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Aircraft Noise Model Improvement by Calibration of Noise-Power-Distance Values using Acoustic Measurements

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To regulate aircraft noise impact on communities surrounding airports, best-practice models are used to predict aircraft noise levels. In this research the Noise-Power-Distance (NPD) tables in the European Doc.29 noise model are evaluated with measurements around Amsterdam Airport Schiphol. Even with accurate input parameters (thrust and distance to the observer), differences in modelled and measured noise levels are found, which are assumed to be due to the errors in the NPD table. To further investigate this, thrust-noise relations are derived from measurements. These relations are found to differ from the original NPD tables. Using the measured thrust-noise relations, the modelled and measured mean noise levels are in agreement and the standard deviation of the differences is reduced by 25% for departure operations. This finding is consequently verified with independent measurements around Oslo Airport Gardermoen. Next to an improvement in best-practice noise modelling, the methods described in this research give insight into the creation and validation of NPD tables.

Nomenclature

F_n	=	Net thrust [N]
L_A	=	A-weighted sound pressure level [dBA]
$N1$	=	Rotational speed of the low-pressure turbine [rpm]
β	=	elevation angle [°]
ΔL	=	difference between modelled and measured sound pressure levels [dBA]
μ	=	average [-]
σ	=	standard deviation [-]
Subscripts		
A	=	A-weighted
DEN	=	Day-Evening-Night
max	=	Maximum

I. Introduction

Aircraft noise has been a growing problem for communities living around airports. To regulate this noise, models are used to predict the expected noise on the ground. Typically, empirical models are used for these calculations as they are fast and have an accuracy of 1 to 2 dB [1]. The European Civil Aviation Conference (ECAC) developed a harmonised approach to aircraft noise modelling called Doc.29 [2–4]. In three volumes it explains how noise should be calculated and how to verify its results. Doc.29, just like other empirical models, works with so-called Noise-Power-Distance (NPD) tables. In these tables, the (A-weighted) noise levels produced by a single aircraft are documented for a set of power settings and distances from the aircraft. The values in these tables are often determined through measurements during the certification of the aircraft and extrapolated for all power settings and distances.

Although noise models are constantly improving, deviations between calculated and measured noise levels remain [5, 6]. NPD tables are sometimes mentioned as the possible source of these errors. In this study, the effect of calibrating the NPD tables is investigated by processing measurements around Amsterdam Airport Schiphol and Oslo Airport

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Gardermoen. This will be accomplished with the help of flight data from the Aircraft Condition and Monitoring System (ACMS) to validate found results.

The research goal is to improve best-practice noise modelling by calibrating the NPD tables based on measurements. As a first step, the input parameters of the Doc.29 noise model are evaluated. The model results using the found input parameters are then compared to the measured noise levels around Schiphol Airport. From the measured levels, relations between thrust and noise are derived and new NPD tables are created. These new tables are used to improve noise modelling by reducing the found difference between model results and by reducing the standard deviation of the differences by 25%.

II. Methodology

In this research, measurements are used to validate and improve the Doc.29 model. For a correct comparison of the model results to the measurements, accurate model input is necessary. To gain a better understanding of how the Doc.29 model works and what its limitations are, an in-depth analysis of its inputs is performed. Further, when comparing model results to measurements around Schiphol Airport and Gardermoen Airport, the characteristics and uncertainties of the microphone systems need to be known. In this section, these subjects are discussed.

A. Doc.29 model

In the ECAC developed Doc.29, calculation instructions on how to model perceived noise on the ground are given. Doc.29 works similar to the Aviation Environmental Design Tool (AEDT) and the Dutch Noise Model (NRM). These are so-called empirical models, i.e., based on measurements.

In Figure 1 a flowchart of the Doc.29 model is given. As mentioned, the model uses NPD tables which require two input parameters, i.e. engine power (thrust) and distance between source and receiver. Distance is found from the (expected) flight path of the aircraft and can thus be estimated accurately. The thrust estimation, however, is more difficult. For the modelling of planned flights, an estimation of the thrust profile is done by so-called procedural steps. For each flight phase (take-off, climb-out etc.), a thrust setting is assumed. A few default procedures can be found in the Aircraft Noise and Performance (ANP)* database. These procedures differ by aircraft weight. The weight of the aircraft is estimated on the expected distance that the aircraft has to fly and thus the amount of fuel it is carrying. Although many studies on how to estimate thrust from historical flights are being performed, a lack of validated data is still present. For thrust estimation methods based on aircraft performance, information about the weight and aerodynamic properties of the aircraft is needed. In Strümpfel and Hübner [7] ADS-B data and the Base of Aircraft Data (BADA) [8] are used which result in an 11% mean absolute deviation for thrust estimation. For this contribution, a different approach is followed and thrust is derived from the acoustic data and consequently validated with flight data from the Aircraft Condition and Monitoring System (ACMS). This method is described in van der Grift et al. [9] and is based on fan tone estimation as described in Merino-Martinez et al.[10]. Here the thrust could be estimated with a 4% accuracy, improving on earlier methods.

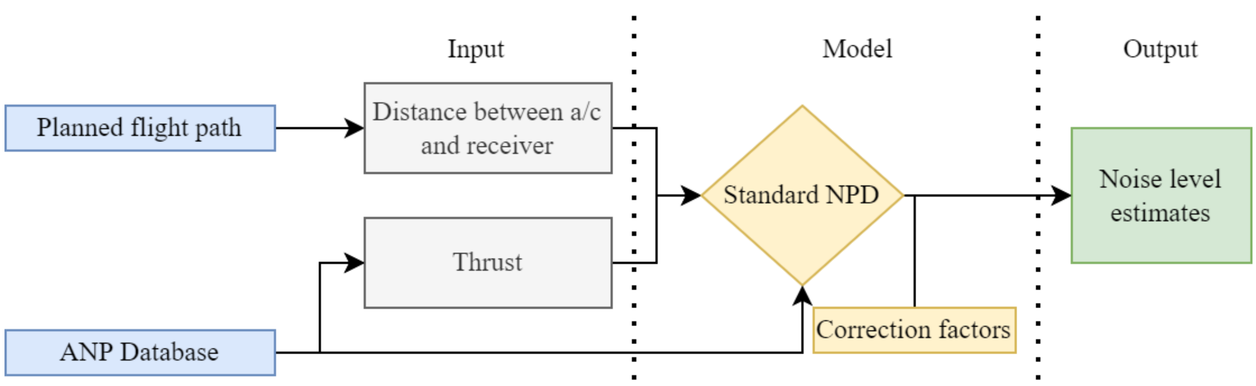


Fig. 1 Flowchart of input and output of the Doc.29 aircraft noise model.

*https://www.easa.europa.eu/en/domains/environment/policy-support-and-research/aircraft-noise-and-performance-anp-data/anp-legacy-data

The NPD tables are given for most aircraft types but are often generalised. For example, the B737-700 and B737-800 make use of the same NPD table. A general NPD correction factor, based on the configuration of the aircraft (engine-frame combination) using the EASA Type Certificate Database and its noise record number, is given for each aircraft. These noise record numbers can be found in national registers such as the Dutch aircraft register† for each specific aircraft tailnumber. The correction factor is a single offset in dBA applied to all NPD values, depending on departure or approach. Over the years, newer and more efficient engines have been placed on aircraft. This development is visible through changes in these correction factors.

The NPD tables are given for a set of standard situations (right underneath the flightpath, ISA atmospheric conditions etc.). For operations deviating from these standard conditions, correction factors are applied. These correction factors can have a significant effect on the calculated noise level.

B. NOMOS measurements

The Noise Monitoring System (NOMOS) encircling Schiphol Airport comprises more than 40 unattended continuous Noise Monitoring Towers (NMTs) that have been operational since 1993. Each tower is equipped with class 1 microphones which have an uncertainty of 0.7 dB for elevation angles surpassing 60°[11]. They stand on poles ranging from 6 to 10 meters in various locations. Primarily designed for public awareness, these NMTs are strategically positioned in and around communities, as depicted in Figure 2. Detailed tower locations are available on the NOMOS website‡.

For the present study, only NMTs meeting the validation criteria outlined in Sahai et al. [12] have been utilised. The number of measurements from each NMT used in this research is shown in Table 1. These stations record noise levels ($L_{A_{max}}$ and SEL) for each noise event and provide down-sampled (8000 Hz) mp3 files. While $L_{A_{max}}$ and SEL values are used to update the entries in the NPD table, the mp3 files are used to derive $N1\%$ from the blade passing frequencies of the engines.

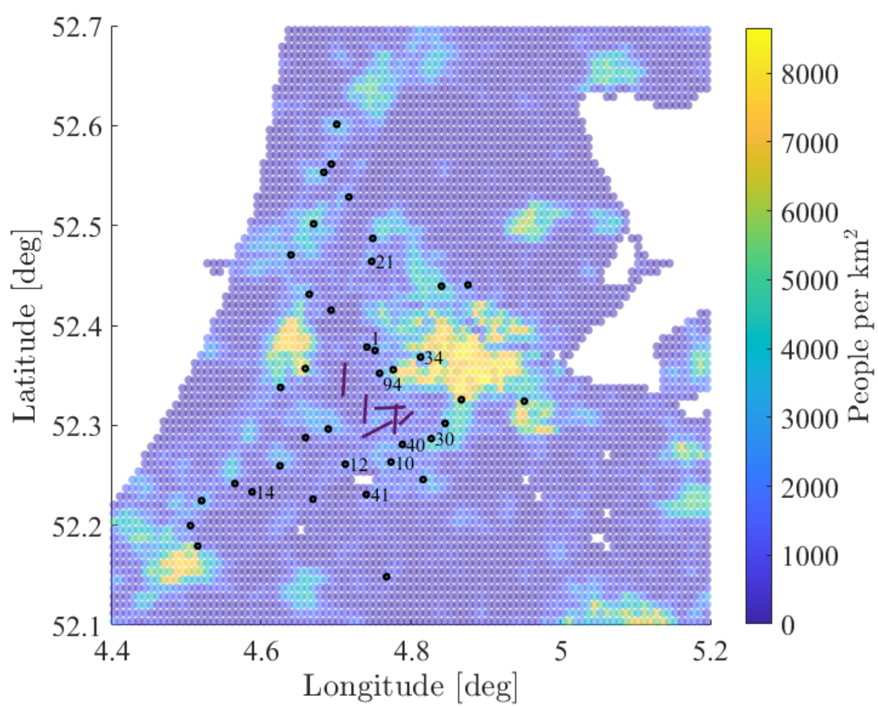


Fig. 2 Locations of NOMOS NMTs with respect to population density. Adapted from [13]

The majority of NMTs operate with a 60 dBA threshold, registering noise events exceeding this limit. However, a newer software implementation, effective February 2022, introduces a dynamic threshold to capture lower noise level

†`https://www.ilent.nl/onderwerpen/luchtvaartuigregister`
‡`https://noiselab.casper.aero/ams/`

events. Nonetheless, to minimise background noise influence, only measurements with $L_{A_{max}}$ >70 dBA are used for NPD table updates. Furthermore, measurements with aircraft elevation angles $\beta > 60°$to the NMT are selected to reduce lateral attenuation and microphone uncertainties, aligning with ISO 20906 standards [14]. Additionally, only recordings taken during specified weather conditions as per ISO 20906 (no precipitation and wind speed < 10 m/s) are considered.

While this study analyses various aircraft types, this paper specifically focuses on the B737NG. The measurements span across the years 2021 and 2022.

Table 1 Number of considered measurements of the B737NG per NOMOS NMT.

NMT	1	10	12	14	21	30	34	40	41	94
# measurements departure	-	27	39	57	25	204	581	1725	114	1084
# measurements arrivals	1023	82	-	1314	24	-	-	-	-	-

C. Oslo measurements

To verify the findings around Schiphol, measurements are also taken around Oslo airport, Gardermoen. Gardermoen Airport is equipped with 12 NMTs out of which two are at the end of the runways (NMT 4 and 5) and nine in departure and/or arrival corridors. The area around Oslo is much less populated in comparison to Amsterdam. This results in lower background noise levels, for some NMTs even as low as 35 dBA. This makes most NMTs suitable for research purposes. The locations of these NMTs are visible in Figure 3.

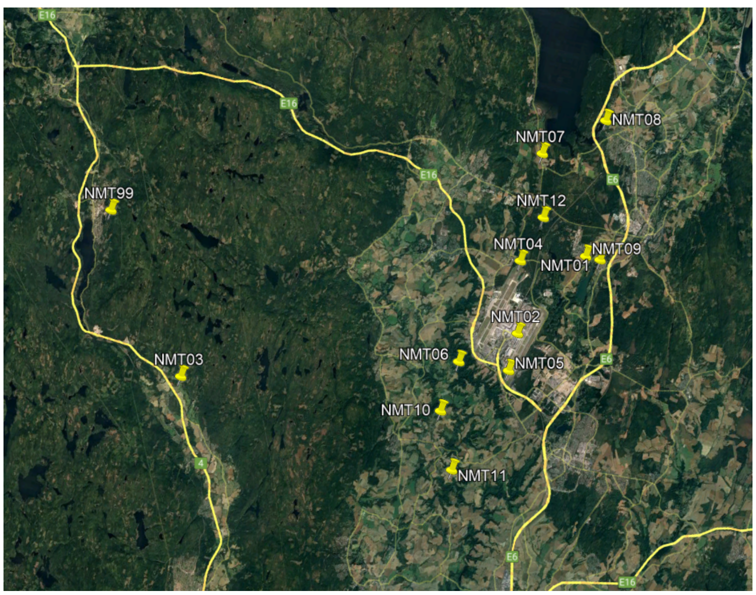


Fig. 3 Locations of the NMTs around Gardermoen airport.

The system used around Oslo is from a different provider (Topsonic) but has similar functionality and output as the NOMOS system. Due to the low background noise levels, also lower measured noise levels are reliable and a minimum of $L_{A_{max}}$ of 60 dB is taken. For this study, similar requirements on operational conditions as for the NOMOS measurements are used with the addition that the ground should be free of snow as this dampens the measured sound significantly. This gave a set of measurements per NMT for a select number of days in 2023 presented in Table 2.

Table 2 Number of considered measurements per Oslo NMT.

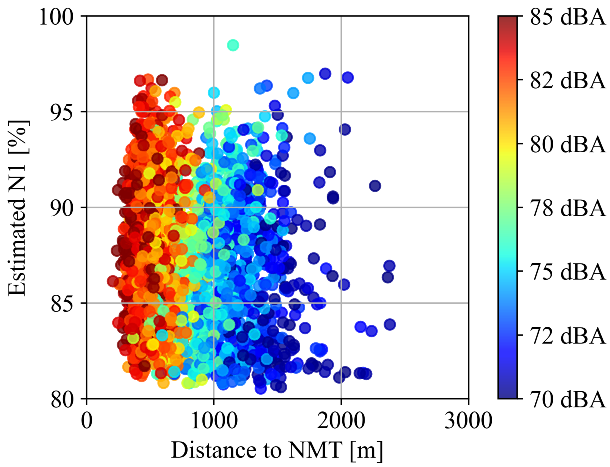
NMT	1	2	3	4	5	6	7	8	9	10	11	12
# measurements departure	9	-	-	2	-	-	47	28	5	-	-	45
# measurements arrivals	-	-	-	-	-	-	-	93	-	-	-	-

III. Model data comparison using standard NPD tables

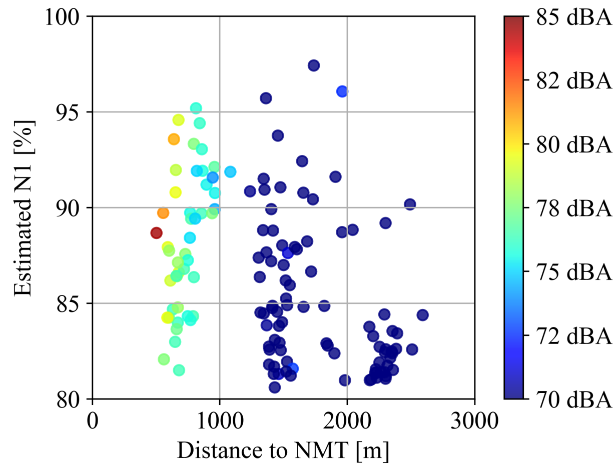
A. Baseline data set using N1%

The baseline data set of Schiphol measurements used for this research consists of roughly 3800 departures for the year 2021 and 2600 arrivals from 2022 for the B737-800 aircraft which are considered to fall within the requirements stated in section II. As mentioned before, the NOMOS measurements provide $L_{A_{max}}$ and SEL, and these will be the parameters that the model results will be compared to. For simplicity, the figures will be shown for $L_{A_{max}}$ only. In Figure 4a the NOMOS measured levels of departure operations are visualised by plotting the $L_{A_{max}}$ versus the acoustically estimated $N1\%$ and the distance of the aircraft to the NMT at the time of the measured $L_{A_{max}}$. A clear relation of decreasing measured sound levels with increasing distance is visible, as expected. However, a relation between measured levels and engine setting is not immediately visible for the departure measurements. For the arrival measurements, depicted in Figure 4c, the effect of changing $N1\%$ is present but, especially regarding $N1\%$, difficult to see in the figures.

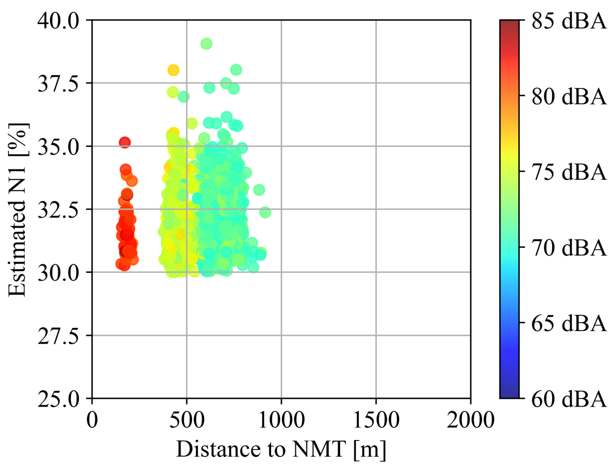
In Figures 4b and 4d the verification data set of Oslo airport for departure and arrival are presented, respectively. Similar patterns are visible as in the Schiphol data set.



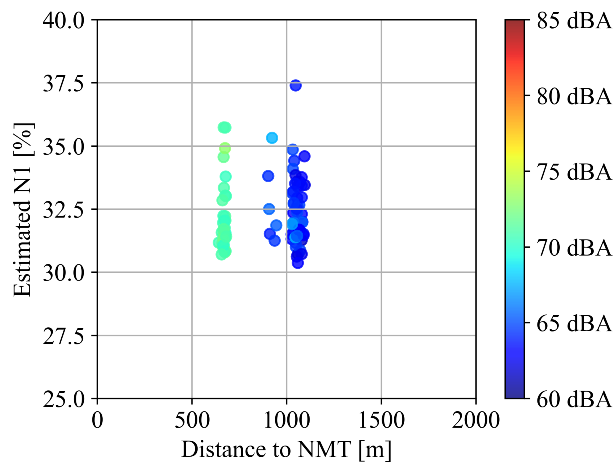
(a) $L_{A_{max}}$ **departure measurements around Schiphol.**



(b) $L_{A_{max}}$ **departure measurements around Oslo.**



(c) $L_{A_{max}}$ **arrival measurements around Schiphol.**



(d) $L_{A_{max}}$ **arrival measurements around Oslo.**

Fig. 4 Sound level of measurements of B737-800 with respect to distance and $N1\%$ for the baseline (AMS) and verification (Oslo) dataset.

B. Difference in sound level between model and measurement

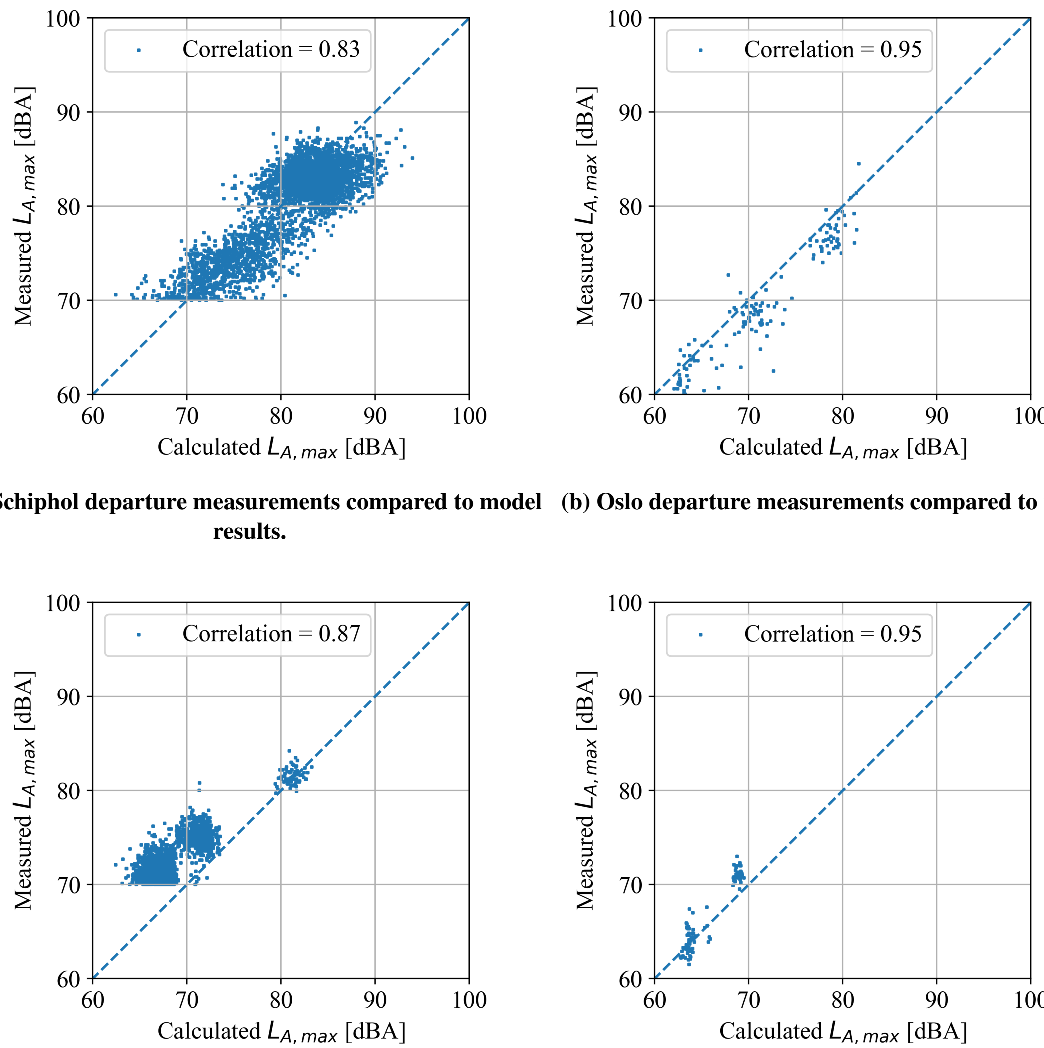
In Figure 5, the measurements are plotted against the Doc.29 model results (with original NPD tables), for the $L_{A_{max}}$. The difference between model results and measurements is given by

$$\Delta L = L_{model} - L_{measurement} \tag{1}$$

Here a negative ΔL means an underestimation of the model. The model-data agreement is summarised in Table 3, where μ is the average difference between the model result and its corresponding measurement of all data points available and σ is the standard deviation of ΔL. The results indicate different outcomes for arrival and departure operations. An offset μ in the arrival operations is visible and the estimated standard deviations are relatively small, while for departure operations the situation is the opposite.

Table 3 Mean and standard deviation of the model results minus the measurements.

		$L_{A_{max}}$ [dBA]		SEL [dBA]	
Airport	**Operation**	μ	σ	μ	σ
Schiphol	Departure	0.8	2.7	0.9	2.4
	Arrival	-2.9	1.6	-1.5	1.4
Oslo	Departure	1.9	2.0	3.5	1.7
	Arrival	-0.9	1.5	0.2	1.6

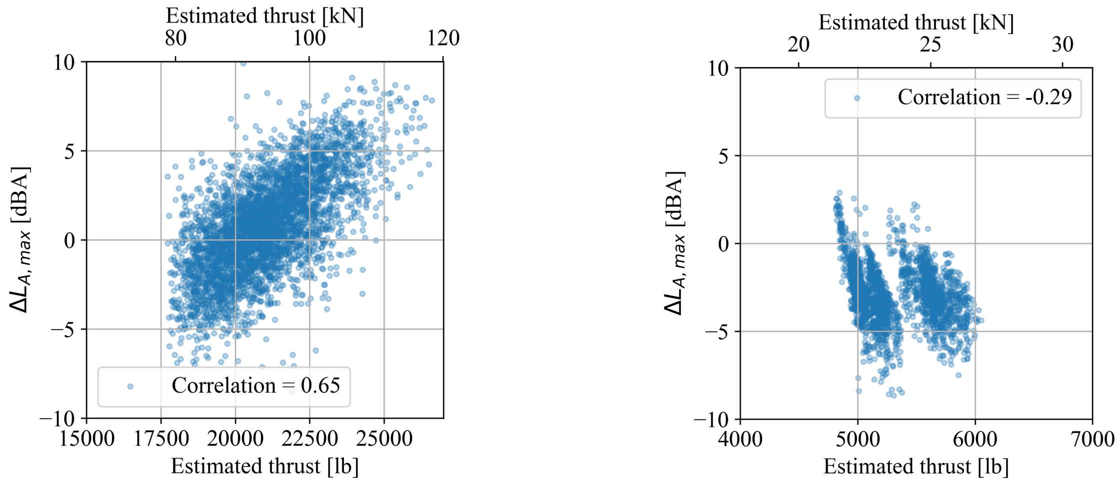


(a) Schiphol departure measurements compared to model results. **(b) Oslo departure measurements compared to model results.**

(c) Schiphol arrival measurements compared to model results. **(d) Oslo arrival measurements compared to model results.**

Fig. 5 **$L_{A_{max}}$ measurements of B737-800 with respect to Doc.29 model results (with original NPD tables), including corresponding correlation coefficient.**

A correlation analysis with the two main input parameters (distance and thrust) reveals that Pearson's correlation coefficient between input parameters and ΔL is highest for thrust during departures. No correlation is found between distance and ΔL. The p-value for both these results is lower than 10^{-10} indicating significance. In Figure 6, ΔL is plotted versus estimated thrust. Here, again, a negative Δ represents an underestimation of the model. This result led to research further investigating the relationship between thrust and measured noise levels.



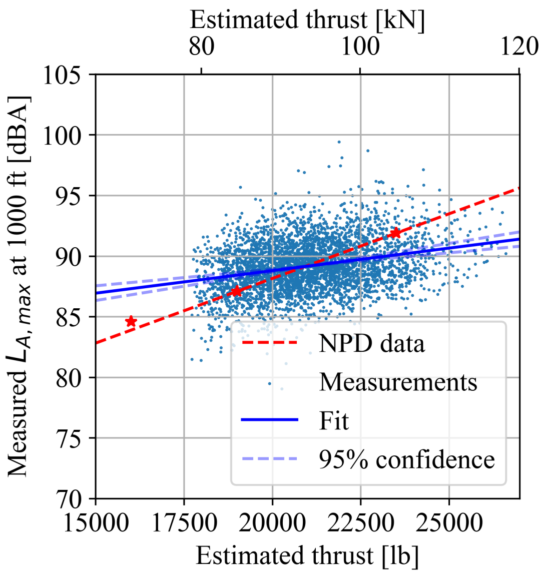
(a) Differences in $L_{A_{max}}$ for departure procedures.

(b) Differences in $L_{A_{max}}$ for arrival procedures.

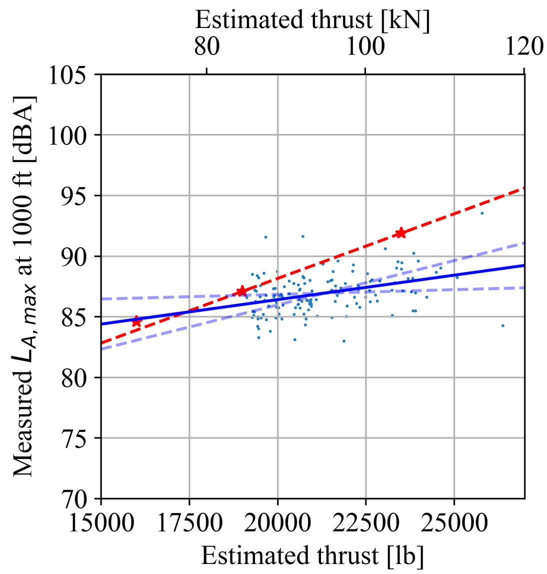
Fig. 6 The differences between model results and NOMOS measurements versus the estimated thrust (including corresponding correlation coefficient).

C. Establishing measurement-based NPD tables

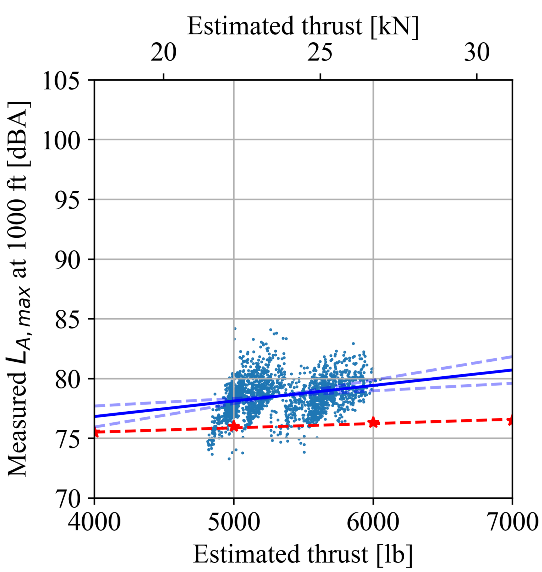
The relation between thrust and measured noise levels is investigated by standardising each measurement to reference conditions as used in the NPD tables. A least-squares fit is found through these measurements and can be seen in Figure 7. The detailed method of this standardisation can be found in van der Grift et al. [9]. When observing these newfound fits, it is seen that the relation between thrust and noise during departure is up to three times smaller than the original NPD relation. This results in an overestimation of noise at high thrust ranges. In contrast, for the arrival measurements, a slightly stronger relation is found. These derived relations will be applied in section IV.



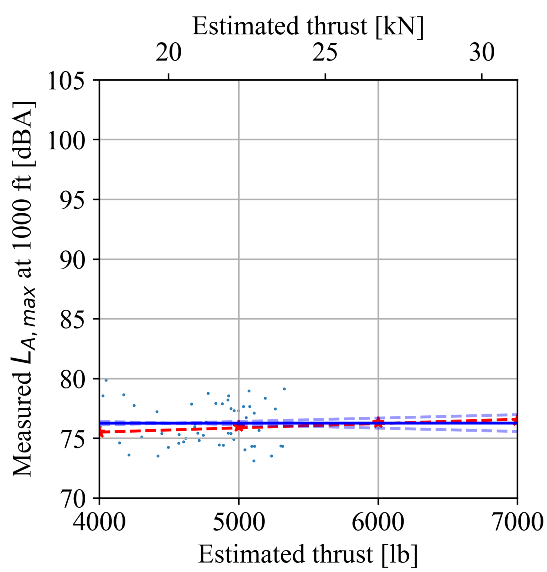
(a) Schiphol departure measurements standardised for 1000 ft. Taken from [9].



(b) Oslo departure measurements standardised for 1000 ft.



(c) Schiphol arrival measurements standardised for 1000 ft.



(d) Oslo arrival measurements standardised for 1000 ft.

Fig. 7 $L_{A,max}$ **measurements of B737-800 standardised to a reference distance.**

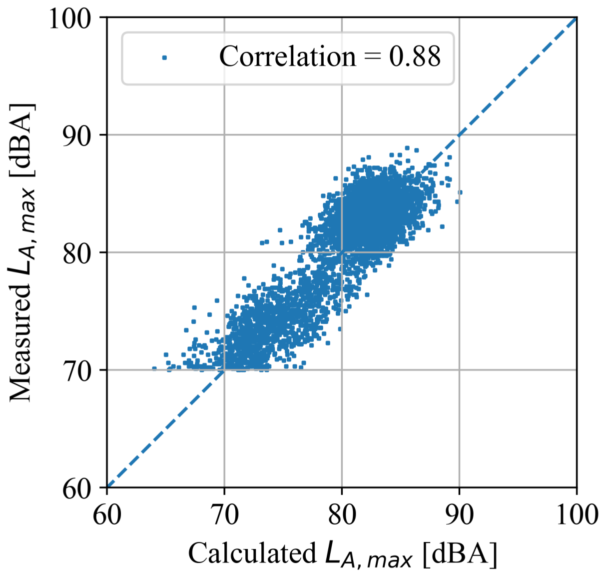
IV. Creation and application of NPD tables based on newfound noise-thrust relations

The use and accuracy of NPD tables is a widely discussed topic. As mentioned before, the way NPD values are retrieved has some remissness. In many studies where the model results are compared to measured values, and systematic errors occur, the NPD values are mentioned as a possible source for error. In the study from Giladi and Menachi [15] a difference between the AEDT model predictions and measurements of up to 4-7 dB was found. Following this result, they suggest a correction of the NPD tables, as well as the way departure profiles are obtained. In Trow and Allmark [16] this correction is applied by altering entries in the NPD table. The changes are based on the differences between model results and measurements corresponding to the specified thrust setting and distance during the time of the measurement.

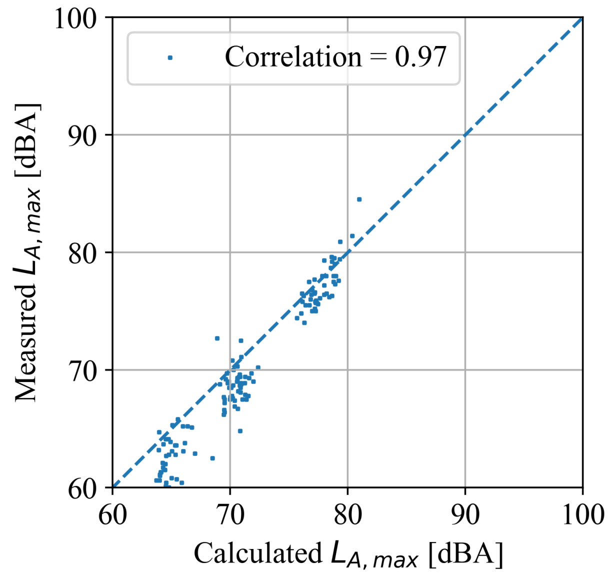
In this contribution, an alternative method of creating new NPD tables is followed. The insights gained from the previous section are used to create new NPD values instead of calibrating them. This new NPD table is then used in the Doc.29 model to evaluate its performance.

A. Effect on single event measurements

To analyse the effect of using the new NPD table in Doc.29, all available data is split into a calibration and verification data set. The calibration data set is used to find the noise-thrust relations and the verification data set is then used to verify the results. The data gathered around Schiphol airport is used for calibration, while the independent Gardermoen data is used for verification. This yields the results shown in Figure 8a and 8b for the departure data set and in Figure 9a and 9b for the arrival data set. The new mean averages and standard deviations are given in Table 4.

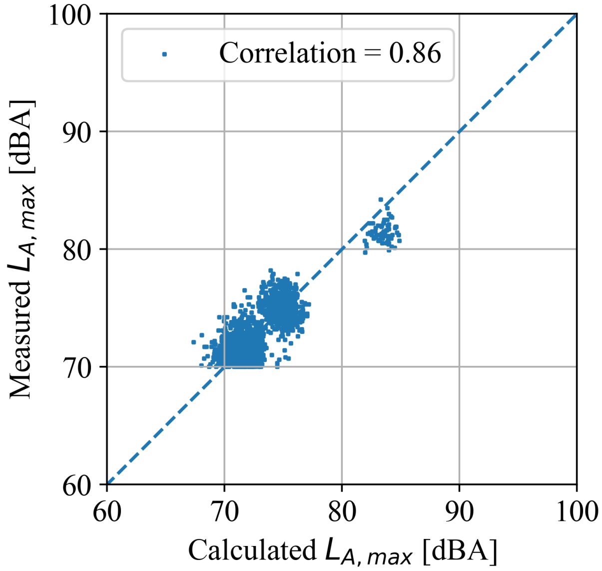


(a) $L_{A_{max}}$ **Schiphol calibration data set using new NPD tables.**

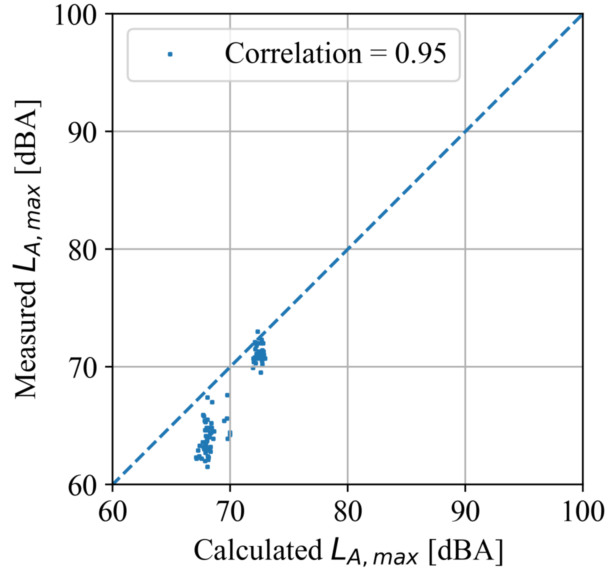


(b) $L_{A_{max}}$ **Gardermoen verification data set using new NPD tables.**

Fig. 8 $L_{A_{max}}$ **model results versus measurements of departure operations using new NPD tables (including the corresponding correlation coefficients).**



(a) $L_{A_{max}}$ **Schiphol calibration data set using new NPD tables.**



(b) $L_{A_{max}}$ **Gardermoen verification data set using new NPD tables.**

Fig. 9 $L_{A_{max}}$ **model results versus measurements of arrival operations using new NPD tables (including the corresponding correlation coefficients).**

Table 4 Results of ΔL for the model using standard and new NPD values.

			$L_{A_{max}}$ [dBA]		SEL [dBA]	
Operation	**NPD**	**Data set**	μ	σ	μ	σ
Departure	Standard NPD	Calibration	0.8	2.7	0.9	2.4
		Verification	1.9	2.0	3.5	1.7
	New NPD	Calibration	0.1	2.1	0.1	1.8
		Verification	1.6	1.6	1.6	1.4
Arrival	Standard NPD	Calibration	-2.9	1.6	-1.5	1.4
		Verification	-0.9	1.5	0.2	1.6
	New NPD	Calibration	0.0	1.4	0.0	1.5
		Verification	3.1	1.7	1.8	1.5

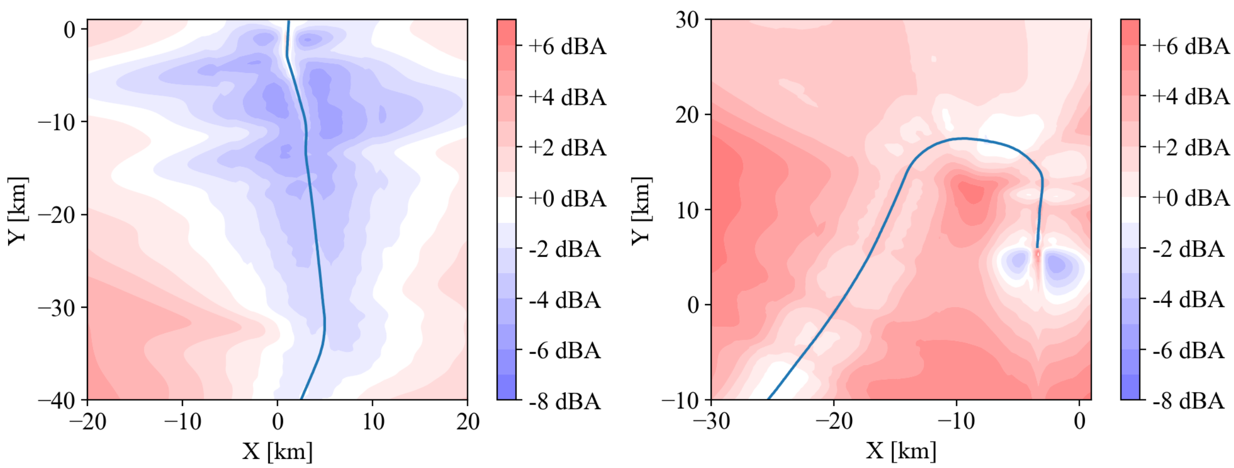
First, we look at the calibration data set. The found results are noticeably different for departure and arrival operations. For the departure operations the small offset μ is removed, but equally important, the standard deviation decreased by 25%. This effect is also visible in the increasing correlation coefficient between model output and measurements. The accuracy of the model results is thus improved. For the arrival data set, the new NPDs removed the offset μ. The σ of $L_{A_{max}}$ decreased by roughly 10%, but σ of SEL remained equal just as the correlation coefficient. Here, using the new NPDs is not as effective in reducing the variation σ as for the departure data set.

Differences are found between the calibration and verification data set with the standard NPD tables. For both departure and arrival data sets, the found offset μ of ΔL of the verification data is higher than the calibration data set. This larger offset μ in the verification data set is caused by on average lower measured noise levels. These measurements are taken further away from the airport and placed in locations with significantly lower background levels. Although both measurement systems around Gardermoen and Schiphol are placed on high poles to minimise ground reflection, the (ground)surfaces surrounding each microphone can have an influence. It is thus important to note that the NMTs around Gardermoen are placed on soft grassland instead of streets or rooftops, thus minimising (ground)reflections. However, the application of new NPD also results in a 20% decrease in σ for departure procedures, thus verifying the model improvement. In contrary, the new NPD tables for the arrivals result in a large overshoot in the model predictions. Here the low standard deviation even increases a bit. For this operation, the new NPD tables are thus not an improvement.

B. Effect on SEL contour

Doc.29's primary use is the calculation of aircraft noise impact on areas surrounding airports. This is done through calculations over a grid for a large number of flights, creating, for example, L_{DEN} contours. For this contribution, the SEL contour of a single flight is considered, using the flight path and $N1\%$ setting of ACMS data. As expected, the use of new NPD tables affects the contour. In Figures 10a and 10b, the differences between the baseline (using original NPD tables) and new models are depicted for an arrival and departure procedure, respectively. Here a negative ΔL (blue) indicates that the new model predicts a lower SEL value than the baseline model, while a positive ΔL (red) indicates a higher SEL value.

The baseline model for arrivals was found to underestimate the noise level, so consequently, the new NPD table results in an increase in the predicted noise levels. One exception is seen at the touchdown on the runway when high thrust levels are required for thrust reversal. For the departure noise contour, the new NPD table results in lower predicted noise levels at the start of the departure when high thrust levels are used. Higher predicted noise levels are seen at later stages in flight and longer distances between aircraft and observer.



(a) Difference in SEL contour for a departure operation.

(b) Difference in SEL contour for an arrival operation.

Fig. 10 Difference in SEL contours between baseline and calibrated models.

V. Discussion

Even though an offset of the model is visible in both the departure and arrival operations, as seen in Table 4, the standard deviation of ΔL differs significantly between these two operations. Departure operations have a large variation in the produced noise levels while arrival procedures show a more constant noise level. This is consistent with literature [15, 17]. The offset can be reduced by implementing a general correction factor, such as the aircraft substitution correction factor (see Figure 1 in section II.A), but these do not influence the variation in differences between modelled and measured values. To increase the accuracy and reliability of the model, this variation needs to be reduced. This is done in this research by using noise measurements and actual tracks as input, as can be seen in the updated Doc.29 flowchart in Figure 11.

By using new NPD tables based on measured thrust-noise relations, the offset μ of the model is reduced to 0. For departure operations, this new NPD also reduced the standard deviation by more than 20%. For arrival operations, this reduction in standard deviation is not seen. From the measured thrust-noise relations derived in the present research, a few interesting things are noted. The original NPD relations show a clear increase in noise level with increasing thrust for departure operations, but almost no increase when looking at arrival operations. Thrust is assumed to be non-dominant during arrival procedures. From the NOMOS measurements, an opposite relation is visible. Departure

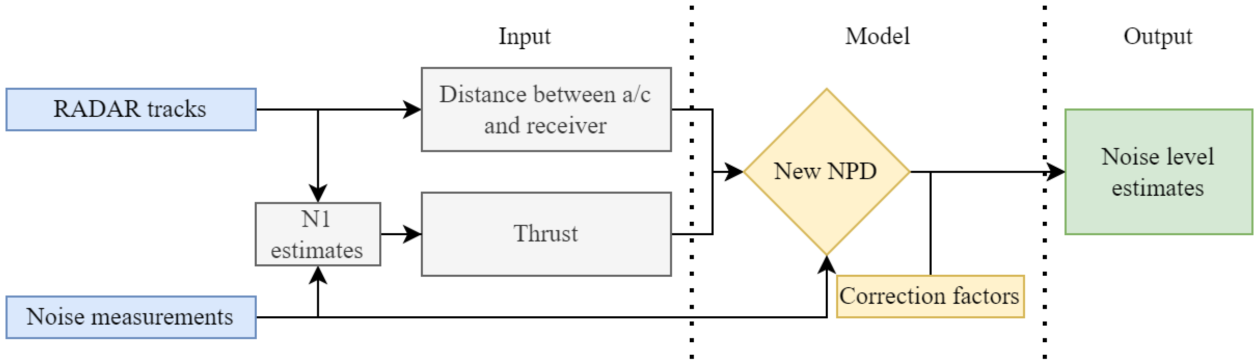


Fig. 11 Flowchart of new method of Doc.29 noise calculations

noise level is not purely dominated by thrust level, while for arrival operations the thrust setting is not insignificant and influences the measured noise levels. This is in line with studies researching the variation seen in arrival measurements [18].

The use of new NPD tables based on measurements reduces the difference seen between modelled and measured values, but still, a maximum 2 dBA standard deviation remains, see Table 4. This could have multiple origins such as measurement uncertainty of the microphones or errors in the used corrections factor. From previous studies, it is shown that the variation due to weather effects, next to atmospheric attenuation effects, is about 2 dB [19, 20]. Nevertheless, the method presented in this research produces a more accurate model. When comparing the modelling methods of Figure 1 with Figure 11, the new NPD, based on recent measurements instead of standard values, is a more dynamic approach to noise modelling.

VI. Conclusion

In this paper, a method to improve aircraft noise predictions is presented by evaluation of the input parameters and Noise-Power-Distance (NPD) tables of the best-practice model Doc.29. First, the uncertainty of the model input is reduced by using the flown track and acoustically derived thrust settings.

The second step is the evaluation of the used NPD tables. Originally, these NPD values were found through (certification) measurements and are used in most best-practice methods. In this research, these NPD values are evaluated by comparing measurements with model results with the actual thrust setting and distance, i.e. not making use of the default flight profiles. By reducing the chance of errors in these input parameters, a remaining part of the differences between model results and measurements ΔL can be attributed to errors in the NPD table. For the B737NG data set, consisting of around 3800 departing and 2600 arriving flights, the offset μ was under 1 dBA and 3 dBA, while the standard deviation σ of these differences was around 3 dBA and 1.5 dBA, respectively. In this research, a new NPD table is created from NOMOS measurements around Schiphol Airport.

All measurements in the data set were standardised to reference conditions as used in the NPD table. From these measurements, interesting conclusions were drawn. For the departure flights, the relation between thrust setting and sound level showed to be less pronounced than originally expected. Applying these new thrust-noise relations to create a new NPD table resulted in an improvement of the standard deviation between model and measurement values of found differences by 25%. This improvement is consequently verified by applying the same new NPD tables on an independent data set at Oslo Gardermoen airport. For the arrival operations, different results were obtained. The new NPD removed the offset μ between the measurements and the model results but did not reduce the standard deviation σ. This implies that the estimated trust setting to noise ratio is not directly the cause of the differences seen between measurement and modelling results. Although an alteration of NPD tables is useful to reduce the offset μ, to reduce the variation σ seen for arrival aircraft, more research is necessary.

Measured thrust-noise relations, and consequently new NPD tables, can improve Doc.29 model predictions on a single event level. Next to an improvement to the best-practice noise model, the methods described in this research give insight into the creation and validation of NPD values.

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