European Union Aviation Safety Agency

RESEARCH PROJECT REPORT

NOISE: Final report

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Royal Netherlands Aerospace Centre

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SUMMARY

Problem area

To support the full scope of noise monitoring activities required by the European Environmental Noise Directive (END) 2002/49/EC as well as the impact assessment of future aircraft noise policies, an adequate noise modelling capability that encompasses all types of aircraft is required. The current international guidance on aircraft noise modelling (e.g. ICAO Doc 9911, ECAC Doc 29, or Directive 2015/996) is limited to fixed-wing aircraft, thus not covering rotorcraft noise although these are within the scope of the END. Helicopters are generating local noise nuisances and, in the near future, drones and new urban mobility aircraft could create additional ones in densely populated areas. Defining a validated noise modelling methodology for these transport modes is therefore a high priority for the EU.

Between 2015 and 2017, the European Commission DG MOVE tendered the contract MOVE-C2-2014-269 to start addressing this modelling gap, with technical support from EASA. Under this contract, a methodology to compute rotorcraft noise was defined. A generic test plan to acquire helicopter data for noise-modelling purposes was designed and subsequently data was acquired for eight small and medium-size helicopter types that are representative of the bulk of the helicopter fleet operating in Europe. Lastly, a software prototype 'NORAH' was developed to compute the noise on the ground for different flight conditions for a single event and for multiple helicopter operations.

Description of work

The purpose of this framework contract was to build on and extend the work of contract MOVE-C2-2014-269 towards developing and validating a full-fledged noise modelling capability for all rotorcraft, representative of today's and of future operations. Foreseen tasks were:

- Extend NORAH noise propagation modelling capabilities, e.g. to account for urban environment, for varried terrain and vegetation, and weather effects;
- Enhance NORAH source modelling capabilities, covering a wider range of flight conditions than available in the noise database;
- Prepare for the rotorcraft noise tests, including: optimisation and update of the generic noise test plan to cover additional flight modes (e.g. hover), identification and prioritisation of the rotorcraft for the noise tests ensuring a good coverage of European fleet, investigation of the availability and costs for renting rotorcraft and test sites;
- Expand the helicopter types in the NORAH hemisphere repository by dedicated noise testing;
- Implement the revised noise modelling methodology into a new software;
- Validate the NORAH modelling method against benchmark data.

Results and Application

Rotorcraft noise modelling guidance was issued and implemented in a software prototype NORAH2. The hemisphere based approach, is suitable for modelling the noise of helicopters and future transport modes such as drones and urban air mobility aircraft. The method was validated by comparison against benchmark data, such as EASA certification noise levels and internationally established outdoor sound propagation method NORD2000.

Several new capabilities were added tot the rotorcraft noise modelling guidance. A hemisphere interpolation method was derived, that greatly increases the user's flexibility, allowing modelling of flight conditions beyond the ones in the noise hemisphere database. Screening effects from buildings and topography are anticipated to play a substantive role for rotorcraft noise impact and therefore the propagation modelling method was extended to enable inclusion of these effects. To enable inclusion of taxi, idling, hover and turns operations in noise impact assessments, specific modelling guidance was introduced.

The hemisphere database was extended with three helicopter types, increasing the percentage from 70% to 80% of the European helicopter fleet that can be represented by NORAH2. The three helicopter types that were added to the noise hemisphere database are the Guimbal Cabri G2, the AugustaWestland A109 and the Sikorsky S-92.

CONTENTS

ABBREVIATIONS

ACRONYM	DESCRIPTION
AAM	Advanced Acoustic Model, also suitable for helicopter noise modelling, owned by the Volpe Center
BPF	Blade passing frequency
CAEP	Committee on Aviation Environmental Protection
CNOSSOS-EU	Common noise assessment methods in Europe
COFDR	Carry on flight data recorder
Directive 2015/996	Directive that describes the common assessment methods for road, rail, air traffic noise and industrial noise sources, developed within the CNOSSOS-EU project
DG MOVE	The department for mobility and transport (DG MOVE) is responsible for the EU Commission's policy on transport for private and professional purposes
EASA	European Union Aviation Safety Agency
ECAC Doc 29	Guidance on aircraft noise contour modelling
ECAC	European Civil Aviation Conference
END 2002/49/EC	European Environmental Noise Directive 2002/49/EC
HELENA	HELicopter Environmental Noise Analysis, helicopter noise model developed in the FP6 FRIENDCOPTER project
ICAO	International Civil Aviation Organization
ICAO Annex 16	Aircraft noise certification standard
ICAO Doc 9911	Recommended method for computing noise contours around airports
LGB	Last good band
MGP	Mean ground plane
MOVE-C2-2014-269	EC issued contract in which NORAH was initially developed
NORAH	NOise of Rotorcraft Assessed by a Hemipshere approach, a rotorcraft noise modelling method
NORD2000	Calculation method for prediction of noise propagating outdoors, for example traffic noise.

1. Introduction

To support the full scope of noise monitoring activities required by the European Environmental Noise Directive (END) 2002/49/EC as well as the impact assessment of future aircraft noise policies, an adequate noise modelling capability that encompasses all types of aircraft is required. The current international guidance on aircraft noise modelling (e.g. ICAO Doc 9911, ECAC Doc 29, or Directive 2015/996) is limited to fixed-wing aircraft, thus not covering rotorcraft noise although these are within the scope of the END. Helicopters are generating local noise nuisances and, in the near future, drones and new urban mobility aircraft could create additional ones in densely populated areas. Defining a validated noise modelling methodology for these transport modes is therefore a high priority for the EU.

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This report is outlined as follows:

Chapter 2	recapitulates the NORAH (1) project outcome;
Chapter 3	describes the NORAH2 helicopter noise modelling methodology;
Chapter 4	summarizes the extension of the NORAH hemisphere database and provides an overview of the helicopter noise measurement campaigns;
Chapter 5	Provides the details of NORAH2 method in a software prototype, and finally
Chapter 6	provides the project conclusions and recommendations;

2. Overview of NORAH1 project

The text in here was adapated from Tuinstra et al, 2018. Helicopter noise emission is strongly dependent on flight conditions and varies heavily with emission angle. Currently used land-use-planning methods in Europe developed for fixed wing aircraft (ECAC Doc 291) are recognized not to be able to represent helicopter noise with sufficient fidelity. The European Commission therefore commissioned the development of a European approach to helicopter noise modelling under contract MOVE-C2-2014-269. The work comprised the definition of a method, the acquisition of helicopter noise databases to feed the model with empirical data and the development of a software prototype.

2.1 Helicopter noise modelling

2.1.1 Fleet model

To be useable for land-use-planning it is required that the model is able to represent the bulk of the European helicopter fleet. In today's fleet, there are over 350 different helicopter types: too many to perform individual noise measurements. The helicopter fleet modelling aims at identifying those helicopters that aggregately represent 70% of the helicopter noise nuisances, therefore enabling the development of a representative noise model based on just a limited set of helicopter classes. For this purpose, a survey of civil helicopters in Europe was prepared. From the circa 7400 helicopter registrations by the end of 2014, about 350 different helicopter types and 92 ICAO aircraft type designators were derived. Subsequently, the predominant type of operation was added to each helicopter type, including data on the expected number of flight hours per helicopter per annum and average number of take-offs/landings per flight hour, and, wherever possible, helicopter configuration-related weight and noise data. Helicopter types with comparable type designator, configuration, weight and noise data were grouped together in approximately 50 helicopter classes.These helicopter classes were ranked by number of helicopters per class, total number of flight hours per class per year and total number of take-offs and landings per class per year. A selection of representative classes eligible for noise measurements, was finally made from the top-20 helicopter class ranking.

To ensure a coverage of >70% of the European helicopter fleet, eight helicopter classes were identified, represented by the helicopters types marked in red in table 1. Together, these helicopter classes represent approximately:

72% of the total number of helicopters
69% of the total number of flight hours per year
82% of the total number of take-offs/landings per year.

Table 1 List of helicopter classes, helicopter types between brackets are mirrored configurations

Helicopter class	ATD	Included helicopter types
AS350 Ecureuil	AS50	AS50, ALO2, ALO3, LAMA, PSW4
Bell 206 JetRanger	B06	B06, B06T, B47T, H12T, R66
Bell 412	B412	B412, B430, S76
EC120 Colibri	EC20	EC20, EC30, GAZL
EC135	EC35	EC35, EC145T2
Robinson 22	R22	R22, CH7, V500, [A600], [BABY], [DRAG], [EXEC], [SCOR], plus a number of homebuilts
Robinson 44	R44	R44, B47G, B47J, ELTO, UH12
Schweizer 300	H269	H269, BRB2, EN28, [ZA6]

Figure 1 Helicopter types selected for noise measurements (top, left to right): Robinson R22 and R66, Eurocopter EC120 and EC135; (bottom) Robinson R44, Airbus Helicopters AS350, Bell B412 and Schweizer S300

2.1.2 Source model

A hemisphere approach was followed to describe the helicopter noise source. Next-generation helicopter noise models (HELENA, Gervais et al., 2010, AAM, Page et al., 2009) all employ hemispheres, demonstrating a clear consensus on how to adequately capture the complex and highly directive nature of helicopter noise. Hemisphere noise levels are defined at a fixed reference distance of 60m and include effects of atmospheric absorption under ICAO atmospheric reference conditions. Hemispheres are given in one-third octave bands, for frequencies between 10Hz (10th band) to 10 kHz (40th band). Hemispheres are defined as function of azimuth and polar angle, binned in intervals of 10 degrees. For a complete helicopter noise source characterisation a set of hemispheres is needed that covers the entire flight envelope. In NORAH the flight envelope is defined as a function air speed and flight path angle, which are parameter that are not difficult to obtain as input for noise modelling. Due to the occurrence of Blade Vortex Interaction the strongest variation of noise levels is found for descent angles. Specific attention should therefore be given to this part of the flight envelope.

It is impractical to obtain noise databases for all 350 helicopter types in Europe, and therefore a substitution method is employed. The premise is that when one would group helicopters of similar characteristics together into a single helicopter class, similar noise emission characteristics can be expected. To allow variations in noise levels within a class, and do justice to the efforts done by manufacturers to make their helicopter models as silent as possible, an offset of hemisphere levels based on the difference between registered certification levels of the class reference and the helicopter type under consideration is applied. For helicopter types that are shown between brackets in table 1 the helicopter configuration is mirrored with respect to the reference and hence the azimuth angle needs to be reversed.

2.1.3 Propagation model

Unlike the Noise Power Distance relationships employed in ECAC Doc 29, the modelling of source and propagation is carried out seperately. In order to predict the noise levels experienced by a person on the ground from the helicopter noise hemispheres, atmospheric propagation effects need to be accounted for. The noise levels are attenuated with increasing distance due to spherical spreading losses (1/R), atmospheric attenuation (SAE ARP5534, 2013), ground attenuation and reflection (Chien & Soroka, 1975).

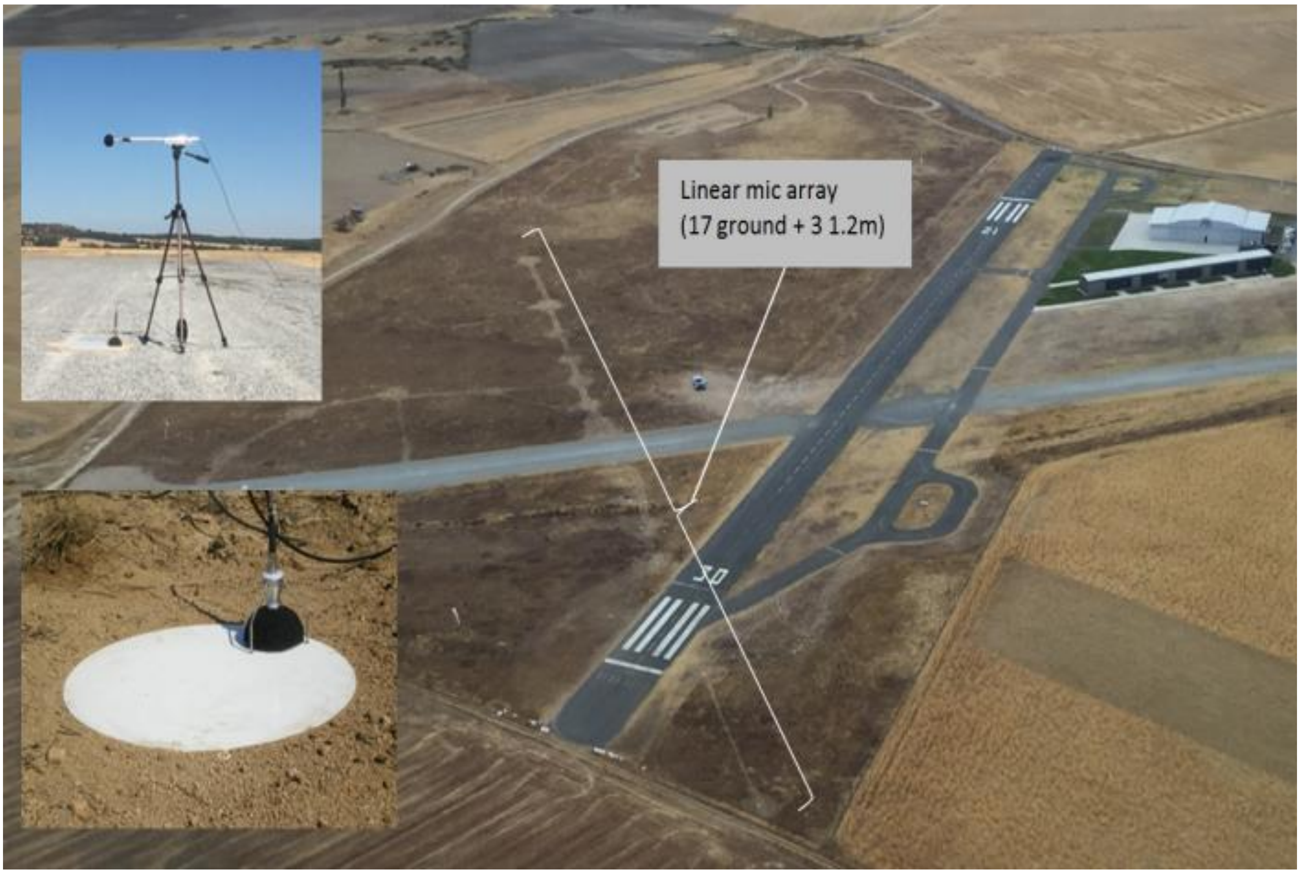

Figure 2 Test setup at Marugan airfield

2.2 Acquisition of the helicopter noise databases

2.2.1 Microphone measurements

To ensure the highest data quality, where applicable, the noise measurements were performed according the guidelines and restrictions as outlined in ICAO Annex 16, Chapter 8. Eight helicopter types were rented from helicopter operators for the noise measurements. These included the R22, R44 and R66 helicopter types, EC120 and EC135, AS350, B412 and S300 helicopter type (see figure 1). The noise measurements were performed at two test sites in the Netherlands (NLR-Flevoland and former airforce base Luitenant-Generaal Bestkazerne) and one test site in Spain (Marugan airfield, Figure 2).

A 420-metre-wide microphone line array comprising 17 microphones on 40cm diameter ground plates was used to perform the noise measurements. The setup allows for the detailed capturing of the directivity pattern for the emission angles that are relevant for noise nuisance evaluation. Additionally, 3 microphones were mounted on a tripod at 1.2m height at certification positions for data quality control purposes.

The setup allows noise measurements for the following emission angles:

- Polar emission angles that occur within the 10dB-down time interval based on Sound Exposure Level
- Azimuthal (or lateral) emission angles +/- 60° from the vertical (for flyover procedures)

Although it is desirable to measure lateral angles exceeding 60° this would have resulted in an exponential growth in complexity and cost of the measurements due to the exceedingly complex experimental setup required. 1/3 Octave band spectra were acquired with a 0.1s interval for a 10Hz to 10kHz frequency range. A central ground station consisting of a mobile office on which a 10m mast with weather station was mounted, was used to measured temperature, relative humidity, barometric pressure, wind speed and direction. Measurements were automatically stored on a PC and actual weather conditions continuously checked against applicable ICAO limits.

2.2.2 On-board measurements

A novel carry-on flight data recorder (COFDR,Timmerman et al., 2017 and Uiterlinden et al., 2017) was developed and used to instrument the rented helicopters. The helicopter trajectories were synchronically measured with the noise measurements by differential GPS. To acquire live data from the helicopter instrument panel an NLR in-house developed on-board video data acquisition system with real-time image processing was employed, recording relevant meta-data such as velocity of the helicopter and rotor RPM. All tests were performed at 90% MTOW or higher. The COFDR was able to record helicopter attitude, position, ground speed and the video of the helicopter instrument panel. Life processing of the video recordings made of the helicopter instrument panel allowed aquisition of indicated air speed (IAS), rotor rpm (RPM), vertical speed (VS) and altitude (ALT) indicators.

The flight data was provided real-time to a guidance application. This unit supports the flight test engineer and the pilot to correctly perform the flight tests within the procedural margins.

Typically, a single helicopter noise measurement campaign consisted of a two-day programme with 4-5 hours of effective measurements per day. The measurements covered ICAO Annex 16 reference procedures and, in addition, “real-life operating” procedures and flight conditions (see figure 3). In total, the combined helicopter noise measurement campaigns covered more than 170 test conditions, 800 runs and 60 flight hours.

2.2.3 Hemisphere processing

Prior to the hemisphere generation process, the noise measurement data were corrected and scaled to hemisphere reference conditions at each time instance. This involves the steps outlined in figure 3. Raw measured 1/3 octave bands are corrected for cable length, microphone frequency response, free field and windscreen response.

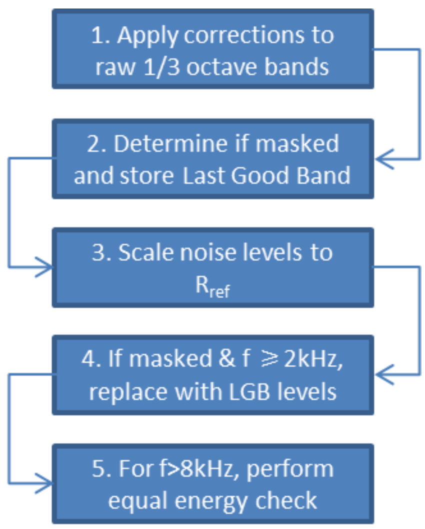

Figure 3 Flow chart preprocessing of noise data

Parts of the measured spectrum maybe masked by the background noise, which needs to be accounted for by determination of the Last Good Band (ICAO Annex 16, 2017) as function of time. Subsequently, noise levels are scaled to a reference distance of 60m. Masked bands are replaced by the scaled LGB levels. Finally, an *equal energy check* is performed for unmasked scaled noise levels above 8kHz. In case the scaled noise levels increase more than 3dB in the next one-third octave band, the following band levels are replaced by the current band level. The rationale is that there is no physical reason for noise levels increasing strongly at the highest frequencies and this is most likely an artefact in the scaling process.

By a binning process the noise levels are averaged on a hemisphere with 10 degrees azimuth and polar angle intervals, leading to a hemisphere for each individual measurements. After processing all repeat runs the hemispheres representing a single flight condition are merged into a single hemisphere. To ensure high quality of the noise data it is demanded that 90% of the acquired velocity samples are within ±5kts of the nominal velocity and that 90% of the acquired position samples located within the airspace contained between γ±γ/12 degrees.

2.3 Software prototype

A software prototype (van Oosten et al., 2018) for assessment of helicopter noise around airport was developed for implementing the proposed method - based on the high- level design given in figure 4. The *Single Event Module* is the main noise calculation engine and contains all processes needed to calculate the noise at an observer grid for a single helicopter flying a given 4D trajectory in accordance with the method described in section 2. The *Multi Event Module* is a shell around the Single Event Module. Based on the user defined input it triggers this latter Module for each individual operation and captures the output for subsequent merging so as to calculate and output the total noise at the observers' position.

This core is fed with all required input data through plain text files that can easily be created with any text editor. Three levels of input exist. *Fixed input* (1) files shall not be edited by the user. This mainly concerns the database with hemispheres. *Case independent input* (2) files shall be defined by the user, however only once for a study or airport scenario. This input can be seen as a database containing all (user-definable) parameters that may occur for the various scenarios within the study. In the *Case dependent input* (3) files the user can build a specific scenario ("case") by selecting the relevant values for the different parameters from the case independent databases and in addition shall provide calculation options.

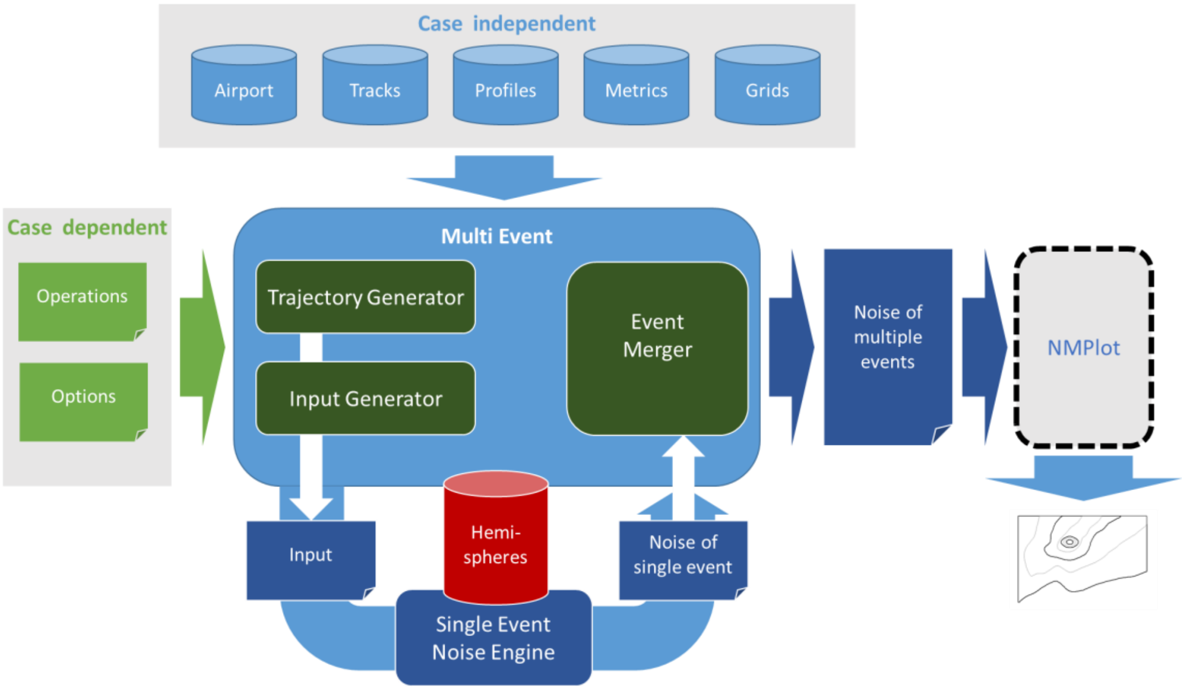

Figure 4 High level design of software prototype NORAH

The output of the core is a data file containing the final noise levels received at the required observer positions. In order to facilitate future integration and also to maximize performance, both core modules (Single-Event and Multi-Event) were implemented in FORTRAN 95 and Python respectively, with ASCII interfaces that can easily be generated by and read from programming languages like C/C++, Python, Matlab, VB.net, C# and FORTRAN. Whilst the development of a GUI was outside the scope of the project, such a facility can easily be added. The software consists in two console programs (*NORAH.exe* and *SingleEvt.exe*) that operate in a three level folder structure (Airport, Case and Single Event level). At airport level, helipads, tracks, profiles and noise metrics are defined by means of ASCII tables with fixed names. Whilst noise metrics and profiles usually are common to most airports they are defined here to provide increased flexibility to the user. At Case level, airport operations and run options are defined. At Single event level, the noise levels calculated for each operation defined in the case are stored. For easy inspection of the calculation results the tool supports “nmplot” output format.

2.4 Recommendations

At the end of the first NORAH project the recommendations were formulated for further model development:

- The base premise behind the helicopter fleet model that helicopters types of similar characteristics possess comparable noise characteristics should be further validated.
- The A109 class should be considered first when extending the NORAH noise database. Covering 8% of the number of helicopters and 6% of the flight hours and take-offs and landings in Europe, this class would have a high impact on the aggregate percentage of helicopters that could be represented by the NORAH model.
- To broaden range of helicopter weight classes represented in the model, the noise database should be extended by inclusion of heavy helicopter types – notably of the A139, S92 and AS32 class.
- Hemispheres are derived for helicopters in steady flight conditions, considering various velocities and climb/descent angles. Further research into the relevance of noise hindrance due to transition between steady flight conditions, accelerated/decelerated flight segments, turns and hover is recommended in order to improve the model’s fidelity.
- The software prototype allows selecting velocities and path angles for which hemispheres are available. Although a broad range of hemispheres and related flight parameters are included, this is a limitation when compared to fixed-wing aircraft noise models like ECAC Doc 29. To increase the flexibility of defining flight trajectories interpolation between hemisphere conditions should be allowed.
- For the present method the lowest considered frequency was reduced from 50Hz to 10Hz in order to capture the main rotor Blade Passage Frequency (BPF). The characteristic low frequency thumping noise of helicopters is known to cause hindrance, which is however not captured in any existing noise metric. The study of low frequency noise hindrance due to helicopters and development of a suitable noise metric is therefore recommended.
- Finally, the propagation module should be further extended to include shielding effects, for example due to noise barriers, buildings, mountains, and other geometries in order to further increase the fidelity of the predictions.

3. Helicopter noise modelling methodology

A comprehensive description of the NORAH 2 Rotorcraft noise modelling method is published (Tuinstra et al., 2023) and available for download on the EASA website. Inhere the improvements with respect to the NORAH method are reported, which are:

- Hemisphere interpolation to allow greater freedom to set flight parameters in the noise modelling.
- Inclusion of screening effects from buildings and topography.
- Inclusion of specific operations such as hover, taxiing and turns.

3.1 Hemisphere interpolation

The NORAH method originally only allowed modelling of flight conditions that are present in the hemisphere database. The rationale was that the trajectories that are modelled by NORAH and the related noise hemispheres are always agreement, resulting in high qualitity noise predictions. In practice however users of NORAH found this overly restrictive, for example when modelling actual flown trajectories (measured by radar), and requested more flexibility. The approach summarized in this section allows interpolation of measured hemispheres based on flight path angle and velocity.

The rotorcraft noise source is described by a set of hemispheres covering a range of flight conditions relevant to noise emission. The flight condition is characterised by both airspeed and rate of flight angle of the rotorcraft. In particular for descents, helicopter noise will vary strongly depending on airspeed and descent angle (see Figure 5). These variations should be captured in the hemisphere data set that make up the source model. Hemispheres shall be available at descent angle intervals of minimum 3 degrees and 4 different velocities are recommended to cover the operational range. The climb region is sufficiently covered by considering a number of climb angles, e.g. 3, 6 and 9 degrees, at the best rate of climb speed (V_y) or a speed typically used in take-off procedures. It is recommended to further: (i) include the maximum climb angle as stated in the aircraft flight manual; (ii) keep level flight conditions at 90% of the speed at level flight for maximum continuous power (V_H) and +10 kts (or V_H whichever is the smallest), -15 kts and -30 kts increments on 0.9 V_H.

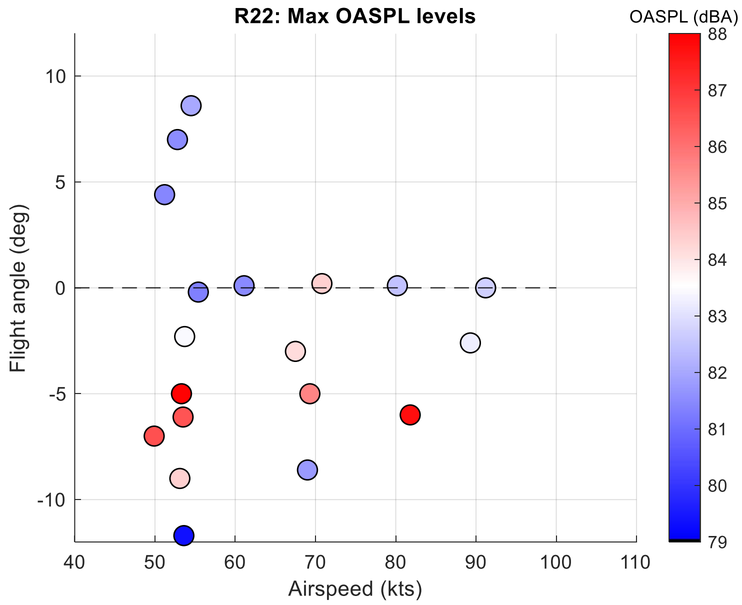

Figure 5 R22 maximum A-weighted sound pressure level at centre microphone, from NORAH1 database.

The hemispheres can be interpolated between the flight conditions to allow for modelling of flight conditions which are not in the database. The interpolation method requires a normalization of the flight path angle γ and airspeed *V*. If the required hemisphere flight condition is within the convex hull of the database flight conditions, distance-scaled-triangle-interpolation is applied. Delaunay triangulation is used to mesh the flight envelope (figure 6a) after which triangle interpolation can be applied (figure 6b).

In case that the required database point is outside of the convex hull, nearest neighbour extrapolation should be used. Nearest neighbour extrapolation uses the hemisphere with the flight conditions closest to the required flight condition.

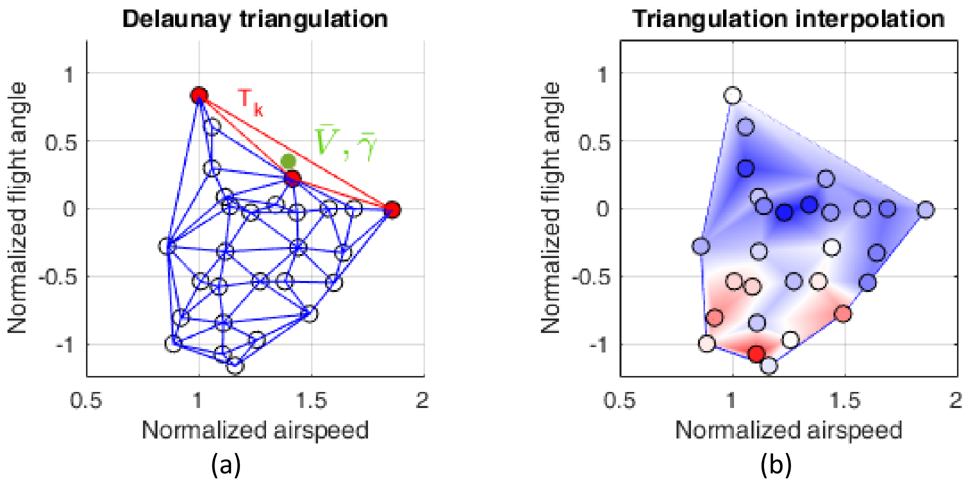

Figure 6 (a) Delaunay triangulation applied to normalized flight conditions of NORAH EC120 helicopter hemispheres, as example Triangle T_k is indicated (b) Distance scaled triangulation interpolation.

3.2 Screening effects from buildings and topography

The NORAH method aims to providing a modelling approach for rotorcraft. Although there is a focus on helicopters, which are the most common occurring rotorcraft in Europe, noise of urban air mobility concepts and drones will likely become more important in the future. Unlike fixed wing aircraft, rotorcraft often operate closer to the earth's surface, typically around 300m altitude. One may anticipate that screening effects for buildings and topography will play a substantive roll for rotorcraft noise impact. Following the guidelines set out in CNOSSOS-EU (Common Noise Assessment Methods in Europe, Kephalopoulos et al. 2012) a modelling method is introduced in NORAH2 to account screening effects for buildings and topography.

3.2.1 Ground absorption for varying topography

The NORAH method originally assumed flat terrain of a particular type (i.e. surface impedance). If the terrain height and surface is varying the effective ground absorption may be different from the case of horizontal ground with even flow resistivity. To account for this, the real vertical cross-section between the source and the receiver shall be represented by the corresponding *Mean Ground Plane* (MGP). This can be calculated by least square regression of the polyline of the straight segments that form the terrain profile (see for example Figure 7).

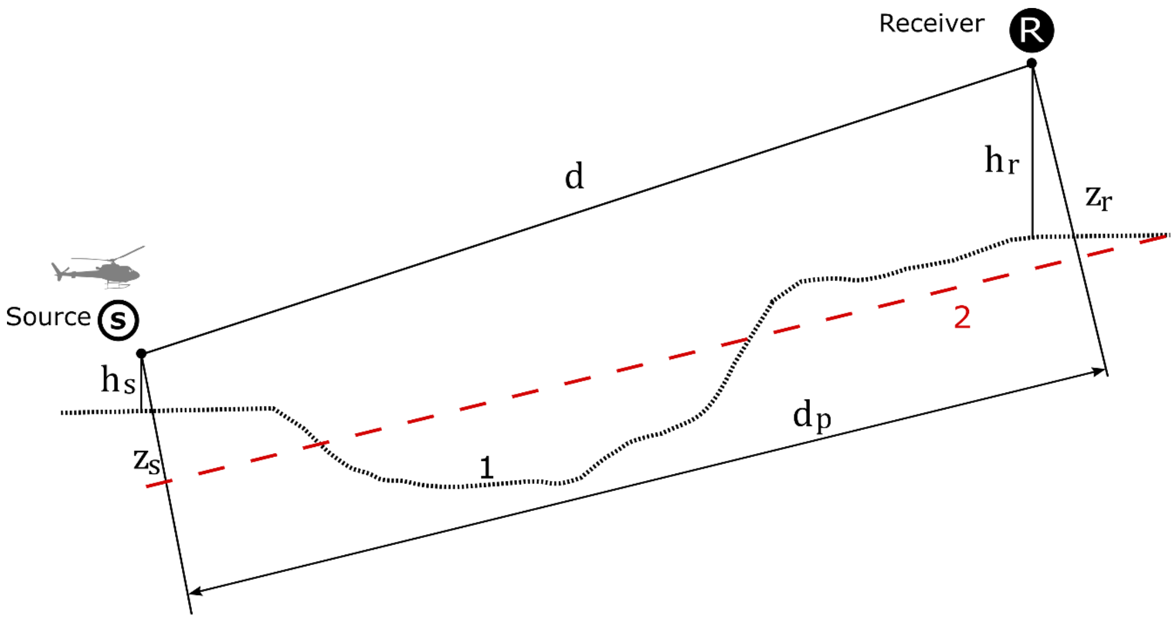

Figure 7 Equivalent heights in relation to the ground, 1: actual relief, 2: mean ground plane, dashed red line

The acoustic absorption properties of the ground are mainly linked to its porosity. Compact ground is generally reflective and porous ground is absorbent. Different types of ground classes are supported, varying from hard asphalt surfaces to soft moss/snow covered surfaces. If the type of ground is not identical across the terrain profile (see for example Figure 8), the flow resistivity is a distance weighted logartimic average.

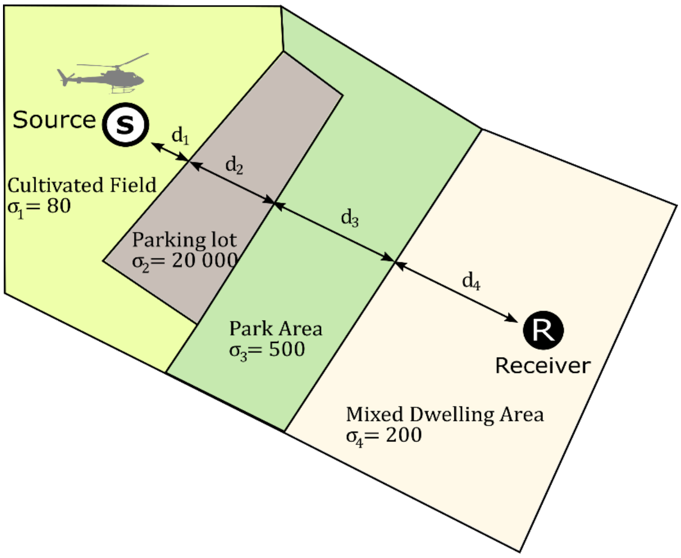

Figure 8 varying surface types over a propagation path

3.2.2 Screening effects from buildings and topography

In case the direct line of sight is blocked, by screening of building- and topography edges algorithms that account for diffraction effects have to be used. This screening effect shall be calculated by use of the *Path Length Difference* as the dominant parameter. When an obstacle interferes with the line of sight between a source and a receiver, this is the difference between the shortest path above/around the obstacle and the direct source-to-receiver line (as if the obstacle was not there). As a general rule, the diffraction should be studied at the top of each obstacle located on the propagation path. If the path passes 'high enough' over the diffraction edge, this effect is negligible and can be ignored.

The used model can be used to process the diffraction on thin screens, thick screens, buildings, earth berms (natural or artificial), and by the edges of embankments, cuttings and viaducts. NORAH2 specifications for screening effects are built upon the Cnossos-EU method. In this method diffraction are only calculated for obstructions. Cnossos-EU does not define the term obstruction, but all the related figures in the method illustrate constructed items like screens or buildings without reference made to topography.

In NORAH2 screening from *topography* is only be considered if the line-of-sight is obstructed. The smallest screening effect is in this case (the path length difference is just above 0) at minimum 5 dB . Negative path length differences are not considered for topography. This is done for two pragmatic reasons. 1) This would require an algorithm to detect sharp edges in natural terrain profiles which is not readily available, and 2) natural terrain is normally very far from the theoretical "thin vertical screen" assumption on which the method is founded. It would obviously be incorrect to account for diffraction from almost-flat terrain which accidently is close below the line-of-sight. The effect of such terrain is well modelled by the ground attenuation model described above.

Screening from *constructed* obstacles (e.g. buildings) is nevertheless defined according to the full method description, including the use of negative *Path Length Difference*. This accounts for situations where rays connect the source with an observer via a direct line of sight, barely passing over the screening object. To include effects of screening of thin objects in the software, the (user) input must define all obstacles specifically. This is currently not supported in NORAH2. Figure 9 illustrates the methodology behind calculation of the attenuation due to diffraction. For a full description of the method refer to Tuinstra et al. (2023).

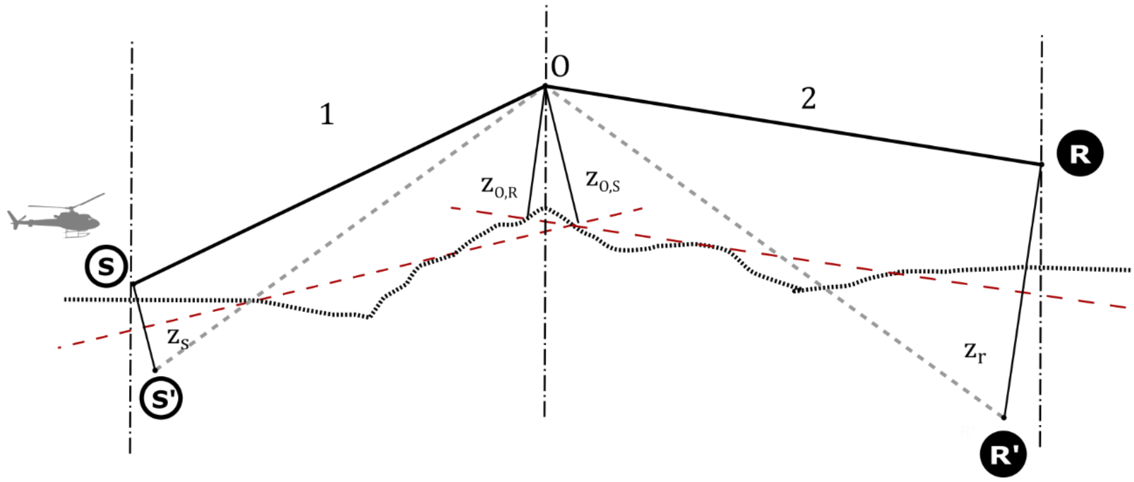

Figure 9 Geometry of a calculation of the attenuation due to diffraction

1: Source side
2: Receiver side

where

S is the source;
R is the receiver;
S' is the image source in relation to the mean ground plane source side;
R' is the image receiver in relation to the mean ground plane receiver side;
O is the diffraction point;
z_s is the equivalent height of the source *S* in relation to the mean plane source side;
$z_{o,s}$ is the equivalent height of the diffraction point *O* in relation to the mean ground plane source side;
z_r is the equivalent height of the receiver *R* in relation to the mean plane receiver side;
$z_{o,r}$ is the equivalent height of the diffraction point *O* in relation to the mean ground plane receiver side.

3.3 Modelling of specific operations

The NORAH method models flight operations as a combination of steady state sections with fixed flight path angle and speed for each section. No guidance nor provisions in the software prototype were offered. NORAH users have indicated the need to account for turns, hover, idle and taxi operations for noise modelling of rotorcraft. Recommendations on how to account for these specific operations are provided below.

3.3.1 Turns

To model the noise levels in turns hemispheres are used that are tilted using the aircraft bank angle (see Tuinstra et al., 2023, section 3.3). The hemisphere with the closest matching velocity and flight trajectory angle should be employed. The interpolation method described in section 3.1 interpolates between flight conditions and therefore for a given velocity and flight path angle, the right source description is automatically selected in a software implementation.

3.3.2 Hover, idle and taxi

In case noise measurements and source descriptions for hover and idle are available these should be employed. Hover, idle and taxi noise charateristics are only defined as function of polar angle only. Several approaches are given for various levels of data availability:

1. Measure noise levels as function of polar directivity for in-ground hover, measure out of ground hover, full-rpm idle and reduced-rpm idle
2. Measure noise levels as function of polar directivity for in-ground hover; measure out of ground hover, full-rpm idle and reduced-rpm idle for a single polar angle and assume an indentical polar directivity as for hover-in-ground-effect
3. Measure noise emission characteristics for in-ground hover as function of polar directivity, for hover-out-of-ground-effect, full-rpm idle and reduced-rpm idle assume indentical polar directivity, correcting noise levels with an empirically derived off-set of +12dB, -12dB and -2.5dB

In the case that no hover data is available, as a first approximation the noise data from 2 sideline microphones during level flight with the lowest available speed may be used to derive a “hover hemisphere”.

4. Extension of the hemisphere database

The NORAH database originally comprised 8 helicopter types, varying from light to medium heavy helicopters. The helicopter database contents is indicated in section 2.1.1 and through a class representation system was able to represent approximately 70% of the European helicopter fleet.

The NORAH database was extented (Table 2) to increase the coverage of helicopter types for which hemisphere noise data is available. An analysis of the Eurpoean helicopter fleet revealed that heavy helicopters were underrepresented in the database, which lead to the selection of the Sikorsky S-92 for noise measurements. The Leonardo Helicopters A109 helicopter class[1] represents approximately 6% of the European helicopter fleet and its inclusion in the database considerably extends the fleet coverage of NORAH. Lastly, the Guimbal Cabri G2 was identified as becoming a progressively more prominent small helicopter type in the European helicopter fleet. Therefore it was selected for inclusion in the NORAH database.

The extension of the NORAH hemisphere database, allows class representation of

- 81% of the number of helicopter,
- 78% of the number of flight hours,
- 89% of the number of take-offs and landings

in Europe. Details pertaining to noise measurements and hemisphere processing are available in van Oosten et al. (2024). In the subsequent sections a brief overview of the performed noise measurements is provided for each of the helicopter types listed in Table 2.

Table 2 Selected helicopter models and test sites for the test campaigns in SC03

HELICOPTER TYPE	Test site	TEST PERIOD
Guimbal Cabri G2	Mollerussa (Spain)	April 2022
Leonardo Helicopters A109	De Peel (Netherlands)	July 2023
Sikorsky S-92	Stavanger (Norway)	September 2022

4.1 Guimbal Cabri G2

4.1.1 Helicopter charteristics

The Guimbal Cabri G2 (Figure 10) is a two-seat light helicopter with a Fenestron-type tail rotor and characteristics as summarized below.

General characteristics

- **Crew:** 2 (Removable controls for left seat)

[1] The class comprises the A109, B105, B427, B429, BK17 and EC45

- **Length:** 6.31 m (20 ft 8 in)
- **Width:** 1.24 m (4 ft 1 in)
- **Height:** 2.37 m (7 ft 9 in)
- **Gross weight:** 700 kg (1,543 lb)
- **Empty weight:** 420 kg (926 lb)
- **Powerplant:** 1 × Lycoming O-360-J2A piston engine , 108 kW (145 hp)
- **Main rotor diameter:** 7.20 m (23.6 ft)
- **Tail rotor diameter:** 0.600 m (23.6 in)
- **Number of main rotorblades:** 3
- **Number of tail rotorblades:** 7
- **Certification noise level:** 75.7 dBA SEL (ICAO Annex 16 Chapter 11)

Figure 10: Guimbal Cabri G2 (source: Anotec)

4.1.2 Test site and microphone setup

The noise measurements were performed at Mollerussa Airfield in spain employing a 420m long linear array (Figure 11) allowing measurements for maximum lateral angles of ±60°. The array comprised of 17 microphones mounted on a 40cm diameter ground plate in an inverted microphone setup and 3 tripod mounted microphones at noise certification reference locations. Additionally, a quarter circle microphone setup was employed for hover noise measurements with both ground plate mounted and tripod mounted microphones at 30° interval.

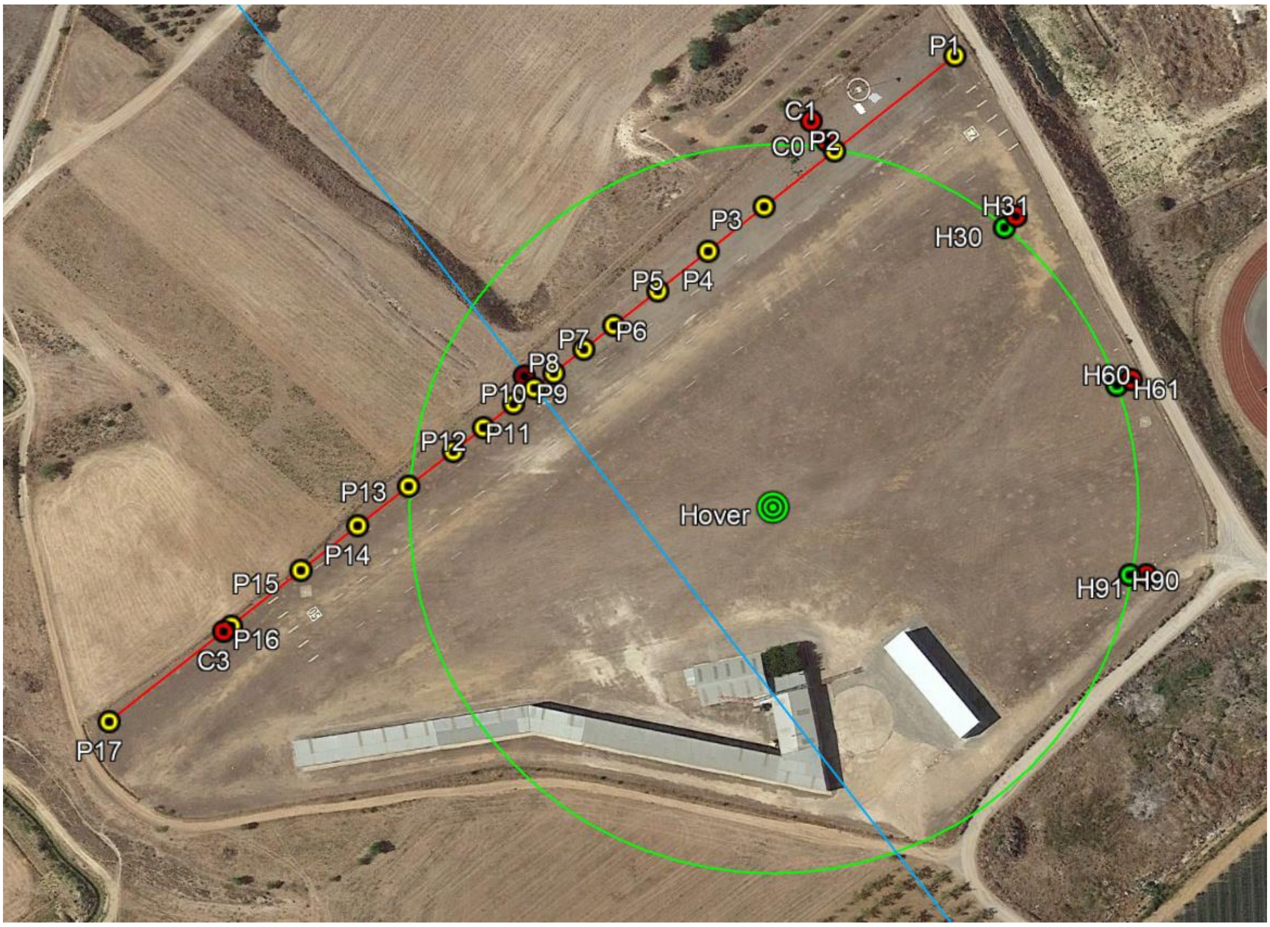

Figure 11: Microphone layout at Mollerussa Airfield, Linear and quarter-circular microphone arrays [Source: Google Earth/Anotec]

4.1.3 Acquired hemispheres

Figure 12 shows a graphic representation of the test matrix with the airspeed on the x-axis and rate of climb on the y-axis. The best rate of climb speed (Vy, green line) , maximum continuous power speed (Vh, blue line) and never exceed speed (V_{NE}, red line) are indicated as well. Following the methodology described in van Oosten et al. (2024), the noise hemispheres were derived for the Cabri G2 and listed in Table 3.

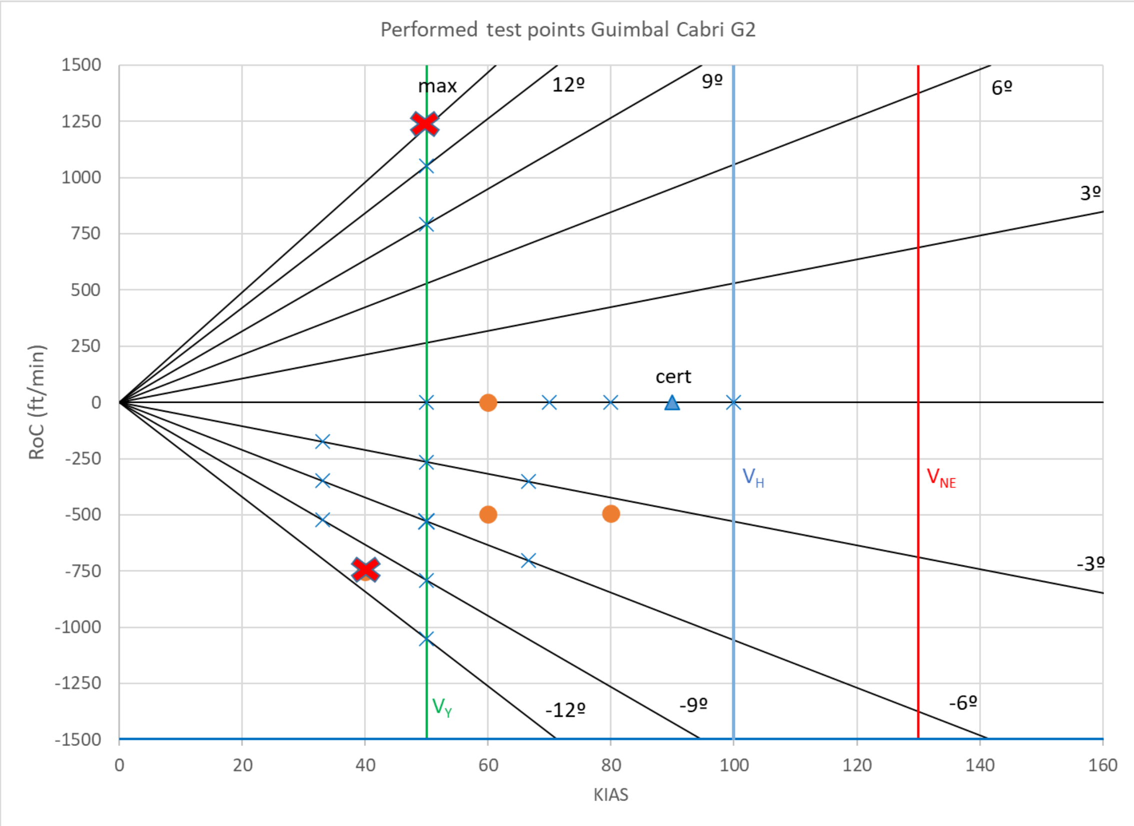

Figure 12: Guimbal Cabro G2 test points. The orange dots indicate points to test the interpolation algorithm [Source: Anotec]

Table 3 : Hemispheres derived from test points

	Speed (kts)	Angle º
Flyover	52.2	0.0
	60.5	0.0
	70.4	0.1
	80.0	-0.1
	89.0	0.1
	89.4	-0.4
	99.1	-0.3

	Condition	Height (m)
Hover	HIGE	1.5
	HOGE	30
	HOGE	60
	Flight Idle	0
	Ground Idle	0

	Speed (kts)	Angle º
Takeoff	50.8	8.3
	50.6	11.1

	Speed (kts)	Angle º
Approach	48.9	-11.1
	50.5	-8.6
	35.9	-8.1
	63.9	-6.5
	49.8	-6.1
	33.3	-5.3
	58.9	-4.9
	31.7	-3.8
	79.2	-3.6
	48.9	-3.0
	68.1	-2.8

4.2 Leonardo A109

4.2.1 Helicopter characteristics

The AgustaWestland A109 (Figure 13, now Leonardo) is a medium weight, twin-engine, eight-seat multi-purpose helicopter designed and initially produced by the Italian rotorcraft manufacturer Agusta. General characteristics are summarized below.

General characteristics

- Main rotor diameter – 11.0 m
- Number of main rotor blades – 4
- Number of tail rotor blades - 2
- Max. Gross weight – 2600 kg (page 49/569 of AFM)
- Minimum weight – 1500 kg (page 50/569 of AFM)
- Basic empty weight – 1741 kg (page 177/569 of AFM)
- Main fuel tank usable capacity – 440 kg (550l) (page 168/569 of AFM)

Figure 13 Agusta A109 at Luitenant Generaal Bestkazerne

4.2.2 Test site

The noise measurements on the A109 were performed at the Luitenant-generaal Bestkazerne, a former ariforce base in the Netherlands. A 420m long linear array (Figure 14Figure 11) was use that comprised of 17 microphones mounted on a 40cm diameter ground plate and 3 tripod mounted microphones at noise certification reference locations. The centre of the array was located several meters next to a taxi runway. Since the flight procedures were flown in parallel to the taxi runway , this could be used for pilot orientation. The hover spot is furthermore indicated, which was located 150m distance from the array centre microphone.

4.2.3 Acquired hemispheres

An overview of the test matrix for the A109 is provided in Figure 15. The best rate of climb speed (Vy) , maximum continuous power speed (Vh) and never exceed speed (V_{NE}) are indicated by the green, blue and red line respectively. Noise hemispheres were derived for the A109 and listed in Table 4 together with the number repeat runs that were used to construct the hemispheres.

Figure 14 Microphone array layout at the Lt. Gen. Bestkazerne in the Netherlands

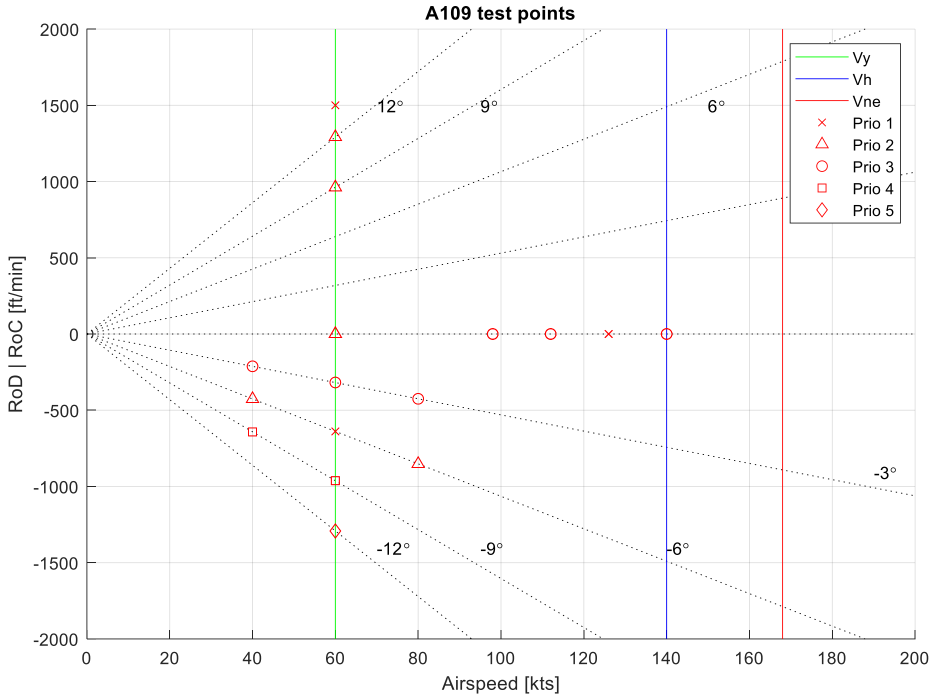

Figure 15: Executed test points for the Agusta A109

Table 4 List of hemispheres

Hemisphere condition	Number of averages
Planned hemispheres	
A109_Approach_42kts_3deg	2
A109_Approach_43kts_6deg	5
A109_Approach_41kts_9deg	4
A109_Approach_60kts_3deg	3
A109_Approach_59kts_6deg	5
A109_Approach_60kts_9deg	6
A109_Approach_60kts_12deg	4
A109_Approach_74.2kts_3deg	2
A109_Approach_73kts_6deg	2
A109_Take-off_63kts_9deg	3
A109_Take-off_64kts_12deg	1
A109_Take-off_62kts_0deg	6
A109_Fly-over_99kts_0deg	4
A109_Fly-over_113kts_0deg	4
A109_Fly-over_126kts_0deg	8
A109_Fly-over_140kts_0deg	3
A109_Fly-over_146kts_0deg	3
Addional hemispheres	
A109_Take-off_67kts_9deg	1

A109_Take-off_68kts_12deg	1
A109_Approach_79kts_6deg	1
A109_Approach_81kts_3deg	1

4.3 Sikorsky S-92

4.3.1 Helicopter characteristics

The S-92 (Figure 16) is a large multi-purpose helicopter powered by two turboshaft engines with a capacity of 19 passangers. Its general characterstics are listed below.

General characteristics

- **Crew:** 2 (pilot, co-pilot)
- **Capacity**: 19 passengers
- **Length**: 68 ft 6 in (20.88 m) [88]
- **Width**: 17 ft 3 in (5.26 m) fuselage
- **Height**: 15 ft 5 in (4.70 m)
- **Empty weight**: 15,500 lb (7,031 kg)
- **Gross weight**: 26,500 lb (12,020 kg)
- **Max takeoff weight**: 27,700 lb (12,565 kg)
- **Powerplant**: 2 × General Electric CT7-8A turboshaft engines, 2,520 shp (1,880 kW) each
- **Main rotor diameter**: 56 ft 4 in (17.17 m)
- **Number of main rotorblades:** 4
- **Tail rotor diameter**: 11 ft 0 in (3.35 m)
- **Number of tail rotorblades:** 4

Figure 16: Sikorsky S-92 (source: Anotec)

4.3.2 Test site and microphone setup

The noise measurements on the S92 were performed at the Stavanger Airport in Norway (Figure 17). A line array (Figure 18) consisted of 12 microphones, of which 9 were mounted on a ground plate and 3 on a tripod. The 2 sideline certification locations (C1 and C3) were displaced 30m towards the runway, in order to avoid interference from the road surface near C3. Furthermore P1 had to be displaced significantly from the main array to avoid interference with the tarmac. This will not have a significant influence for hemisphere construction, which takes into account the actual microphone location. The hover spot is furthermore indicated, located 150m distance from the array centre microphone above the runway.

Figure 17: Stavanger airport – runway 10/28 with notional location of microphone array (source: Google Earth)

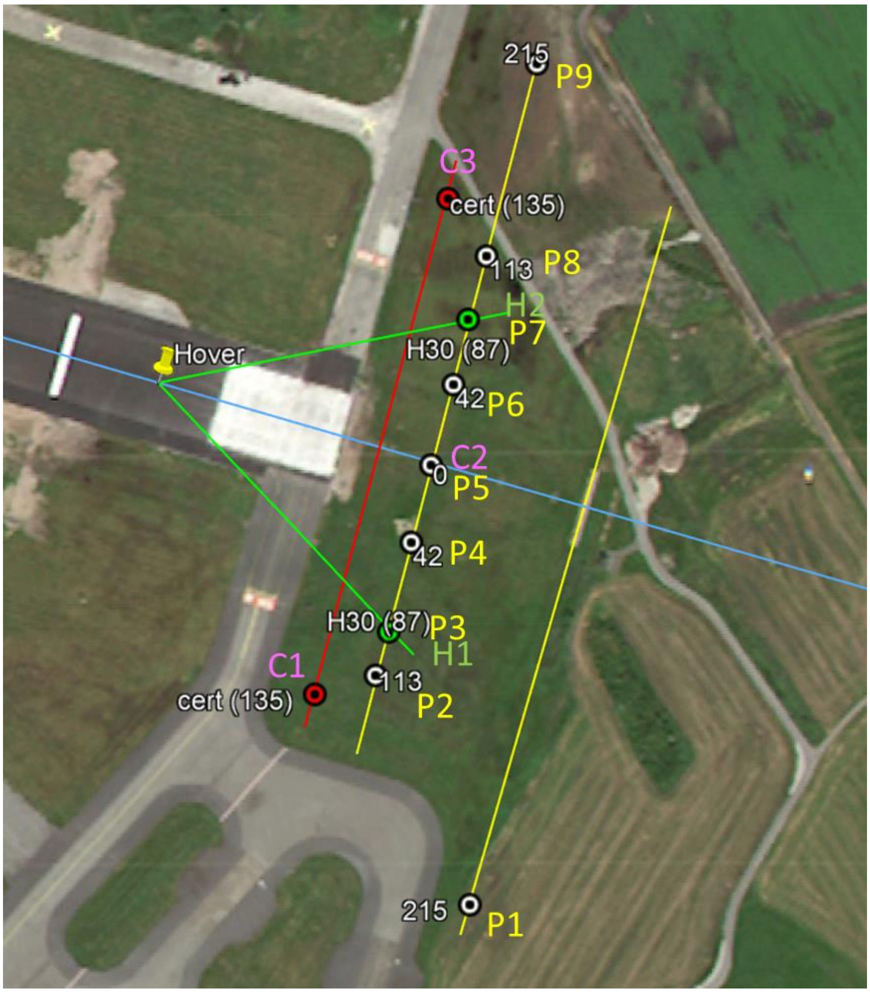

Figure 18: Microphone layout at Stavanger airport [Source: Google Earth/Anotec]

4.3.3 Acquired hemispheres

The test matrix for the S92 is illustrated in Figure 19. The best rate of climb speed (Vy) , maximum continuous power speed (Vh) and never exceed speed (V_{NE}) are indicated by the green, blue and red line respectively. The certification conditions are indicated by the triangle symbols. A list of obtained hemispheres is provided in Table 5.

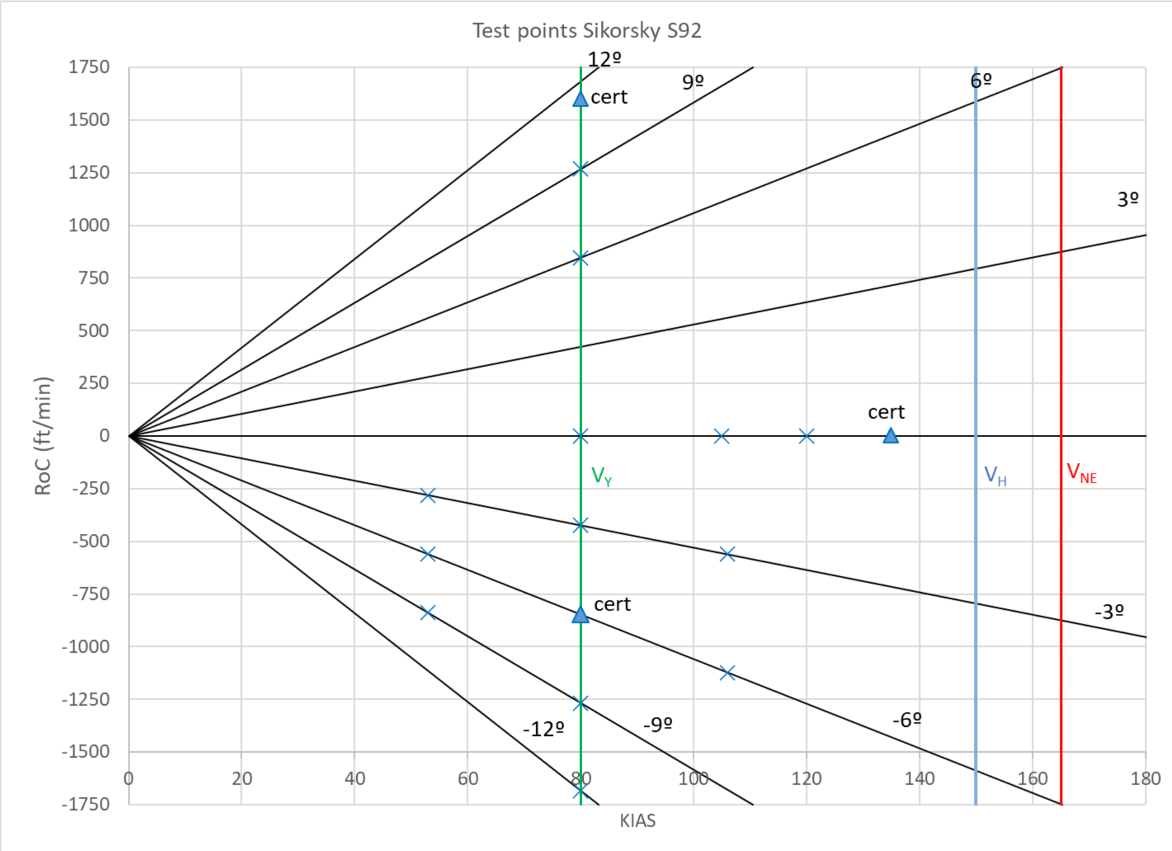

Figure 19: S92 test points.

Table 5 : Hemispheres derived from test points - Takeoff

	Speed (kts)	Angle º
Flyover	133.9	0.0
	80.3	0.0
	105.0	0.0
	120.1	0.0

	Condition	Height (m)
Hover	HIGE	1.5
	HOGE	30
	Flight Idle	0
	Ground Idle	0

	Speed (kts)	Angle º
Approach	78.8	-6.5
	53.0	-6.8
	104.6	-6.5
	80.7	-3.8
	53.5	-5.1
	106.1	-3.2
	79.3	-8.9
	54.4	-10.0
	80.2	-12.5

	Speed (kts)	Angle º
Takeoff	85.3	10.9
	80.5	5.3
	79.5	7.7

5. Software prototype

The NORAH software prototype was updated to reflect the newly introduced methods (see chapter 3) and include the extended hemisphere database. In here the NORAH architecture is outlined providing an general overview of the contents of the software package. The NORAH software prototype is accompanied with user manual (Diez et al., 2024) that described the software architecture, input and output syntax in detail and provides several examples. The NORAH2 software prototype can be found on the EASA website, together with training video's demonstrating how to use it.

5.1 Architecture

Figure 20 shows the architecture of NORAH2 which builds on the architecture of NORAH1. Changes in comparison to the NORAH1 software (see section 2.3) are the option of using radar trajectories as input, the inclusion of topography, the interpolation between hemispheres, the inclusion of flight operations like hover, taxi, and turn, and the inclusion of the NAx and EPNL noise metrics.

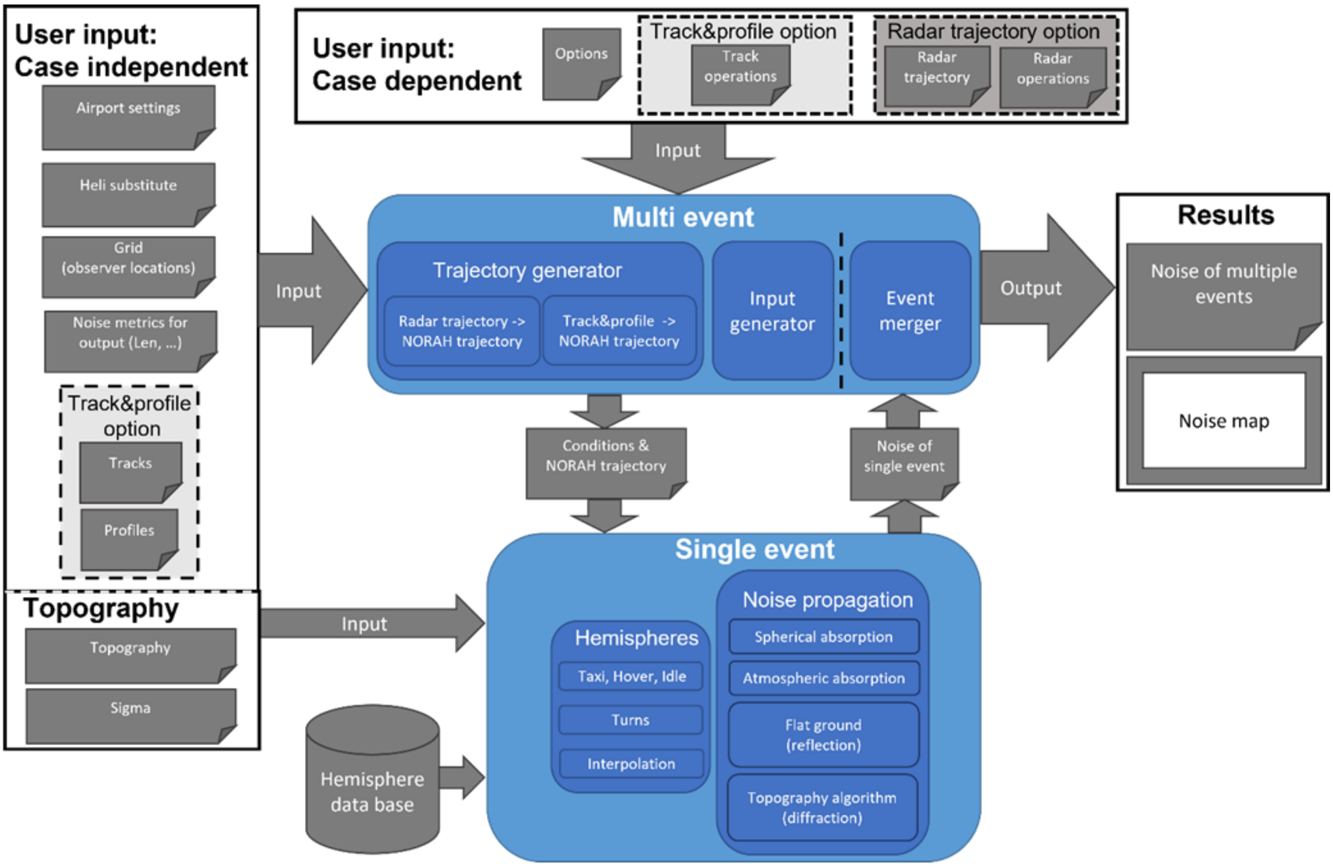

Figure 20 NORAH2 software architecture. Files are presented as gray boxes. Reading and writing processes of files are shown by gray arrows.

A short description of the main modulus of the NORAH2 prototype software is provided below.

User input: Case independent

The user shall define these files only once for a study. This input can be seen as a database containing all (user-definable) parameters that may occur for the various scenarios within the study. NORAH2 has the option to use radar trajectories as input format.

User input: Case independent - Topography

In NORAH2 it is now possible to define a topography as digital elevation model (DEM). Together with the topography file a file with the flow resistivity values sigma in kg/(s·m^3) (or Pa·s/m^2) of the local ground needs to be given. If no topography file is given the surface is treated as flat, soft ground.

User input: Case dependent

The user can build a specific scenario ("case") by selecting the relevant values for the different parameters from the case independent databases. A case can contain one or multiple events. For each of those events flight tacks and rotorcraft specs need to be provided. Flight tracks in NORAH2 can either be given as radar trajectories in combination with a radar operations file or in form of tracks& profiles where a track operations file is used to select the tracks and profiles predefined in the case independent input module. For both input formats the user needs to define the mode of operation (e.g., approach, fly-over, hover) in those files. This is important to choose the correct hemispheres.

Single-event Module

This is considered the main noise calculation engine and contains all processes needed to calculate the noise at an observer grid for a single rotorcraft flying a given 4D trajectory. The module accesses the extended NORAH2 hemisphere database and interpolates or alters those hemispheres using the input trajectory depending on the flight operation. Based on the empirical hemisphere source characterization and propagation modelling, the noise at the observer grid is calculated and saved to a file. For a given helicopter type, the NORAH2 single event module now allows for triangle interpolation for flight conditions not covered by the hemisphere dataset. The single event module was extended to account for topography in noise propagation modelling.

Multi-event Module

The multi-event module is a shell around the single-event module. Based on the user defined input, the multi-event module prepares the 4D NORAH trajectories as input to the single-event module and triggers the single-event module for each individual operation.The output files containing the noise for single operations are read by the multi-event module and merged to calculate and output the total noise of multiple operations at the observers points and on the noise map.

Hemisphere Database

The single event module accesses the database containing all the measured helicopter noise hemispheres and triangulation. The NORAH2 hemisphere database was extended to include the Guimbal Cabri G2, the A109 and S92. Furthermore, a specific hemisphere format was added to support noise emission calculations for special operations such as hover-in-ground-effect, hover-out-of-ground-effect, taxi and idle.

Results

Results from the multi-event module are given in two forms (i) as noise levels at the chosen observer points, and (ii) on a grid that can be presented as a map (for the noise metrices chosen in the input).

5.2 Validation

The validation of the NORAH 2 software prototype has focussed on the quality of the hemisphere database and the correct guidance description and implementation of the 'screening effects from buildings and topography' module. In Olsen et al. (2024) a detailed desctiption of the validation process and results is provided. The key validations steps are:

- Validation against certification levels
- Comparison with established noise prediction models
- Independent implementation of the new propagation methodology

5.2.1 Validation against certification levels

During the acquisition of hemisphere databases for the G2, A109 and S92 three tripod microphones were added at certification positions. This allows direct comparison with the EASA Certification Noise Levels database (Table 6). Overall good agreement is found, with a maximum discrepancy of 1.6 dB and standard deviation of 0.4 dB. This demonstrates overall good quality of the noise measurements.

Table 6 Comparison of measurement results against certification levels for three helicopter types

Helicopter	Operation	Unit	Certification	Measured	Difference
Guimbal Cabri G2	Flyover	SEL	75.8	75.7	0.1
Agusta A109	Take-off	EPNdB	92.4	92.4	0.0
Agusta A109	Flyover	EPNdB	89.8	88.8	1.0
Agusta A109	Approach	EPNdB	91.7	90.1	-1.6
Sikorsky S-92	Take-off	EPNdB	95.3	94.6	0.7
Sikorsky S-92	Flyover	EPNdB	98.7	97.2	1.5
Sikorsky S-92	Approach	EPNdB	96.9	97.5	0.6

To evaluate the NORAH2 implementation itself, executed test certification procedures with the S-92 were simulated, using GPS-track data as input and the acquired hemispheres. A maximum discrepancy of 1.8 dB and standard deviation of 1.2dB was found for the three certification points when comparing prediction against measurement.

5.2.2 Comparison with NORD2000

To validate ground- and topography modelling of NORAH2, a comparison against an established – preferably more advanced – methodology was carried out. A duplicate of the single event module of NORAH 2.0 was created, where the "ground reflections and diffractions from varying topography" module was replaced by

Nord 2000 algorithms. Nord 2000 is a more advanced model compared to NORAH 2.0 and can be regarded as a state-of-the-art methods like the European Harmonoise model and the Swiss model SonAir.

An artificial case was defined for a R22 helicopter departure operation, in the vicinity of a mountain ridge and varying surface type. Figure 21 shows the obtained noise contours that are generally in good agreement, with differences typically in the order of ±1dB. The key conclusion from the comparison with Nord 2000 is that new sound propagation method, and its implementation in NORAH 2.0 software, is sound.

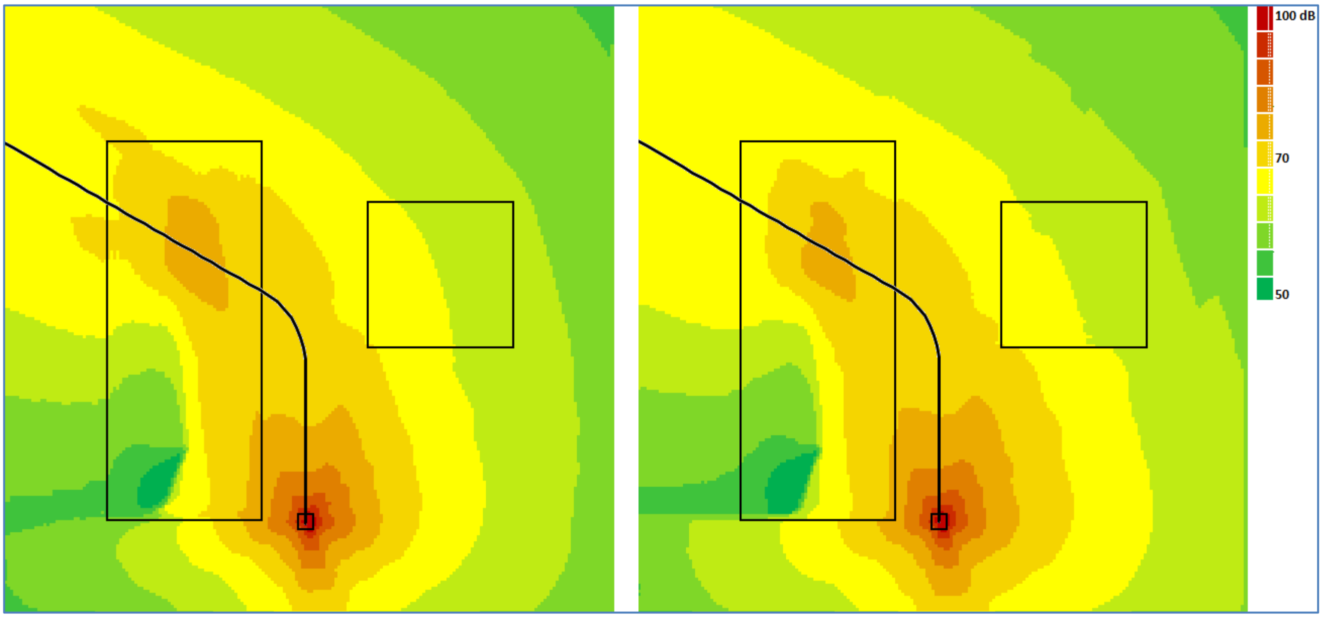

Figure 21 Noise map according to NORAH 2.0 (left) and NORD 2000 (right), rectangle box indicates a mountain ridge topography elemement, square box indicates an area with changed surface impedance

5.2.3 Independent implementation of the Screening effects from buildings and topography

The methodology in NORAH 2.0 for calculation of ground reflection and screening effects is a complex module based on the method Cnossos-EU (Kephalopoulos et. al, 2012). In order to validate the implementation and rotorcraft modelling guidance, an independent MATLAB implementation of the module was realized. This indendent implementation was derived directly from the Rotorcraft Modelling Guidance, confirming that the guidance is complete and without ambiguity or errors. A number of questions were raised from the validator back to the development team, predominantly concerning ambiguities and unclear parts in the descriptions of method details. A couple of bugs were indentified and resolved in the software prototype implementation. After clarifications in the document and updates of the NORAH2 source code, the validation concluded with agreement between NORAH2 and the independent MATLAB implementation and a updated modelling guidance (Tuinstra et al. 2023).

6. Conclusions and recommendations

6.1 Conclusions

A rotorcraft noise modelling method was defined and implemented in a software prototype NORAH2. The hemisphere based approach, is suitable for modelling rotorcraft noise of helicopter, and noise created by future transport modes such as drones and urban air mobility aircraft.

Several new capabilities were added tot the rotorcraft noise modelling guidance. A hemisphere interpolation method was derived, that greatly increases the user's flexibility, allowing modelling of flight conditions beyond the ones in the noise hemisphere database. Screening effects from buildings and topography are anticipated to play a substantive role for rotorcraft noise impact and therefore propagation modelling method is extended to enable inclusion of these effects. To enable inclusion of taxi, idling, hover and turns operations in noise impact assessments, specific modelling guidance was introduced.

The hemisphere database was extended with three helicopter types, increasing the percentage from 70% to 80% of the European helicopter fleet that can be represented by NORAH2. The three helicopter types that were added to the noise hemisphere database are the Guimbal Cabri G2, the AugustaWestland A109 and the Sikorsky S-92.

The modelling method, hemispheres and software prototype will be made available to noise modellers to support noise impact assessments and further research in the field of rotorcraft noise modelling.

6.2 Recommendations

A software prototype and guidance for rotorcraft noise modelling was developed to following the current best practices. Validation has been focussed on the implementation of the methods and the hemisphere data quality It is recommended to broaden the validation into following areas:

- Assess the validity of the current helicopter substitution method.
- Assess of the accuracy of the solutions proposed to model taxi, hover and turn.
- Compare single-event validation of the NORAH predicted noise levels with measured levels, including effect of topography and screening.
- Although challenging, perform a multiple event validation, by comparing NORAH output for a mix of fleet and operations with measurements of noise monitoring stations.

To broaden the range of rotorcraft classes represented in the model, the noise database can be further extended, with in order of priority:

- the inclusion of new heavy helicopter types, specifically the A139, AS32 class;
- incorporation of manned/unmanned (e)VTOL aircraft ;
- the inclusion of the AS55, AS65 and H500 class.

The modelling method was extended to include shielding effects, for example due to noise barriers, buildings, mountains, and other geometries in order to further increase the fidelity of the predictions. The current input format is suitable for definition of topography variation, but not particularly well suited for the definition of an urban environment. Buildings are typically in the order ~10m scale and would require a grid resolution in the order of a few centimeters to provide sufficient accuracy. Suitable input formats (vector based) and ray path tracking algorithms are recommended to be included in the NORAH software prototype to allow effective noise modelling in an urban environment.

The lowest considered hemisphere frequency is 10Hz in order to capture the main rotor Blade Passage Frequency (BPF). The characteristic low frequency thumping noise of helicopters is known to cause hindrance, which is however not captured in currently used noise metric. The study of low frequency noise hindrance due to helicopters and development of a suitable noise metric is therefore recommended.

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