach a high efficiency whilst staying within limits for vibrations, most helicopter designs aim for a blade tip speed

in the range of 0.6-0.7 Mach [6]. Most helicopter aerodynamics thus take place in the subsonic region. The interaction of the helicopters main rotor and its direct environment is the main topic in helicopter acoustics.

## 2.2. Controls of the helicopter

Characteristic to the helicopter is the presence of at least one main rotor. It serves the helicopter with three tasks: provide lift in vertical direction to overcome the gravitational pull caused by its own weight, provide forward thrusts and control the attitude and position of the helicopter in order to bring stability [40] [26].

The pilot of the helicopter has four means to control the helicopter. To control the pitch of the blades of the main rotor, the collective is used. By pushing the collective down, the swash plate of the rotor is pushed down and the pitch angle, and thus the lift of the blades is reduced. The throttle sets the Rotations Per Minute (RPM) provided by the engine. Ideally this does not change during the flight. The cyclic stick also controls the swash plate, but in a different way than the collective. The cyclic stick changes the angle of the swash plate, creating an uneven lift. Pushing the stick forward will result in an upwards motion of the plate on the rear side. This will then give the back more lift, resulting in more forward thrust. Lastly, the anti-torque pedals control the tail rotor. As the main rotor spins in one direction, a torque is created. To prevent the helicopter from spinning, the tail rotor produces a counter-torque.

Different to fixed-wing, provisions of lift, forward thrust and attitude and position control are all tasked to the main rotor. This means, that for every flight condition, the setting of the main rotor is different. A forward flight requires more lift to the rear side of the swash plate, which is given by cyclic input. Descending requires a little loss of lift, manoeuvred with the collective. For every flight condition, forward, descent, climb or turn there is thus a different rotor setting. This means that the front, left, right and back have a different angle regarding the incoming air flow.

### 2.2.1. Asymmetric aerodynamics

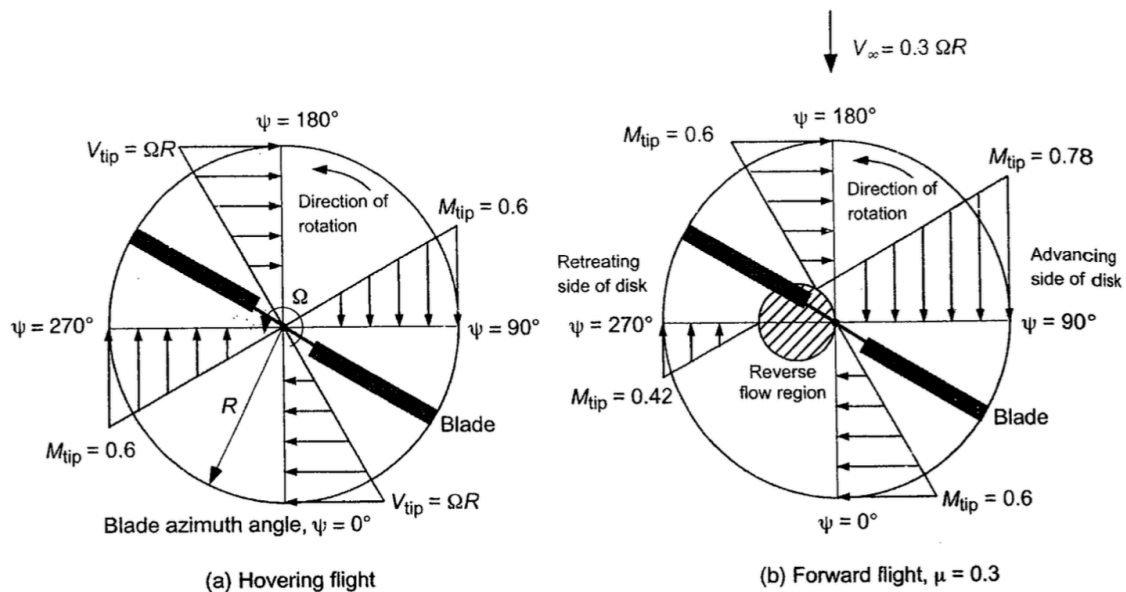
In a single rotor configuration, the preceding blade will fly against the direction of the airflow and the retrieving blade will fly in line with the direction of the airflow. This results in a velocity difference. The addition of the airflow velocity on one side shifts the velocity distribution of the blades in perpendicular position to the flow upwards. In Figure 2.1 a counterclockwise (CCW) rotating helicopter is shown, the azimuth angle ( $\psi$ ) is defined zero when the blade points to the rear side, downwind of the flow. The left image depicts a CCW helicopter whilst hovering and the right image depicts the (CCW) helicopter in forward motion. For a CCW helicopter this means that on the right side of the rotor disc the velocity on the blade is  $\Omega * R + V_\infty$ , with  $\Omega$  the rotational velocity,  $R$  the distance from the measured point to the centre of the rotor and the freestream velocity ( $V_\infty$ ). The velocity distribution increases linear along the span of the blade. In hovering, the velocity difference is equal for all sides. In forward flight the advancing side has a larger velocity difference with the freestream. This means that flight conditions with a forward component the velocity distribution on the blades of the main rotor is asymmetrical.

In Figure 2.1 the velocity distribution on the blades is shown in the right figure (b). This unequal velocity distribution would in theory lead to more lift on the right side than on the left side, [40]. This situation should be avoided for dynamical reasons, as the helicopter would get a very strong rolling moment. To avoid this situation the angle of attack (AoA) is trimmed. The retreating side has a higher AoA to compensate for the subtraction of the flow velocity.

The unequal lift is thus solved by trimming the AoA of the blades, but the rigid connection in combination with asymmetric pressure distribution would cause vibrations [40, page 58]. Therefore, a flapped hinge is often used. This allows the blades to flap and thus avoid any tension build up.

Asymmetry in the aerodynamic profile is caused by the different situations in the advancing and preceding blade. The results are a different velocity, a different AoA and flapping movement. This is for a clean inflow, in reality however, the air around the blades is heavily influenced by vortices caused by the helicopter itself.

Figure 2.1: Distribution of incoming velocity for hovering flight (left) and forward flight (right) [26]



### Vortices

A vortex is a flow of air that rotates around an axis. At an airfoil there is a higher pressure below the blade and a lower pressure above the blade. Air then tends to leak over the trailing edge, which in a forward motion gives a vortex that starts at the tip of the blade. A helicopter blade produces a tip vortex at the edge of the blade, leaving a circular motion behind the blade. This results in an addition to the drag and is called induced drag. Next to that, the air behind the blade experiences turbulence from the vortex.

Helicopter blades create a rather strong vortex at the tip of their blades [26, page 56]. The succeeding blade then passes through turbulent air, which gives more noise than a passage through 'clean' air. Thus in the noise scope, it is of interest to understand when their vortices occur and when they interact with the blades.

## 2.3. Noise sources for the helicopter

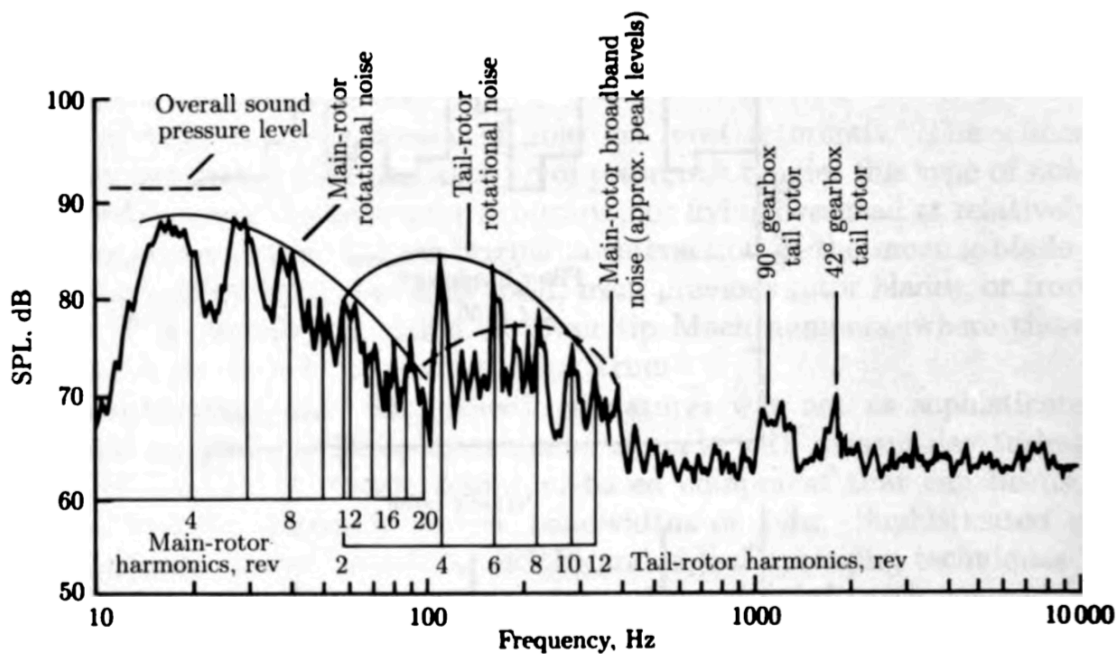
The whole spectrum of helicopter noise sources can not simply be explained with one flight condition as an example. As explained in section 2.2, for each flight condition both the configuration as well as the interaction with the surrounding air is different. As a consequence the dominating noise source changes per flight condition. The following section will first explain the sources of noise separated by the type of noise they create; harmonic/tonal or broadband. Then it will discuss two types of impulsive noise, that do not always occur, but when they do, they form a distinctive dominant source of noise, [18].

The noise spectrum of the helicopter can be split into broadband, harmonic-with the rotor and noise that is harmonic but not with the main rotor. For most helicopters, noise created by the main rotor has the largest contribution to the noise spectrum, see an example of the UH-1A in Figure 2.2. Another distinction can be made between noise that is always there and noise that only occurs in certain flight conditions. The noise that is steadily present is called lower harmonic noise. Of the impulsive phenomena, two are known to cause a lot of noise: Blade Vortex Interaction and High Speed Impulsive noise.

### 2.3.1. Broadband noise

Broadband noise is not harmonic with the blade passing frequency, or any other frequencies. Sources of broadband noise are mainly airframe noise and broadband noise created by the main rotor [6]. The broadband noise created by the main rotor is caused by a.o. random aerodynamic interactions, turbulence due to boundary layer effects, vortex shedding, flow separation, re-ingestion of the rotor wake and

Figure 2.2: External noise spectrum of a UH-1A (single rotor) in hover. [37]



atmospheric turbulence. [6]. With respect to the tonal noise created by the main rotor, the contribution to the noise spectrum of broadband noise is much lower and thus not a topic of research yet for military helicopters.

### 2.3.2. Harmonic noise

Besides the main rotor, other components also have a rotating component which creates a tonal noise. The engine has a tonal noise component, driven by the revolutions of the drive shaft. However due to a much higher frequency, the tonal noise has a higher frequency and is absorbed more by the atmosphere [18]. Engine noise is more a problem for the inside of the helicopter, [23]. A same explanation counts for the tonal noise of the gearbox, where high frequency rotations result in a high frequency tonal noise. [18]. Figure 2.2 shows an example of a noise distribution for the UH-1A (military) helicopter. From this graph, the relative proportions of the noise sources can be seen. Although the tail rotor has a non-negligible contribution, it is not considered to be part of the main contributors.

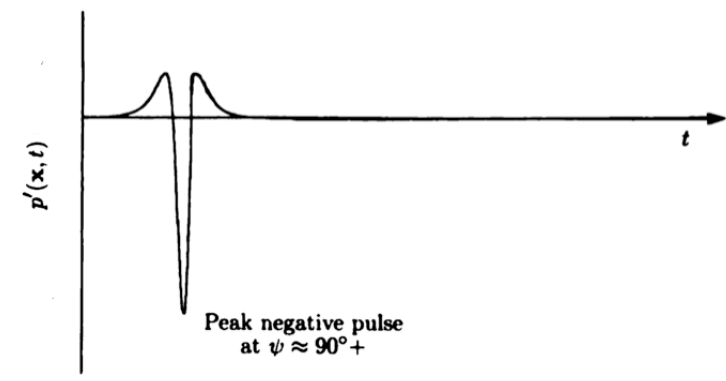
Overall, the noise of a helicopter is dominated by the noise caused by noise sources harmonic with the rpm of the main rotor [37]. The lower harmonic is always present during flight. Two mechanism can be distinguished, the steady loading noise and thickness noise. These mechanisms are described by the Ffowcs Williams - Hawkins equation. In 1969 Ffowcs Williams and Hawkins rearranged the Navier Stokes Equations into an inhomogeneous wave equation. This equation has monopole and dipole sources on the body surface and a quadruple source distribution in the volume surrounding the body [4]. These quadruple sources are used to model High Speed Interaction and thus only need to be added when the (rotor blade) tips speeds reach transonic.

#### Loading noise

Observing from a fixed point from the disc, the air parcel in the area spanned by the blade experiences a blade passing at the pace of the blade passing frequency. This blade has a chordwise pressure distribution, which is required to give the helicopter lift. Every time the blade passes through the medium, the presence of the blade accelerates a portion of air. This creates a momentum injection. For uniform inflow conditions, this can be described by a set of aerodynamic dipole sources. [18]. This relates to the the dipole term of the Ffowcs Williams - Hawkins Equation [58].

A determining factor for this process is the pressure distribution of the blade. When the load factor of

Figure 2.3: Thickness noise: far-field acoustic pressure [37]



the helicopter changes, the pressure distribution on the helicopter blades changes as well. For helicopter operations often the AoA is increased to create more lift for the same rotational speed. This thus increases the loading noise. In a turn for example, a higher load factor results in more noise.

### Thickness noise

Observing the same parcel, see subsection 2.3.2, the passing of the blade will cause a displacement of air. This displacement of air is periodic with the (blade passing) frequency of the main rotor. The blade has a thickness and thus pushes the air that was there before the blade away. After the passage, air can go back. At the tip of the blade, the speed of the incoming air compared to the blade is the highest. Here the largest pressure wave, and thus noise is formed. The noise that is observed is mainly present in the low frequency domain, occurring at the blade passing frequency and higher harmonics. The shape of the vortex created at the tips of the blade changes shape with speed and design of the blade. If the speeds at the tip reach the transonic domain, High Speed Impulsive harmonic noise is created. The periodic displacement of mass can be modelled with a monopole. The thickness effect can be identified by a large negative pulse, see Figure 2.3, which is derived by modelling [37] and [63]. The characteristic peak is also used to identify the noise contributions of thickness noise in measurements, e.g. [39]. The strongest negative peak occurs at  $\psi = 90deg$ , this is when the advancing blade has a maximum speed difference with the incoming flow (right-hand side for CCW helicopters).

### 2.3.3. Impulsive noise

In some flight conditions the phenomena ‘blade slap’ or blade bang occurs, this can be a result of blade vortex interaction (BVI). The blade then interacts with the vortex from the preceded blade. In a fast forward flight the tip of the blade may approach sonic speeds. The noise due to shockwave formation due to local supersonic flow is called High Speed Interaction (HSI) noise [30]. Both BVI and HSI only occur in certain flight conditions, however, when they occur they are known to be a dominant noise source. Much research ([32], [63], [56]). is performed on how the Ffowcs Williams–Hawkins equations can be adapted for BVI and HSI.

### Blade Vortex Interaction

Aircraft wingtips create vortices as well, but what is special about the helicopter is that in some flight conditions a vortex created by the preceding blade is in the path of the upcoming blade. Thus with every rotation the incoming air is always affected by the passage of the preceding blade. This often occurs in (slow) landing approaches, [18]. The phenomena is called Blade Vortex Interaction and has been the subject of various research, see, [60], [31], [59], [56]. This produces the well-known “chop-chop” sound of a helicopter.

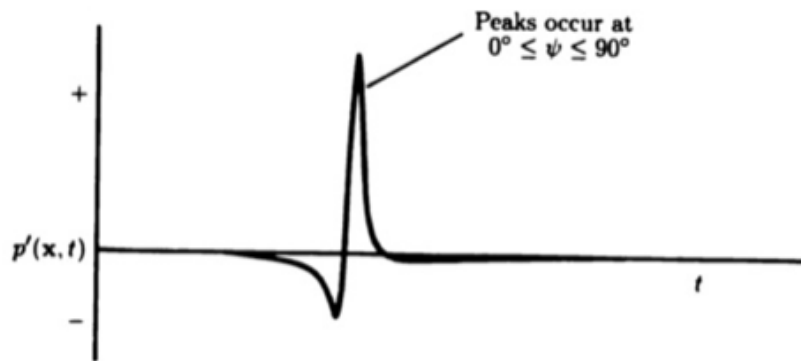


Figure 2.4: The Angle of Attack, lift and acoustic pressure time plots for an advancing (left) and retreating (right) blade on a counter clockwise helicopter. [37]

To understand what happens to the blade when it passes a vortex, two separate cases have to be discussed: advancing and retreating blade. For a CCW helicopter, the advancing blade is on the right-hand side. A vortex (turning clockwise) then causes a change in angle of attack. The dip and increase for the advancing side Figure 2.4 lead to a positive peak in the derivative of pressure over time ( $p'(x, t)$ ). The opposite holds for the retreating side. The positive peak as a result of BVI can be seen in Figure 2.4

The interaction of the blade and the tip vortex can be described as a [47, p.1] “rapid fluctuation of aerodynamic loads”. The intensity and directivity are both a function of the angle between the vortex and the blade and the ‘miss’ distance. The miss distance described the distance between the vortex and the rotor disc.

So in order to reduce the BVI noise the angle between the vortex and the blade could be made less “frontal”. This tactic was used in the development of the Blue Edge [20, page 3] rotor blade tip. The Blue Edge blade tip has a forward-backward sweep and reduces the interaction with the vortex. However, changing the blades or blade tips is not always possible. Military helicopters do not (yet) have special blades to reduce BVI.

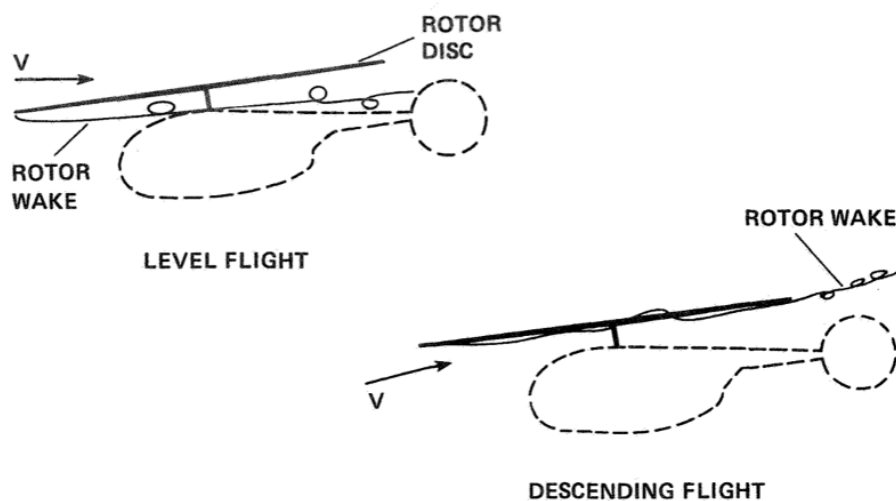
Blade Vortex Interaction (BVI) does not occur in all flight conditions. It occurs when the miss distance is reduced such that the upcoming blades pass through the vortex. In a descending flight the miss distance is reduced and thus BVI occurs. In Figure 2.5 the displacement of the wake can be seen. BVI is also known to occur in a decelerating turn. This was a subject of study for the AS350 in a recent study [34]. Tests were performed with the AS350. A turn to the left in level flight was flown. In this turn a  $35deg$  roll was reached. The turn was flow accelerating, starting with a speed of 90 kts, and decelerating. An  $0.1g$  acceleration over a  $0.1g$  deceleration diminished the maximum noise level by  $\Delta L_{a,max} 12.4dB(A)$ . The most loud observed noise levels were perceived on the outside of the turn.

A tandem (with two rotors) helicopter with two rotors has an aft blade of the front rotor passing through the wake of the front blade of the aft rotor. This doubled passing of a blade through vortices give a tandem helicopter a strong (asymmetric) noise profile. Such helicopters, e.g. Chinook, have BVI noise in most flight conditions.

### High-speed impulsive noise

When a helicopter has a great forward speed, the tips of the blade can reach transonic speeds ( $M = 0.9$ ). In such a fast forward flight, the negative peak related to thickness noise then grows in amplitude (also narrows) (see a.o. [32, page 1519]) to an extent such that the negative peak dominates the noise spectrum. This extreme case of thickness noise is called High Speed Impulsive noise. The (current) helicopters of the RNLAf do not reach transonic speeds at the tips.

Figure 2.5: Helicopter in forward flight (left) and in descending flight (right) [37]



## 2.4. Directivity of helicopter sound

A helicopter, with its different noise phenomena, cannot be assumed to be a homogeneous noise source. The exact process has not yet been captured in models. Some experiments ([39]) have been conducted to assess the directivity of different noise sources.

In *Aeroacoustics of Flight Vehicles*, [37][ch. 2] F.H. Schmitz discusses a flight experiment where a (relatively silent) plane flew in front of a UH-1 helicopter for acoustic measurements. Several observations were made:

- The loud blade chop was sometimes not heard in the cockpit even though it was measured by the microphones
- The amount of blade chop noticed in the cockpit and later in the pressure spectrum varied with speed and descent rate
- The change of pressure spectrum with respect to the angle between helicopter and aircraft showed different behaviour for lateral and longitudinal directivity angles.

The experiment confirms that the sound produced by the helicopter cannot be assumed to be a homogeneous spherical source. Quite the opposite, for a specific flight condition a non-homogeneous sphere of sound is produced. The experiment described in [37] and [38] gives insight in the directivity of the noise sources of the helicopter.

Earlier work [39] already compares measurements with theoretically predicted directionality of noise. This is done by comparing the acoustic pulses in measurements with a sweep of microphone positions. According to [37] the blade vortex interaction occurs between  $\psi \approx 0$  and  $\psi \approx 90deg$ , the subsequent decrease of pressure is a result of the thickness noise contribution which has its (negative) peak at  $\psi = 90deg$ .

In the results of the experiment described in [38] and [37] are displayed in the section below. First the measurements in lateral direction are elaborated, then the measurements in longitudinal direction (at angles in front and lower than the helicopter).

The helicopter flew by at high speed in level forward direction. The thickness noise, recognised by its sharp negative pressure pulse, reached its maximum at an  $\beta = 0deg$  at the in plane angle. The magnitude of this pressure peak decreased and had half amplitude at  $\beta = 53deg$ . The sharp positive pulse following the negative peak is caused by blade vortex interaction. Likewise with the thickness noise, the blade vortex interaction noise was also observed the strongest in-plane right in front of the helicopter.

Figure 2.6: Acoustic directivity for the UH-1H at level flight, 115 knots IAS, lateral acoustic directivity ( $\alpha = 7deg$ , level flight. [38]

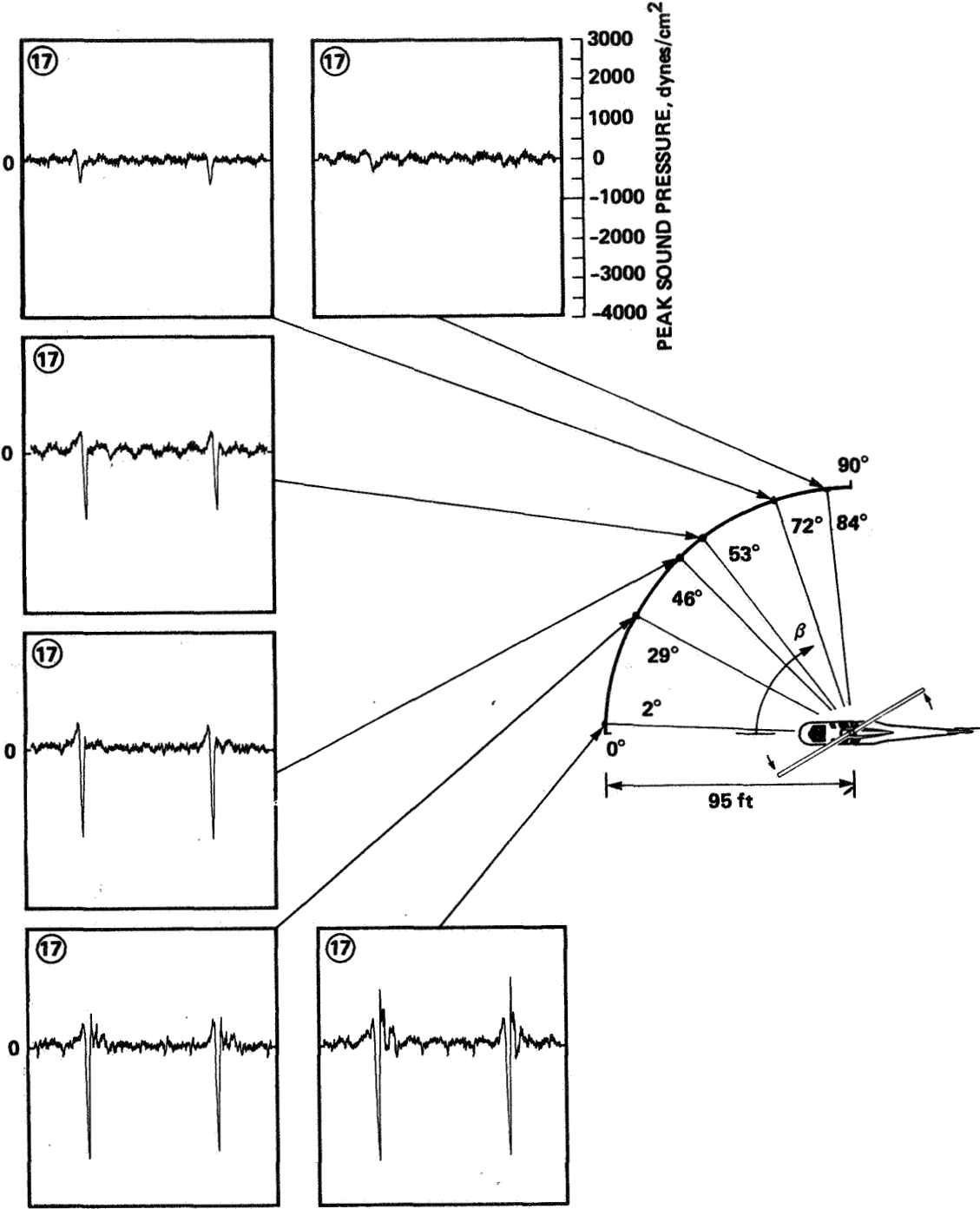
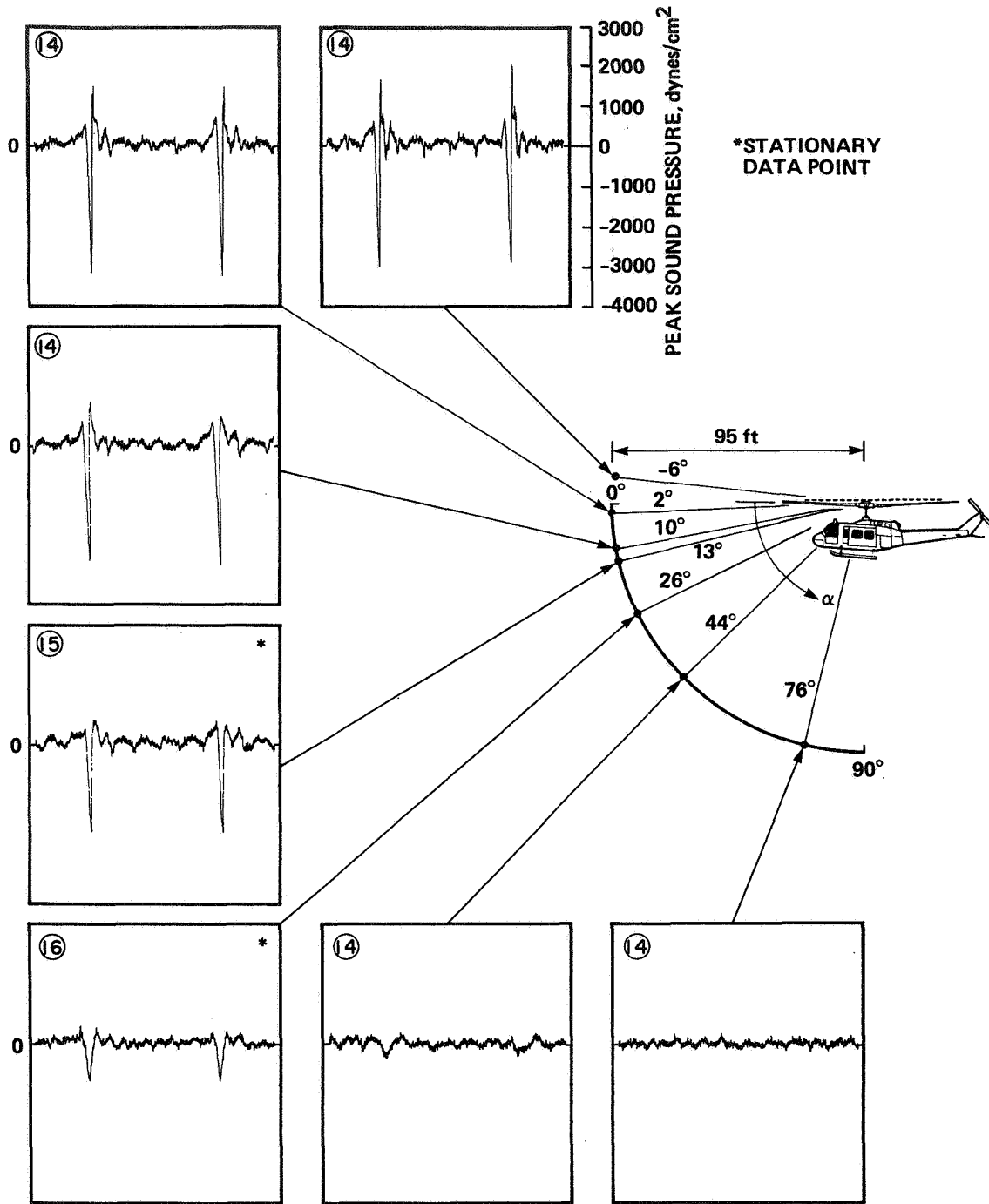


Figure 2.7: Acoustic directivity for the UH-1H at level flight, 115 knots IAS, longitudinal acoustic directivity ( $\alpha = 7\text{deg}$ , level flight. [38])



The same conditions, high speed in level forward direction, hold for the measurements in longitudinal direction. The thickness noise (negative pressure pulse), reaches its maximum at an  $\alpha = 0deg$  at the in plane angle. This decreases, half amplitude at  $\alpha = 13deg$ .

For each flight condition a helicopter has a different configuration with different aerodynamics and thus a different noise profile. This noise profile is varies with latitude and longitude. A helicopter in forward flight at fast speed will experience BVI. An observer in the far field will perceive different noise depending on the angle. This measured directionality is important when modelling helicopter noise as the relative position of observers on the ground to the helicopter will result in different observed noise levels.

Much research has been performed to understand the aerodynamics and acoustics by studying a parcel of air through which a blade passes. However, to obtain the acoustics as received by a (human) observer, the helicopter as a whole and all its interactions with the freestream need to be modelled. Such a model is not available for the helicopters of the RNLAf.

The research mentioned in this chapter all regard noise from an aerodynamic perspective. If the amount of pressure waves can be reduced eventually the helicopter will become less noisy. However, for a receiver, a negative or a positive peak is all the same as the effective pressure is sensed in the ear.

The takeaway from these aerodynamic researches for acoustic modelling is that the presence of BVI and or HSI can rapidly change the aerodynamic profile of the helicopter. These effects do not act linear but appear in turn, descent (BVI) or at high speeds (HSI). As a consequence, the noise created by a helicopter should be regarded separately per flight condition.

Next, pressure graphs in Figure 2.6 and ?? display a non-uniformity of the pressure plot for the various angles. This is consistent with the notion that the helicopter as a noise source cannot be assumed to be homogeneous in any direction. Thus for each helicopter, in each flight condition for each angle(s) the noise should be assessed.

# 3

## Quantification of annoyance due to sound

Noise is unwanted sound that distracts and might eventually annoy people. Although a single event is not likely to do harm, long noise exposure can lead to stress or sleep deprivation [24]. Helicopters are loud and have a distinctive sound. To explain why they are annoying, it does not do justice to only use decibels as metrics. This chapter will investigate how noise can be measured and explain what units are being used.

### 3.1. What is noise?

Humans can be distracted and even be annoyed by sound. When certain sounds disturb a number of people to such an extent that it leads to stress, sleep deprivation and other negative health effects, it becomes an environmental problem. Whether a stimulus, such as sound, can lead to stress has already been studied in the sixties. Richard Lazarus [25] described a stress model. When an impulse from the environment has a negative effect on the concentration and thus ability to perform a task or activity, the performance of the human is under threat. The human may then find resources to prevent the interference or reschedule the activity. If these resources are unavailable, and/or if rescheduling is impossible, the disturbance can be perceived as bothersome. Reoccurring or permanent disturbance can build up stress.

The above explains why aviation noise in residential areas receives a lot of attention. The remedies for disturbance by noise are limited, especially in the relaxation activities. Residents cannot be expected to enjoy their garden in another location. Similar arguments can be given for sleep disturbance. Humans require a low background noise level with little tolerance for peak levels during their sleep. The probability of awakenings and amount of highly disturbed people have been widely researched; an overview is given in [24].

Even though the amount of helicopter flights is substantially lower than aircraft, rotorcraft usually fly at lower altitudes above residential areas. The RNLAf does not fly in the night hours, but evening and day flights pass areas close to residential neighbourhoods. This is not unique in the Netherlands; the US Army reports of community annoyance in the 1970s [16]. Yet, not too much has been altered on the configuration of the helicopter to reduce its noise. To diminish annoyance experienced by the community, solutions are more likely to be found in noise abatement. Most low-hanging fruit has already been picked with noise abatement arrival routes, reduction of night flights and Initial Points that evade residential areas. To evaluate what has been done and what might be possible in the future, it is important to seek a method for evaluation.

At the moment the legal noise limits of the airport are reported yearly in a metric “Kosteneenheden” which takes amount of flights, duration and loudness in decibels. This is a legal report aimed to guard the noise exposure due to landing and take off activities at the airport. On a yearly basis, the landing and take off activities are evaluated to see if their noise exposure is within the established noise contour.[11] Apart

from their legal obligation, RNLAf has established noise abatement procedures and is looking for further ways to reduce the noise nuisance for the neighbours. The “Kosteenheden” report evaluates on a yearly basis and regards only activities at the airport, not the surroundings. Therefore, it is not aimed for and not suitable to explain the experience of local communities.

### 3.2. Noise metrics

To assess measures to reduce community noise, various metrics have been proposed. Sound is essentially a pressure wave with a specific amplitude and frequency. A sound is heard by the pressure disturbance it causes. Taking the standard frequency of a 1000 Hz, the following holds: When the effective pressure of a sound wave is louder than the threshold for the human ear ( $p_{e0} = 2 \cdot 10^{-5}$ ) it is audible. The Sound Pressure Level (SPL) then has a value of 0 decibels (dB), see Equation 3.1. In Table 3.1 a selection of noise metrics based on physical properties such as frequency (Hz), volume (dB) and time of the event or moment of the day is shown.

A helicopter is not a single sound source, i.e. the rotorcraft has several sources that separately produce noise. The sound pressure level of these sources can be added, using Equation 3.2

For humans, the sensitivity of sound is not the same for every frequency. To gain insight into whether a sound is low or more in the high spectrum of frequency, the sound can be expressed in pressure band levels. By assigning a passband ( $\Delta f$ ) in Hz, the level of the sound can be assessed per band of frequencies. The Sound Pressure level within such a band is then called Pressure Band Level (PBL), Equation 3.3.

$$SPL = 10 \cdot \log \left( \frac{p_e^2}{p_{e0}^2} \right) \quad (3.1)$$

$$SPL_m = 10 \log \sum_{i=1}^N 10^{SPL_i/10} \quad (3.2)$$

$$PBL = 10 \log \left[ \frac{P(f)\Delta f}{p_{e0}^2} \right] \quad (3.3)$$

Humans are more susceptible to tones with certain frequencies. Because typical frequencies in helicopter noise vary, see Figure 2.2, it is important to understand how loud sounds with different frequencies are perceived.

To research the sensitivity of the human ear for different frequencies, test listeners were asked to indicate when a sound with a particular frequency was perceived as equally loud as the 1000 Hz test tone [43].

This resulted in equal loudness levels. The equal loudness contour describes sound with reference of 1000 Hz sound. An increase of 10 phon, is perceived of twice as loud. However, loudness does not directly mean annoying. The amount of annoyance (for humans) has also been tested in a similar manner and is expressed in noy [43].

Phon and noy are the basis for perceived noise level metrics. Perceived noise level ( $L_{PN}$ ) uses noy to calculate the overall value of a sound with several frequencies. Effective perceived noise level ( $L_{EPN}$ ) uses a 10 second period for the tone-correction [27]. This is somewhat similar to SEL (10 seconds integration vs 1 second). EPNdB is used in formal certification of aircraft [27].

The equal loudness contour of 40 phon has been used to determine a weighting curve A. With this curve, a correction factor can be determined. These curves exist for 40 phon (A), 70 phon (B), 100 phon (C) and 40 noy (D).  $L_A$  and  $L_C$  and known to be used in helicopter noise metrics. The  $L_A$  is currently used by the noise measurement networks around Gilze Rijen Airport [9].

Noise events do not just differ in frequency and loudness but may also vary in duration. To also take the duration of a noise event in consideration, units were developed that include the duration of the noise event.  $L_{A,eq,t}$  integrates the  $L_A(t)$  over time, see Equation 3.4.

The integration is started at the point where the sound level is ten dB(A) lower than the maximum dB(A) level of the event, see Figure 3.1.

To compare different noise events with different duration,  $SEL$  removes the dependence on the integration time by replacing  $T$  with  $T_1 = 1[s]$ , see Equation 3.5. In this manner, a long event with a medium peak is usually regarded as higher in noise than a very short but high peak noise event.

$$L_{A,eq,T} = 10 \log\left(\frac{1}{T} \int_0^T 10^{\frac{L_A(t)}{10}} dt\right) \quad (3.4)$$

$$L_{AE} = 10 \log\left(\frac{1}{T_1} \int_0^{T_1} 10^{\frac{L_A(t)}{10}} dt\right) \quad (3.5)$$

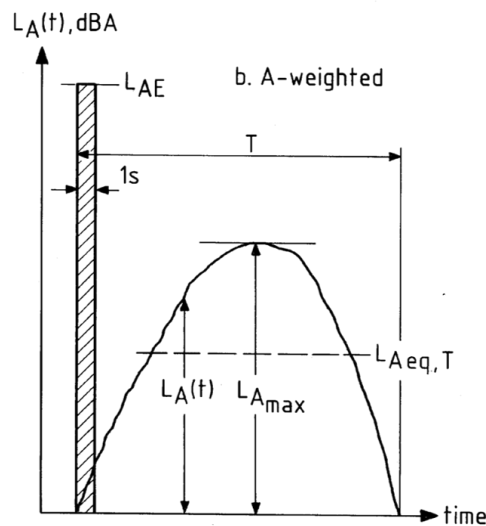


Figure 3.1: Definition of  $L_{AE}$  and  $L_{A,eq,T}$  of a noise event.

The previous introduced concept of noy connects frequencies to perceived annoyance. However, there is more to sound that can enlarge annoyance. In [55] Sound Quality Metrics (SQM) that relate other characteristics, e.g. tonal noise and fast or low frequency oscillations are investigated. The five SQM discussed in [55] are: loudness, sharpness, fluctuation strength, tonality and roughness. These metrics can be combined to calculate the psychoacoustic annoyance (PA) which expresses the unsteadiness (change of SQM over time) in one unit. Next to that, the SQM also give more insight into the annoyance of a noise event.

Some sounds with low frequencies have the ability to put other objects into motion. The resulting vibrations cause a lot of noise. This indirect noise is called "rattle noise", [62]. The C weighting scale includes lower frequencies and can be used when rattle noise can be expected. [62]. By using a correction factor when rattle noise is expected or the C-weighting scale, the noise levels are more adjusted to what a human in a domestic setting experiences. E.g. if all crockery starts to shake because a heavy helicopter flies over, the experienced noise level due to that flyover is larger than the direct noise coming from the helicopter as shaking (induced by the helicopters low noise levels) cups and glasses also make noise.

The above metrics are used to evaluate single events. The metrics below take into account multiple noise events over a longer period of time (usually a year). As evening and night flights are perceived as more disturbing [24], several metrics have been created to 'punish' an evening or night event with an extra decibel weight. Widely used are  $L_{DN}$  (Day and Night) and  $L_{DEN}$  (Day, Evening and Night).

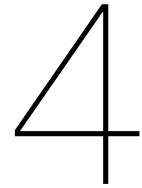
Noise from transport is very different in characteristic, living next to a highway results in a monotone constant background noise, whereas living next an airport gives a (noise) peak for every plane passing. To distinguish the latter units that focus on the peaks were developed.  $NA_x$ , (Noise Above) where 'x' can be replaced by a dB level, assesses the amount of peaks in a time range. This is a simple powerful noise metric, although it does not distinguish very loud events from loud events. Time Above,  $TA_x$  includes the time of exposure. This metric is quite similar to the  $L_{A,eq,T}$  metric.

In Switzerland further research on the relation between noise annoyance and background levels is performed. An Intermittancy Ratio (IR) was developed [5]. It shows the percentage of sound energy created by noise events above a certain threshold with reference to the total sound energy. In this matter, a lot of small peaks score higher than a relatively constant noise source [44].

Further research investigates the resting moments in between noise events. Respite moment, planned in runway use, can possibly help to lower the annoyance. No official metric or scale is developed yet. [28], [57].

Table 3.1: Selection of Noise Metrics used in Helicopter Noise assessment, [43, 27]

<b>Symbol</b>	<b>Unit</b>	<b>Acronym</b>	<b>Units</b>
OSPL	dB	Overall Sound Pressure Level	dB
PBL	dB	Pressure Band Level	dB, Hz
$L_l$ or $p$	phon	loudness level	
$S$	sones	loudness	dB, Hz
$N$	noy	noy value	dB, Hz
$L_{PN}$	PNdB	Perceived Noise level	dB, Hz,
$L_{EPN}$	EPNdB	Effective Perceived Noise level, takes into account duration of event	dB, Hz time
$L_{TPN}$	TPNdB	Tone corrected Perceived Noise level	dB, Hz, time
$L_a$	dBA	A-weighted decibel	dB, Hz
$L_A$	dBA	Overall A-weighted Sound Pressure Level	dB, Hz
$L_{a,max}$	dBA	Maximum level of noise event	dB, Hz
$L_{ae}$	dBA	Sound Exposure Level	dB, Hz, time
$L_{a,eq,T}$	dBA	Equivalent A-Weighted Sound level	dB, Hz, time
$L_C$	dBC	C-weighted decibel	dB, Hz
$Ke$		Kosten Eenheid	dB, time of day, number of events
$L_{DN}$	dBA	Day-Night average Level	
$L_{DEN}$	dBA	Day-Evening-Night average Level	dB, Hz, time of day
$NA_x$	-	Number Above certain dB(a) level	dB, Hz, number of events
$TA_x$	s	Time Aboven certain dB(a) level	dB, Hz, time
IR	%	Percentage of total sound energy that was created above a certain dB threshold	



# Reducing helicopter noise

Rotating blades can have various purposes and their occurrence is thus widely spread. For a rotating blade in a flow, noise is unavoidable. Research for diminishing noise from rotor blades appears spread over various research fields. Whilst investigating the existing work related to noise by military helicopters, papers from several disciplines were studied. In noise reduction research, five distinctions can be made: Reducing the noise at the source by altering the helicopter design, minimising impulsive noise by avoiding certain flight conditions, optimising the flight path to move noise away from receivers, adapting architecture to reduce the noise perceived or investigating non-acoustic factors and attempt to reduce the annoyance from noise.

## 4.1. Quiet helicopters

Reduction of noise at the source is proposed by ICAO as the first step in noise reduction. [21]. Even prior to noise reduction becoming a (main) priority significant improvements were made, being additional benefits of improving the performance of a helicopter. The introduction of turboshaft engines and placement of the engine and exhausts at the topside of the helicopter helped reduce some of the source noise levels [20]. Then, blade design has been improved on aerodynamic efficiency. The British Experimental Programme (BERP) [20] and the Blue Edge [20] rotor blade demonstrate examples where aerodynamic improvement also reduced noise [20]. Furthermore, noise reducing design options have been developed for the tail rotor. Well known are the NOTAR tail [20] and the Fenestrom tail. The latter one reduces noise by its casing which hinders the creation of tip vortices and reduces the energy sent downwards. Next to that, the large amount of irregularly spaced blades spreads the sound energy over multiple frequencies. This diminishes the strong tonal effect. All the above mentioned design improvements are aimed to reduce noise for civil helicopters. For the military helicopters flown by the RNLAf, no or little design changes known by the author have been made to reduce noise. The main customer of the manufacturer, US Department of Defense, has not yet requested design changes for noise reduction in the transport helicopters. Their approach to handle community noise exposure is at the moment more focused on communication.[51]

A number of researches have focused on the understanding and diminishing of noise at the source. The interest is here to create more quiet helicopters. This requires a more fundamental understanding of the aerodynamics of the helicopter. Known to be dominant in certain flight conditions, BVI and HSI get a lot of attention.

Already in 1997, Brentner [3] proposed a method for predicting the high-speed impulsive noise. This work is continued by Liangquan Wang, Guohua Xu and Yongjie Shi [56] who also regard BVI in their impulsive noise prediction method. Morgans, Karabaso, Dowling and Hynes [32] focus on a computationally faster method to facilitate rotorcraft designers on the prediction of transsonic noise which often comes with HSI.

In reducing noise, Shi, Zhao and Xu propose several design changes to reduce the noise as a result of

BVI. However the design adaptations [42, p. 259] proposes are “ an effective approach to reduce BVI noise, make the BVI noise less impulsive (lower high harmonic content in noise energy) and increases the high noise encompassed area”. This would lower the energy in the peaks, but not spread the energy over several frequencies.

Another option in noise reduction at the source caused by tip vortices, is active control [14]. Relatively low-frequency actuation inputs can control the blade response by increasing the distance between vortex and blade which could lower BVI noise. However, [31], reports that success of these techniques comes with increased rotor vibrations.

## 4.2. Noise abatement by flight condition

Another perspective is to look at the flight condition in which noise occurs. This can be used as new limit or optimisation goal in mission planning. To achieve this, a dynamic model of the helicopter is required. Hartjes, in [20], uses an eight degree of freedom model in the European Clean Helicopter Optimization suite (ECHO). The model gives the noise impact for a given simulated motion and (non-standard) atmospheric conditions. The ECHO suite has a set of parameters to represent the Messerschmitt-Bölkow-Blohm Bo-105 helicopter [20]. In 2018 the ECHO suite was used to optimise a night arrival route to a helispot in Rotterdam. The results showed that optimising for noise could lead to 40% reduction in night awakenings. [19] The mitigation strategies that were used were: flying at a high speed (HSI did not reach the population) and avoid steep descents (to avoid BVI), directing the helicopter flight path away from noise-sensitive areas to reduce exposure time, increase incidence angle of receiver and source to profit from atmospheric absorption in the lateral direction by flying at a lower altitude. The ECHO software suite is able to perform noise abatement optimisations and propose new trajectories for certain scenarios but extension of the source data is required to include more difficult manoeuvres. Next to that, to study other weight-class helicopters, the database requires extension.

Stephenson et al. performed several test flights to establish an advice to current helicopter pilots for noise abatement procedures. Several tests were performed with different helicopters, with the heaviest being the AW193 (MTOW 6800 kg) and the S-76D (MTOW 5306 kg). In their research [47] they assess several rules of thumb for different helicopters to reduce noise. Interesting is the presence of 2 weight classes in the same flight test. In some cases, the same advice works for both classes, in others it does not. No conclusion is drawn on the different outcomes per weight class [47, table 1 and 2 p. 13-14]. No such tests for heavy helicopters are known to the author.

## 4.3. Noise abatement by flight path

For many helicopters, especially heavy-weight/military rotorcraft, little dynamic or aeroacoustic models exist or are publicly available. This makes it harder to calculate noise abatement manoeuvres.

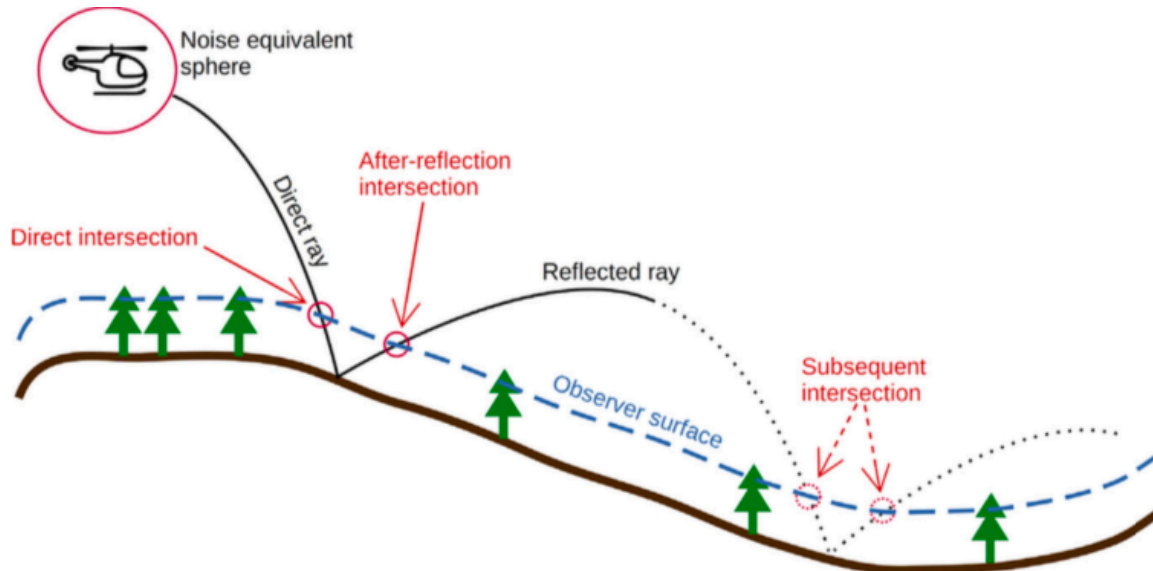
To assure safety and to avoid noise annoyance helicopters are, in most countries, restricted to laws. In the Netherlands, for military helicopters, laws exist for minimum flyover altitudes and noise mitigation. These laws, Luchtverkeersreglement chapter 44,45 and 56 and Regeling beperking geluidhinder luchtvaart include measures such as no exercises between 0.00 and 7.00. On top of that, the RNLAf has additional measures to mitigate noise. Recently, an Initial Point was displaced to guide air traffic further away from a residential area [46].

As no current single event noise prediction model is known for military rotorcraft, a quantitative evaluation on the reduction of noise is difficult to evaluate. Currently, a qualitative assessment by interviewing stakeholders and collecting complaints on the annoyance of the noise is used as evaluation method.

## 4.4. Sound proof architecture

The surrounding of the receiver can play an important role in the perceived noise level. Large objects such as buildings can reflect sound or form shadows, similar to light waves. Noise interaction with the ground, the in ground effect, can increase the noise experienced below the rotorcraft [35]. Research to understand the behaviour of rotorcraft in a complex urban geometry [8] is thus required to comprehend the noise contribution of operations such as emergency response evacuations.

Figure 4.1: Reflection of a sound ray influenced by the ground [41]



A complex geometry can cause the formation of shadow zones and thus influence the noise levels perceived. In these shadow zones, noise is not heard. The presence of a shadow zone is dependent on the atmospheric conditions (throughout the day cooling and heating of atmosphere can introduce shadow zones [43]) and the geometry. A method to predict perceived noise taking into account reflection, bouncing and shadow zones has been recently published by Serafini et al. [41]. Sound perceived at a location could be a reflected sound wave of a helicopter flying far away (not in sight), see Figure 4.1.

Next to that, the architecture of the surroundings play a big role. Some buildings, often houses, are more susceptible for low frequency noise. Low frequency noise can then bring the facade of a house into motion which then lead to a lot of noise by other vibrating objects. This is known as rattle noise, and is perceived as very annoying. Consequently, an extra punishment of 5 dB to the noise impact contour is added when rattle noise is expected [62].

## 4.5. Non-acoustic factors

Lastly, non acoustic factors entail what is in between the sound that people hear and how they experience that. Current research provides many options to express sound and how sound is perceived. Yet some questions remain. Why can humans hear some sounds so well and why are some sounds annoying?

Differences between the experiences of a person in a (scientific) test set-up and a neighbour of a (helicopter) airport are explained with non-acoustic factors. The community attitude plays a role in noise annoyance. Ollerhead and Jones studied the role of non-acoustic factors for the London Battersea airport in 1994 [33]. This was recently redone [10], and similar factors appear to matter in the perception of noise. An overview of the most prevalent factors in the studies are given below, see Table 4.1.

Ollerhead and Jones [33]	Stephen Dance and Louis Gomez-Agustina [10]
<ul style="list-style-type: none"> <li>invasion of privacy</li> <li>belief that the noise could have been prevented</li> <li>perception of safety (fear that noisy aircraft might crash)</li> </ul>	<ul style="list-style-type: none"> <li>invasion of privacy</li> <li>having to choose between noise or too much heat in summer time</li> <li>perception of leisure (unnecessary) flying</li> </ul>

---

Other researchers suggest correctional factors based upon non-acoustic experiences [2]. More research is required to fully understand the relation between humans and how noise is perceived. It appears that the community attitude is local, complex and cannot be easily compared internationally. Clear is, that how annoying a noisy sound is, can be affected by the attitude of the receiver towards the producer. This can also explain why noise experiences documented in noise complaints may differ for similar noise levels.

# 5

## Modelling and measuring helicopter noise

The first objective in helicopter modelling was to understand which noise sources made what contribution to what humans here when a helicopter passes. As explained in previous chapters, the dominant noise source for a helicopter is dependent on flight condition and helicopter type. Recent studies [[60],[63], [31], [59], [56], [32], [42], [14]] investigate impulse noise sources to predict when they become the dominant noise source. The aim of these more fundamental studies is to suggest design changes to reduce noise by changing the aerodynamics of the helicopter.

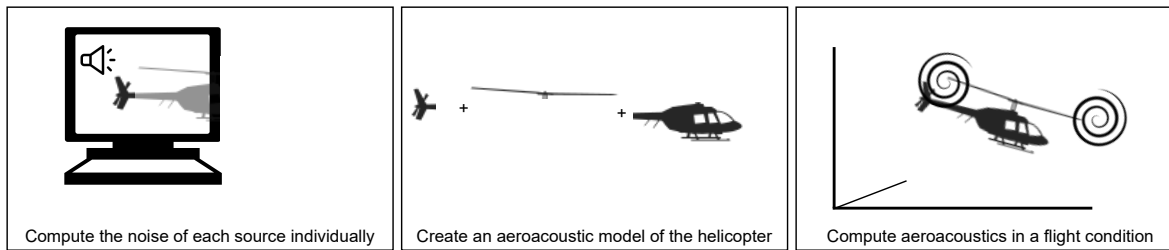
The market for helicopters is still growing and likewise are the flown flights. As helicopters are not likely to become silent or not noisy anytime soon, more and more interest arose to not just focus on quieter helicopters but also look into other ways of reducing noise, see chapter 4. Next to noise, emissions exhausted have been studied. In several places in the world, programs aim to research and reduce these negative effects.

Helicopters fly low and often close to communities. This creates a demand for regulations and studies to reduce the noise annoyance even if the noise itself cannot be diminished. The focus here is to establish a quantity of sound that reached the ground at a certain location. Because the sound created by the helicopter is rather an (complex) interaction with the local atmosphere than a clear process it is an option to not compute the sound but measure the helicopter as a noise source. Several measurements with a microphone array are then combined to a hemisphere. Using hemispheres, the directivity of the helicopter noise is captured and the helicopter can then be modelled as a point source. Another option is to measure a helicopter flying alongside a prescribed path to create a Noise Power Distance table. Lastly, in order to provide more transparency in the loudness of airports, measuring networks have been installed. These noise measuring networks provide constant information on the loudness of passing aircraft (this includes both airplanes as well as helicopters).

This chapter provides an overview of these noise quantification methods. These processes are ordered from fully computational (section 5.1 to fully measuring (section 5.4).

The third process measures a manoeuvre and creates a table that reports noise levels at a certain distance. This captures the noise of a manoeuvre rather than an instant and is used for yearly reports. In yearly reports the weather conditions are often assumed to cancel out differences: this means that on an individual base the noise produced by a manoeuvre may be different from the table. Lastly, several airports have noise measuring networks installed to inform residents on the noise levels produced by aircraft. This is a measuring network that informs how much noise was received at the ground when a helicopter or aircraft flew over that point.

Figure 5.1: Computational modelling of a helicopters noise sources



## 5.1. Computational Modelling

Already in the first half of the 20th century researchers distinguished two mechanisms that create sound for rotating blades: loading and thickness noise, see subsection 2.3.2. After the introduction of the turboshaft engine, the main rotor became the main source of noise. In the 1970's Ffowcs Williams and Hawkins were able to rearrange the Navier–Stokes equations into an inhomogenous wave equation with monopole and dipole sources on the body surface and a quadrupole source distribution in the volume surrounding the body, [4]. The Kirchhoff method is extended in [13] to a moving surface. This breakthrough inspired other researchers to investigate the impulse noise sources. With the aid of more computational power, the mechanisms behind BVI (subsubsection 2.3.3 and HSI (subsubsection 2.3.3 were found. The FW-H equations are the basis for many current tools.

To determine the noise of a helicopter a computational model can be created. This can be done by adding each source individually and thus creating a calculated whole, see Figure 5.1. Manufacturers often use computational models to determine which noise is created by which component. This requires an outstanding understanding of the interactions of the aerodynamics but proves useful in research to diminish noise sources. Such models are used to predict phenomena, see subsubsection 2.3.3 and subsubsection 2.3.3 or to create noise abatement procedures section 4.2. The focus is on understanding the aerodynamics of the helicopter and less on the interactions with weather or on how the helicopter is perceived. For the helicopters of the RNLAf no such noise source models are known to the author.

## 5.2. Modelling with hemispheres

In noise modelling with hemispheres, the helicopter is measured as a whole to accurately capture directivity. This provides less understanding of which noise source causes which noise but gives the option to compute the noise on a ground contour.

### 5.2.1. Process of hemisphere modelling

In accurately calculating/modelling the received noise at several positions a judgement has to be made balancing accuracy and computational cost. Noise is created by aerodynamic flows from sources, as well as interactions of the flows a time and distance later. To oversee the computational effort or complexity of the calculation, a cut is made where the noise is caused by interactions and where the noise is merely a function of distance. This distinction is called the near field and far field, as mentioned in a.o. [61].

For the near field it is important to capture the noise sources due to aerodynamic interactions between medium and passing object/rotorcraft. Measuring the noise created by the helicopter overcomes the not-knowing of the exact process behind the noise, but shifts the focus on accurately capturing the noise.

The most used options to measure the source noise of a helicopter is a hemisphere. The most important assumption here is that for a receiver further away (in the far field) the noise of the helicopter can be modelled with a single noise source at a point in space. [18]. To obtain a noise contour, the flown track is discretised. To every location point a hemisphere is appointed (depending on the flight condition). The noise can then be propagated as a point source towards the receiver. A simplified representation of this process is shown below, Figure 5.2.

Figure 5.2: Overview of helicopter noise modelling using hemispheres

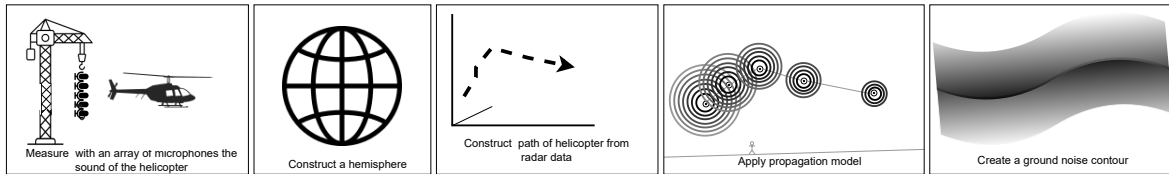
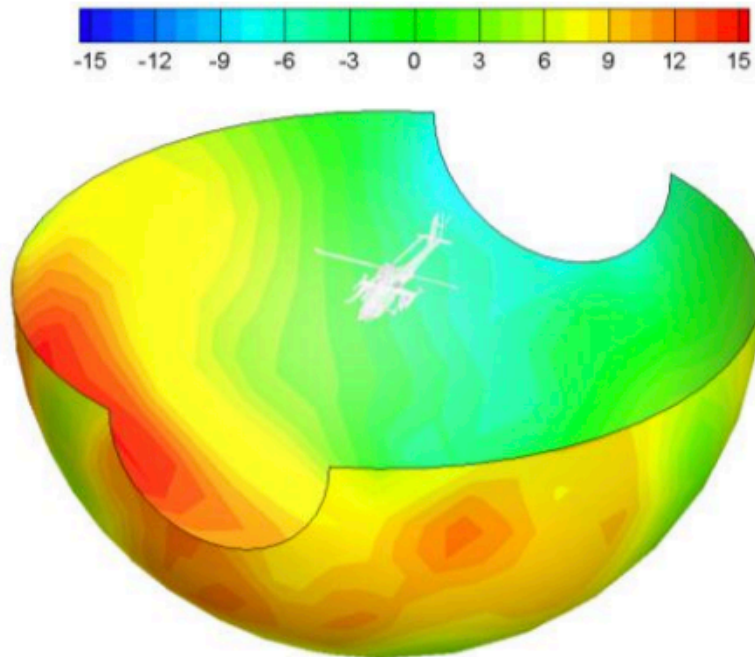


Figure 5.3: Example of a hemisphere from [50]



The process of creating a hemisphere requires an extensive measurement set-up. NLR has created such hemispheres for helicopters of the RNLAf, [50]. Here a setup was used with “a 100m vertical array containing 93 microphones and a horizontal ground array consisting of 13 microphones” [50]. In the data processing, directivity functions were used to construct the hemisphere. Dummel et al [15] used HELENA to compare the accuracy of hemisphere to NPD tables for the EC130 and EC135 helicopter. They concluded an improvement in the accuracy up to 4 EPNdB at a 500 meter distance from the flown track. Furthermore they stated that using the attitude angles of the aircraft, combined with the directionality included in the hemisphere is important in the accuracy of the prediction. An example of a hemisphere is shown in Figure 5.3.

A challenge for the hemisphere source model approach arises due to the highly directive and flight condition dependent noise of the helicopter, see subsection 2.2.1 and subsection 2.3.3. A hemisphere is determined for exactly one flight condition, one helicopter and one loading. Next to that, the atmospheric conditions that affect the source might not be included. Interpolation between hemispheres is not possible (yet). To accurately compute the entire track of a helicopter, an extensive hemisphere database is required. Next to that, the hemispheres are measured for one configuration of a helicopter, especially for military helicopters, the configuration can change. However, the main rotor remains the same, as the main rotor produces the majority of the noise, Figure 2.2, configuration changes are unlikely to produce large differences in the hemispheres.

Known helicopter noise models using hemispheres are:

- HELENA [45]
- RNM [29]

- NORAH [52]
- HAMSTER [7]
- Q-SAM [17]

### **Helena**

The Clean Sky Joint Technology Initiative announced several goals for 'greener' civil helicopter flight. The main focus of this undertaking is accelerating the development of rotorcraft that are less noisy and emit less harmful gasses. To assess the new technologies several tools have been integrated. This framework is called Phoenix, [45] and to evaluate noise HELicopter Environmental Noise Analysis, (HELENA) is used.

### **RNM**

In the United States, NASA Langley developed a new rotorcraft noise model [29]. This replaces the old helicopter noise model, the Helicopter Noise Model used by the FAA, that used a similar technique for the calculation of noise from fixed wing aircraft. With this, a shift is made from using a database where measured A-weighted SEL values versus distance towards a sound hemisphere.

### **NORAH**

In Europe, a European Civil Aviation Conference (ECAC), uses Doc.29 to calculate aircraft noise. In Doc.29 helicopter noise is currently also calculated with a database of A-weighted SEL values versus distance. To improve the accuracy of helicopter noise prediction a new noise model prototype is now tested. This prototype, NORAH, (NOise of Rotorcraft Assesed by a Hemisphere-approach), might replace the Noise Power Distance table method. NORAH is derived from the earlier HELENA model.

### **HAMSTER and Q-SAM**

Other known (hemisphere) projects are Qinetiq's Helicopter Acoustic Measurement System for Trials and Experimental Reduction (HAMSTER, [7]) and Quasi-Static Acoustic Mapping (Q-SAM, [17]).

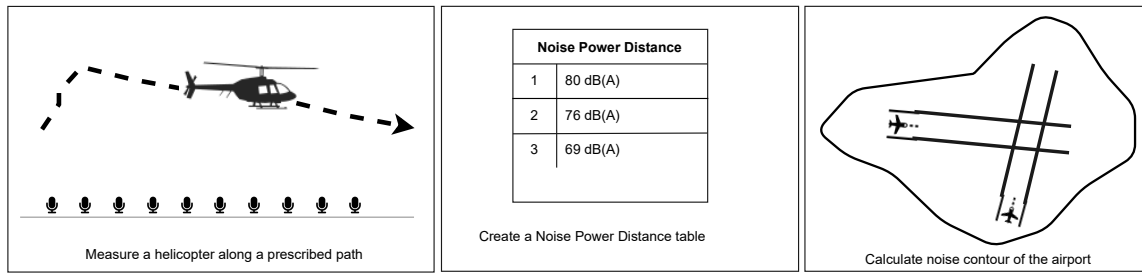
## **5.2.2. Propagation**

Sound emitted by a source loses magnitude over distance. Propagation models calculate how the travelled distance through the atmosphere affects the sound waves. A source emits its sound energy over an ever spreading surface. This results in spreading loss [20]. Next to that, the molecules present in the atmosphere can cause friction and thus a loss of energy called atmospheric attenuation or absorption. Furthermore, the layers divided by altitude of the atmosphere vary in temperature, humidity and sometimes wind. This results in bending of waves, called refraction. This may cause shadow zones, [43]. Previously treated in chapter 4, reflections of the ground also influence what is heard by the receiver, [41]. For single event noise measures, the accuracy of the propagation model plays a big role. An example of a propagation model used by HELENA is AtmosPHERic RefractiOn preDiction mEthod (APHRODITE, [49]).

## **5.3. Noise Power Distance tables**

Another method is to directly measure the noise levels produced by a prescribed path. If this path is flown often and with very similar aircraft, this can provide accurate noise levels. The noise levels are then measured with a set of sound level sensors and recorded in a Noise Power Distance table. If atmospheric conditions are similar or the noise levels are calculated for a large time period (e.g. on a yearly standard atmospheric conditions can sometimes be assumed), these tables can directly be used to calculate the noise levels on the ground.

Figure 5.4: Helicopter noise modelling using Noise Power Distance tables



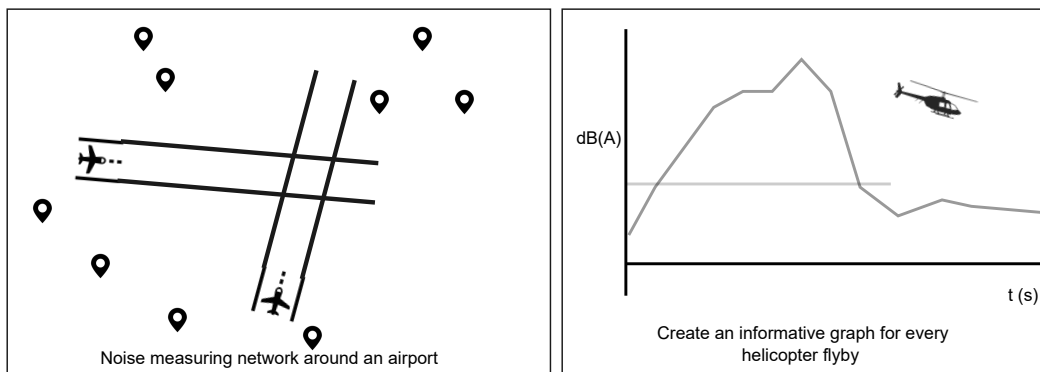
### 5.4. Noise Measuring Network

Whether to calculate or measure noise is an ongoing debate that knows advantages and disadvantages on both sides. In the Netherlands, the noise allowance, capacity planning and the use of the noise allowance are evaluated based upon calculated noise values. Noise measuring networks, installed around airports and near neighbourhoods, have an informative role [44]. The noise measuring networks are not limited to civil airports. Three military airports, Vliegbasis Leeuwarden, Volkel and Gilze-Rijen, have such a network installed. The networks, controlled by Casper [9], track aircraft and measure the decibels produced at the location of the microphone. This informs neighbours on the noise levels produced, next to that, it serves as an informal evaluation tool to compare calculated noise levels. A simplified representation of the noise measuring network installed at Gilze Rijen airport is displayed below, see Figure 5.5.

In 2018 the ministry of infrastructure and water management announced ‘Programmatische Aanpak van het Meten van Vliegtuiggeluid (PAMV), which is a programme that aims to strengthen aviation noise measurements by combining calculating with measuring.[44]

Lastly, the installed noise measuring networks measure the dB(A) levels for each noise event. To provide accurate noise measuring of helicopter flyovers it is important to distinguish a noise event from the background and to know whether this was caused by an aircraft. To distinguish a noise event from the background, the following procedure can be used. A noise event can be viewed as a sound peak in a time series of noise levels. To be called a noise event, the event has to have a certain minimum height,  $L_{Amax}$  and a minimum distance from a previous peak. This peak must also exceed the height of the background level by a determined amount of decibels. A noise event has a maximum length expressed in time or the width of the mountain peak. Challenges here lie in distinguishing several flyovers close to each other and separating aviation and non-aviation noise events. [9] To determine which aircraft caused which noise event, radar tracks of nearby aircraft are connected to noise events. It can occur that the aircraft flies too low to be detected by nearby radars. Then, if the characteristics of the noise event resemble a flyover, the recording is listened to by an expert.

Figure 5.5: Simplified representation of noise measuring network



## **5.5. Comparing modelling and measuring**

Validation of noise prediction models is either done by verifying each computational component individually or comparing the results to other noise predictions. In [15], the predictions are verified with the HELENA model by comparing them to the previous used method, NPD tables. The noise measuring networks are so far not used as a validation method.

# 6

## Conclusions

Helicopters are known to create noise and as they fly relatively close the ground they cause nuisance. The helicopters of the RNLAf whilst performing military exercises in the Netherlands are no exception. Reduction of noise is ideally done by improving the design, however, as this is very time consuming and not always possible other approaches to reduce noise are required. To avoid nuisance, it is also beneficial diminish the noise near the receiver. This can be done by modified manoeuvres.

Determining the amount of noise created by a helicopter can be done with various approaches. To accurately capture the aerodynamic process, source models are made of components. The dominant sources of noise for a helicopter vary per flight condition. What is heard at the ground is dependent on the geometry between the observer and the helicopter and the flight condition of the helicopter. In some flight conditions, impulsive noise occurs. Two phenomena, Blade Vortex Interaction and High-Speed Impulsive noise are known to be loud and when they occur, they dominate the noise spectrum. For the Apache, Blade Vortex Interaction will occur in descent, depending on the acceleration it may occur in a turn. The Chinook is a tandem helicopter and will have Blade Vortex Interaction in every flight condition. The military helicopters do not fly at speeds high enough to cause High Speed Interaction.

All noise reduction is aimed at reducing unpleasant experiences of humans. It is therefore important to understand what exactly is perceived as loud, and what is annoying for humans. The A-weighting was created to compare the loudness of sounds at different frequencies. Some noise metrics evaluate noisiness over a longer period of time, e.g.  $L_{DEN}$ . These metrics use an extra punishment for noise events in the evening and or night. Other metrics are useful to assess one event, e.g.  $SEL$ . This metric integrates the A-weighted sound level over time. In this manner, noise events of different duration can be compared.

At the airforce base in Gilze Rijen, several measures have been installed to reduce noise annoyance. Currently, qualitative noise annoyance experiences are used to evaluate these measures, e.g. keep track of complaints. However, as there are many non-acoustic factors involved with experiences, this evaluation method may not be suitable. To evaluate if installed or future noise abatement measures effectively reduce the noise perceived by nearby communities, a quantitative methodology would be helpful. This methodology should assess noise levels caused by the fly-over of the helicopter as perceived by observers. This should be done on a single event base. As the focus here is on understanding what is received at the ground, it need not to be known which part of the helicopter causes which noise.

This gives the opportunity to measure the noise of the helicopter as a source rather than model it. To capture the complicated noise profile of a helicopter in flight, hemispheres can be used. Since the noise profile of a helicopter can vary a lot per flight condition, a large database of hemispheres is required. A database with hemispheres for the RNLAf helicopters exists. This hemisphere database set is compatible with HELENA software, however this combination has never been used. The HELENA noise model

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is a platform where several methods can be opted. Various choices in modelling may be altered to obtain a result close to what is perceived by an observer on the ground. This requires investigation in the existing hemispheres, constructing the flight paths and choosing an appropriate propagation model. To use these predictions to determine if annoyance is reduced a certain accuracy and reliability are required.

The goal of modelling ground noise is reducing the annoyance for inhabitants in areas where helicopters pass by. Therefore, the metrics used are aimed to represent what noise levels would be observed at a ground location. The question then is, "How can HELENA be used to predict ground noise exposure for helicopters of the RNLAf on a single event basis?".

In order to evaluate if HELENA can provide accurate and reliable ground noise predictions for a large set of flights the ground noise will be computed and compared to measured values. The measured values are provided by the measuring network, as they measure every passing flight, enough measurements are available to create a dataset for iteration and evaluation. The measuring network delivers a  $L_{a,max}$  and  $SEL$  value for every fly-by. These values of the microphones will be compared with the calculated values of HELENA. The measuring networks around the airport have so far only played an informative role, it is to be researched if they can also be used as validation.

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# III

## Supporting material

# 1

## Comparing results from modelling with measurements obtained in test flight for the Chinook

On the 9<sup>th</sup> of September a test flight was performed with a CH-47F Chinook at the military airport in Deelen. The Chinook performed a series of flights, shown in Figure 1.4. Flyovers were measured for climb, level flight and turns. The measurements for climb and level were compared to HELENA calculations.

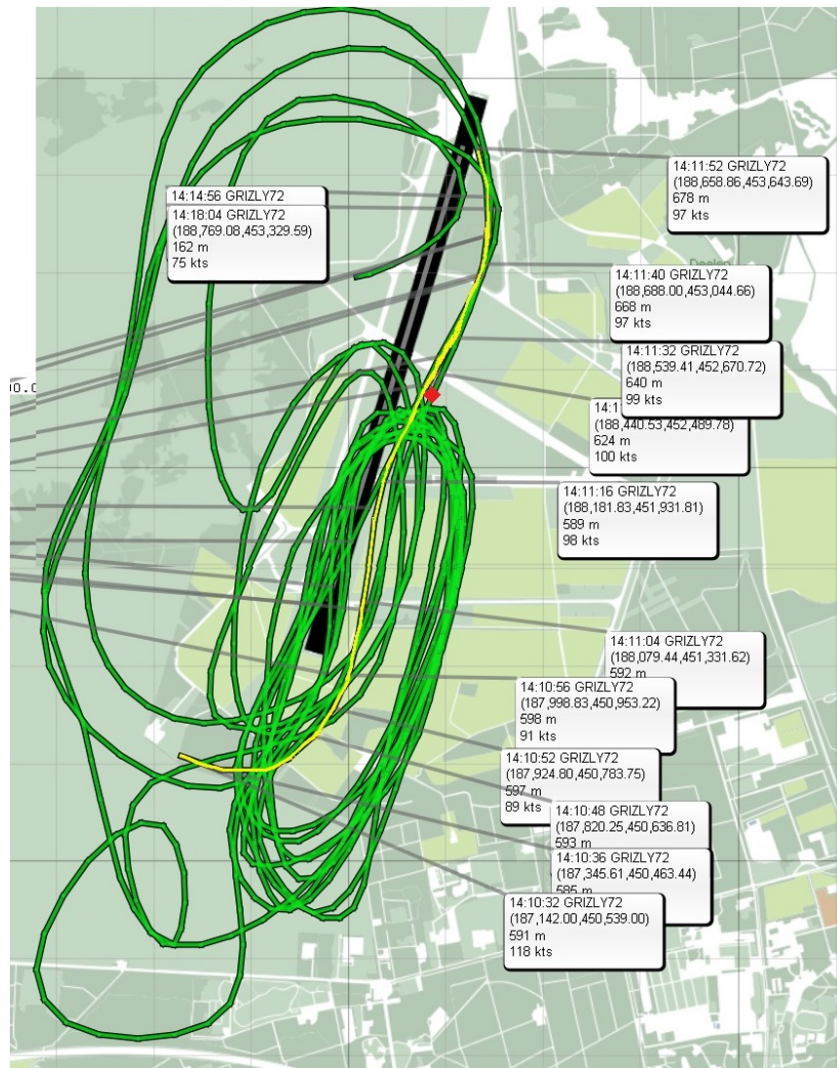


Figure 1.1: Some of the tracks flown by the Chinook at Deelen airport. Microphone is located at the red dot.

The microphone was placed at 1.2 metres height in high grass to minimise ground reflection. The Deelen airport is located in a nature area and the background varied between 35-40 dBA, with no wind or rain present, this provided ideal circumstances.



Figure 1.2: The microphone used at Deelen airport used for measurements.

The following flights were used for comparison:

1. Climb flights (4.5 deg  $FPA/650 fpm$ ).

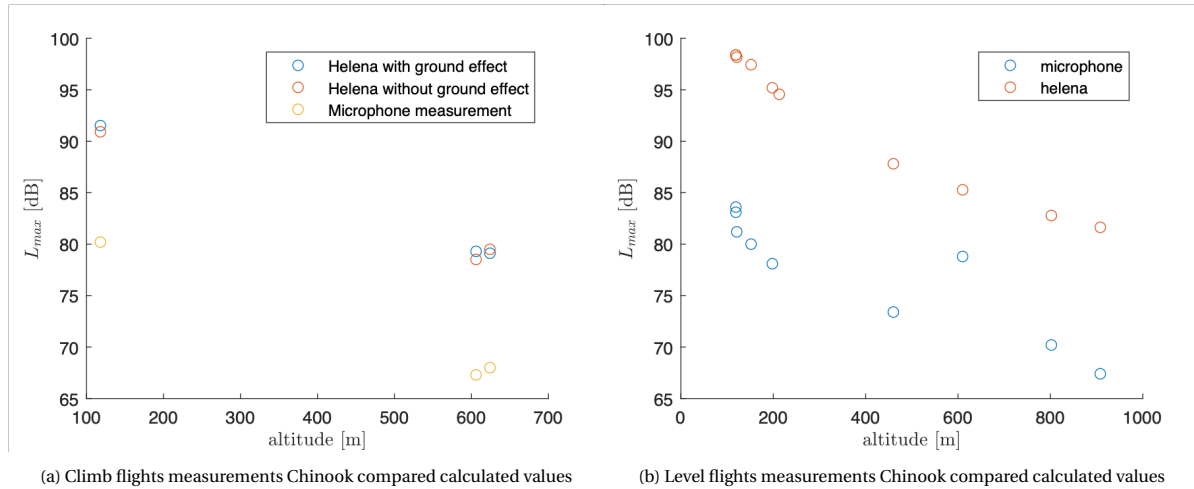
- At 118 metre (390 ft)
- At 606 metre (1900 ft)
- At 624 metre (2050 ft)

2. Level flights (100 kts)

- 118 metre (390 ft)
- 121 metre (400 ft)
- 152 metre (500 ft)
- 198 metre (650 ft)
- 213 metre (700 ft)
- 460 metre (1510 ft)
- 610 metre (2000 ft)

- 802 metre (2630 ft)
- 908 metre (2980 ft)

The results of the comparison between HELENA and the measurements for the level flight showed a large (mean) deviation of  $\mu = 14 \text{ dB}$  with a variance  $\sigma = 3.4 \text{ dB}$ . This indicates that HELENA has a strong overestimation. Note that the A-weighting was deliberately not used here as the Chinook has much sound energy in the lower frequencies. For the climb flight a similar result was achieved, a mean deviation of  $\mu = 11 \text{ dB}$  with a variance  $\sigma = 0.4 \text{ dB}$  show a strong overestimation by HELENA.



The tests flights showed that HELENA cannot be used to model ground noise for the Chinook helicopter. This could be due to the fact that the hemispheres were recorded for the CH47-D type and the flights were flown with a (brand new) CH47-F. Although the exterior of the helicopter did not change much, the flight control system was renewed. All flights were flown using the autopilot, a system that was not available when the hemispheres were measured. Flying using the autopilot has the advantage that the inclination angles of the blade can be set and trimmed perfectly before the helicopter is near the microphone. This gives a very stable and possibly quiet flight. The renewed Automatic Flight Control System (AFCS), in combination with a brand new helicopter and a very clear day might explain to why the difference in noise is so large. Newer helicopters tend to be quieter as they have had less maintenance and thus the rotor configuration is unaltered. Older helicopters may have changed parts, fortifications, slightly deformed parts or maybe the blades are not as symmetric as they were initially. After maintenance, the helicopter's rotor needs to be balanced again. If the weight distribution is slightly different, the blades will be calibrated to provide stable flight. However, (a slightly) asymmetric rotor configuration could create unaccounted for aerodynamic effects, and potentially more noise.

On the other hand, the magnitude of the difference between the measurements of the microphone and the calculations, suggests that several reasons might be behind the cause. It is unknown how much flying with AFCS influences the noise. It is known that AFCS was not present during the recording of the hemispheres but it was used in for the flights in the experiment. In general, the lesser changes of the rotor blades the lesser noise, see also [1].

If the Chinook is compared with measurements from the Casper system the A-weighted value is used as the Casper system does not provide unweighted values. The Chinook has a significant amount of sound energy in the lower frequencies. This is reflected when a flyby of a Chinook is expressed in a  $L_{A,max}$  or a  $L_{max}$ . An A-weighted  $L_{A,max}$  has a much 'lower' (its 2 different metrics) value than a not A-weighted. Thus, comparing A-weighted values for the Chinook raises a concern, would the agreement still exist if the metric was changed from  $L_{max}$  to  $L_{A,max}$ ?

To give an idea for the metric difference, Casper measurements for near direct flyovers were compared with the A-weighted maximum noise values of HELENA. Not that this is not a calculation versus measurement plot, but gather of both measurements and calculations for (near) overhead flyovers.

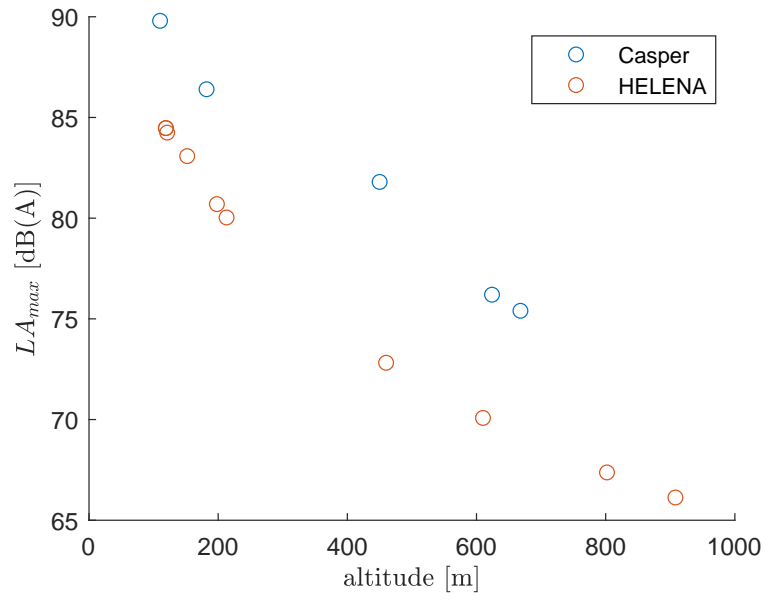


Figure 1.4: Measurements from Casper for (near) direct flyover at several heights compared with Helena calculations of the experiment

- [1] Pascioni et al. "Medium-Sized Helicopter Noise Abatement Flight Test". In: *Vertical Flight Society 76th Annual Forum* (Oct. 2020).

# 2

## 1/3<sup>rd</sup> Octave band frequency analysis

Table 2.1

<b>Centre Frequency</b>	<b>(Hz)</b>	<b>50</b>	<b>63</b>	<b>80</b>	<b>100</b>	<b>125</b>	<b>160</b>	<b>200</b>	<b>250</b>	<b>315</b>	<b>400</b>	<b>500</b>	<b>630</b>	<b>800</b>
Lower Band Limit	(Hz)	44.7	56.2	70.8	89.1	112	141	178	224	282	355	447	562	708
Upper Band Limit	(Hz)	56.2	70.8	89.1	112	141	178	224	282	355	447	562	708	891

Table 2.2

<b>Centre Frequency</b>	<b>(Hz)</b>	<b>1000</b>	<b>1250</b>	<b>1600</b>	<b>2000</b>	<b>2500</b>	<b>3150</b>	<b>4000</b>	<b>5000</b>	<b>6300</b>	<b>8000</b>	<b>10000</b>
Lower Band Limit	(Hz)	891	1122	1413	1778	2239	2818	3548	4467	5623	7079	8913
Upper Band Limit	(Hz)	1122	1413	1778	2239	2818	3548	4467	5623	7079	8913	11220