ANALYSING THE EFFECT OF UNDETECTED FLIGHTS IN THE COMPARISON OF MEASURED AND MODELLED AIRCRAFT NOISE

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ABSTRACT

Aircraft noise has a severe impact on communities around airports. For noise regulation, yearly average noise levels L_{DEN} are modelled for large areas around the airport. To validate and improve the noise model, noise monitoring terminals (NMT) can be used. These NMTs, however, are often placed further away from the airport and in areas with higher background noise levels than ideal measurement conditions. Thresholds placed on the NMTs prevent them from capturing too much background noise but also prohibit them from measuring lower noise levels from aircraft. This research addresses the potential effects of undetected flights on the measured L_{Night} and L_{DEN}. For this, the Doc 29 modelling method is used. The case study is Schiphol Airport, where 41 NMTs are placed at different distances from the runways. Analysis of undetected flights showed that newer aircraft, such as the A320-NEO, were often not measured. Applying weighted least-squares to the available noise level measurements and supporting data gives insights into the possible aircraft-induced noise levels of undetected flights. These insights are used to improve the alignment between measured and modelled L_{Night} and L_{DEN}.

Keywords: *aircraft noise models, noise monitoring terminal, L_{Night}, L_{DEN}, least-squares, noise thresholds*

1. INTRODUCTION

The growing presence of aviation is causing increasing annoyance in communities around large airports [1]. To address aircraft noise, regulations often focus on designing optimized flight routes and restricting the number of flights at specific times and locations. Both these measures rely on calculations of annoyance with the help of aircraft noise models such as the European Civil Aviation Conference Doc 29 [2]. These so-called best-practice noise models are used to calculate yearly average Day-Evening-Night noise contours L_{DEN} which represent the noise experienced on the ground due to all flight movements during that year. These models are generally accurate within 1-2 dB [3], although validating them against actual noise measurements can be challenging.

The most common validation methods compare noise measurements with model predictions for single flights. Several studies have demonstrated good agreement between measurements and best-practice noise models for such flights [4, 5]. Research comparing measured L_{DEN} has shown the potential to observe broader trends, such as the effect of quieter aircraft types [6]. For studies focusing on single flights, the measurements used often stem from large aircraft or areas near airports, as these locations provide more reliable data. The louder noise events and shorter distances between aircraft and microphones reduce the likelihood of disturbances affecting the measurements. This results in a selective dataset [7]. This selective sampling, known as measurement bias, can significantly affect validation results. For this research, the effect of this measurement bias is studied by analysing eight years of measured and modelled data around Amsterdam Airport Schiphol.

The airport is equipped with the Noise Monitoring System (NOMOS) consisting of 41 different Noise Monitoring Terminals (NMTs) placed at different distances from the runways as seen in Fig. 1. These NMTs are often placed in and around communities as their primary goal is to inform the public about aircraft noise. A Dutch national research campaign into the validity of these NMTs for the use of noise model validation has been performed [8] where every NMT is given a score based on, among others, location, background noise and possibilities of reflection and obstruction. Only the NMTs suitable for noise model validation purposes are selected for the research presented in this contribution.

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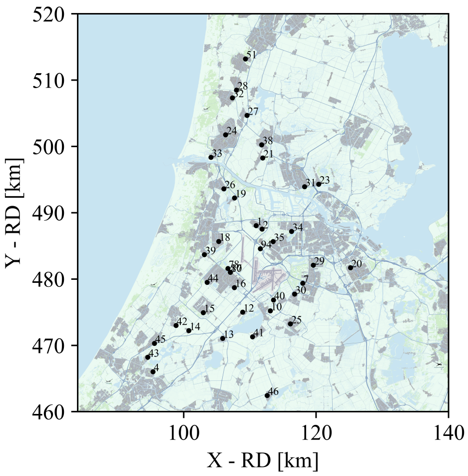

Figure 1. Locations of the 41 NOMOS NMTs around Schiphol Airport in Rijksdriehoek coordinate system.

NMTs register aircraft noise by measuring increased noise levels while accompanied software uses radar data to check for aircraft nearby simultaneously. To prevent noise events coming from background noise or community noise events (cars, dogs, alarms etc.), NMTs are equipped with thresholds. These thresholds are often defined by the background noise level at that location. A 10 dBA difference with the peak noise level $L_{A,max}$ is the standard to adequately remove background noise levels [9]. Around Schiphol, background noise levels are often 45 dBA, resulting in thresholds around 58-65 dBA depending on location and time of the day. Generally, nighttime thresholds are 5-7 dBA lower due to less background noise.

Although thresholds decrease the chance of contamination of aircraft noise events by other factors, they also prevent the recording of aircraft noise not reaching the threshold, such as quieter aircraft like the A320-NEO or flights at large distances.

This research examines the relationship between measured and modelled L_{Night} and L_{DEN} levels around Schiphol Airport, with the aim to investigate the potential of this relationship to address the impact of undetected flights on measured L_{DEN}. First, an analysis identifies the quantity and types of flights not measured by the NMT. Using measured data and a least-squares estimation method, the noise levels of these undetected flights are predicted. Secondly, these estimates for the noise levels of the undetected flights are obtained and used to enhance the measurement set. Both measured and modelled L_{Night} and L_{DEN} levels are calculated and compared. The findings reveal that the absence of these flights primarily influences NMTs located further from the airport.

2. DATA DESCRIPTION

This research utilizes two main types of data: model results and measurements. The model results, provided by Schiphol Airport, consist of yearly averaged L_{Night} and L_{DEN} results for the entire grid around the airport, roughly 80x80 km. Every operational year (November 1st to October 31st) the airport presents noise contours resulting from all flights of commercial traffic and general aviation. These contours are modelled according to Doc 29 practices [2]. The modelling process involves predictions of future runway usage and operations along with their associated noise contours. Following the conclusion of each operational year, the actual operations, including flown flight tracks, are evaluated, and the final modelled L_{Night} and L_{DEN} noise contours are published. [1] This research utilizes these finalized noise evaluations from the years 2017 to 2024. The main input for the Doc 29 model, the Aircraft Noise and Performance (ANP) database and its corresponding Noise-Power-Distance (NPD) tables, are also utilized for this research [10].

The second type stems from the NOMOS stations. This data consists of operational characteristics of all flights and measurement data. All flights are logged, including their tracks, aircraft type, operation type and departure/arrival time. The system also calculates the Point of Closest Approach (PCA) to each NMT around the airport. For each flight, there are thus 41 PCAs (corresponding to the 41 NOMOS stations), together with information such as slant distance, elevation angle and height during the PCA. As Schiphol is a large hub airport with close to 500,000 flights per year, this results in a very large dataset. If a noise measurement is recorded and coupled to a flight, the measured Sound Exposure Level (SEL or L_{AE}) and maximum A-weighted noise level $L_{A,max}$ are saved. This full set of information gives the possibility to evaluate flights for which no noise was measured.

In Fig. 2 the percentage of flights with a PCA within 25,000 ft that do not have a correlated measurement for each NMT is given. Although variation is still present, there is a correlation between the modelled L_{DEN} and the percentage of measured flights relative to the amount of (undetected) flyovers. This shows that in regions with lower L_{DEN}, so-called low-noise regions, flights are often not measured, probably because of their low levels relative to the ambient noise. The NMTs depicted in red are those not suitable for noise model validation. These NMTs will not be used in Section 3 but are shown in this paper for completeness.

For a selected subset of NMTs, the noise level L_A per second over a time series was analysed to investigate potential reasons for aircraft non-detection. NMTs located near the runway showed distinct peaks in noise level corresponding to aircraft present directly overhead. During busy periods where aircraft departed or arrived every minute on a runway, aircraft events were sometimes merged. This results in two aircraft being recorded as a single event and thus one flight being undetected. For NMTs placed further from the runway, small fluctuations were observed in the time series, but these did not constitute

[1] `https://www.schiphol.nl/nl/jij-en-schiphol/gebruiksprognose-alles-wat-je-maar-wilt-weten/`

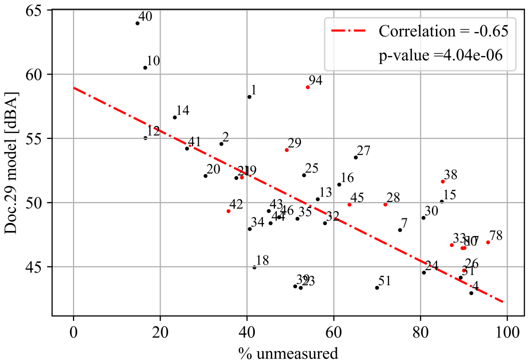

Figure 2. Percentage of undetected flights per NMT in comparison to the modelled L_{DEN}.

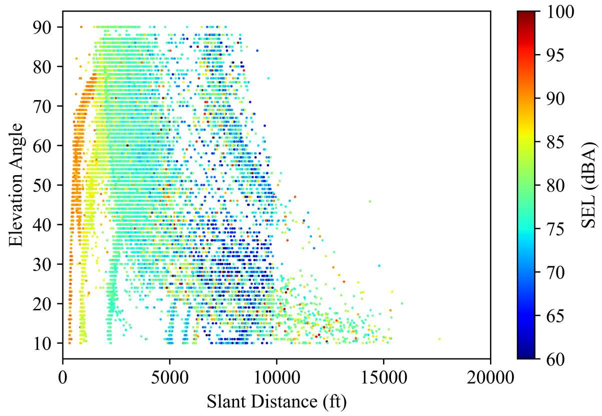

Figure 3. Measurements of the B737-800 for all NMTs for relative elevation angle and slant distance.

clear aircraft noise events. It is important to consider these uncertainties when drawing conclusions.

Some pre-processing steps are executed before the measurement data can be used to improve data quality. As the measurements are taken in an uncontrolled environment, care should be taken in which data can be used. Firstly, measurements of transit aircraft and helicopters are removed as they are not included in the modelling results. Further, measurements of aircraft where the PCA is under a 20° elevation angle are removed due to their likelihood of measurement disturbances. Although ISO20906 [9] prescribes only using measurements above 60°, this results in a low number of measurements. The downside of this assumption is that the chances of measurement disturbances, such as the ground effect, are higher for these low-elevation angle measurements. Lastly, multiple w-tests are applied to identify strong outliers by comparing individual measurements against their normalized residual. This results in a list of likely false measurements, which are consequently removed from the dataset. For a single aircraft, the B737-800, the measurements relative to their elevation angle and slant distance at PCA are shown in Fig. 3. The measured noise levels decrease with distance, but around threshold levels at 10,000 ft, the presence of background noise starts to be visible in the noise measurements. It is hypothesized that this causes the increased SEL values.

3. METHODS

In this research, the amount of aircraft noise is quantified in yearly averaged L_{DEN}, which is calculated per measurement location using

$$L_{DEN} = 10\log\left(\sum_{i=1}^{N} 10^{(SEL_i+W_i)/10}\right) - 75 \qquad (1)$$

where SEL_i are the individually measured SEL values at the NMT and W_i are the assigned penalties for day (0 dBA), evening (5 dBA) or night (10 dBA) flights. The factor -75 is to average over all seconds within a year calculated through $10\log\left(1/(365*24*60*60)\right)$. For L_{Night}, a daily eight hour period is used, resulting in a factor of -70.2.

To analyse the effect of the flights that are undetected by the NMTs, an estimation of their noise impact needs to be made. Although it would be easiest to calculate the noise of the undetected flights with the Doc 29 model, this would result in a model-to-model comparison. So, we opted for a different method of estimating missed 'measurements' by using existing measurements and operational information of the undetected flights.

3.1 Categorization of data

The key parameters influencing SEL estimation for current measurements include a set of the most impactful factors, which are listed below:

- Aircraft types (over 200 types)
- Operation type (2 types: arrival and departure)
- NMTs region (2 types: high-noise and low-noise)
- Slant distance of individual measurements
- Power setting during flyover

Based on these parameters, the data can be categorized into groups, which are all separately analysed. Aircraft types are given by ICAO codes, and the operation type is either arrival or departure. The location of an NMT can be in a so-called high-noise or low-noise region. This is determined by the average modelled L_{DEN} over the past 8 years. This split is defined at 52 dBA, as it results in a rough 50/50 split of measurements per group. The slant distance, measured during the PCA, is the most important parameter used for determining the noise level of an aircraft. Although most parameters are available for this research, the power setting of an aircraft during flight is difficult to obtain. For this study, a power setting estimation will be made based on the NPD table of the corresponding aircraft and the slant ranges and SEL measurements.

Given the variety of aircraft types, many groups had limited measurements. To address this, aircraft are categorized by their ANP type, which is then used to identify their corresponding NPD ID. While most aircraft have an ANP label, smaller aircraft are not in the ANP database and are thus classified using the older Dutch Noise Model (NRM). This model groups aircraft into one of nine weight classes and four noise certification categories, with an additional group for aircraft under 6000 kg (group 004). A detailed description of these noise groups can be found in [11]. A total of 64 different aircraft groups are formed.

3.2 Least-squares fit for unmeasured data

To estimate the SEL of undetected flights, we make use of the least-squares (LS) method. A simple logarithmic fit of $y = a\,\log(r) + b$ is used, where y are the measured SEL values, r is the slant distance at PCA in ft and a and b are the to-be-estimated unknown parameters included in $\hat{x} = [\hat{a}, \hat{b}]^T$. A logarithmic relation between measured noise and distance is taken in line with the geometrical spreading of noise, also prescribed in Doc 29 [2].

For fitting this LS, only reliable measurements are used, which excludes measurements over 10,000 ft. However, most of the undetected flights are around or larger than this distance. Using a LS to extrapolate measured noise to these larger distances fully neglects the effect of engine setting. Therefore, we opted to make use of the NPD tables and incorporate them in the LS fit to produce a regularized weighted LS fit.

NPD tables cover relations between distance and noise for different power settings. In best practice, the modelled noise value is found by interpolating the different thrust settings (linearly) and the distances (logarithmic). For this research, this interpolation is reversed by using the measured SEL values and slant distances at PCA to get a rough thrust estimate. For each ANP type, this resulted in a distribution of estimated thrust following a Gaussian pattern. The median of this thrust distribution is then used to find the most representative NPD curves as seen in orange in Fig. 4.

To use the information of the NPD curve in the LS approach, a weighted LS is used to estimate the parameters in $\hat{x}$ by defining the model matrix A, the measurement vector y and the variance-covariance matrix Q_y. For unweighted LS, Q_y can be defined as an identity matrix. For the weighted LS, a second set of equations is created containing distances and SEL levels from the defined NPD curve. It is assumed that the measurements are most accurate up to 8,000 ft, after which the determined NPD curve has a higher weight (lower sigma). In this study, all measurements have the same weight ($\sigma_1 = 1$) and all points on the NPD curve have a larger weight. In this manner, large matrices can be avoided. Incorporating two models of observation equations, $y_1 = A_1 x + e_1$ and $y_2 = A_2 x + e_2$, the weighted LS estimate of x simplifies to:

$$\hat{x} = (A_1^T A_1 + \sigma_2^{-2} A_2^T A_2)^{-1} (A_1^T y_1 + \sigma_2^{-2} A_2^T y_2) \quad (2)$$

where subscript 1 is linked to measurements and subscript 2 is related to NPD values. For this research, the standard deviation of NPD values is set to $\sigma_2 = 0.1$. This results in the improved estimates of weighted LS fit, as shown in red in Fig. 4. The measurements and NPD values align well in the first 8,000 ft, after which the unweighted LS flattens out compared to the NPD. The weighted LS fit more closely follows the NPD curve.

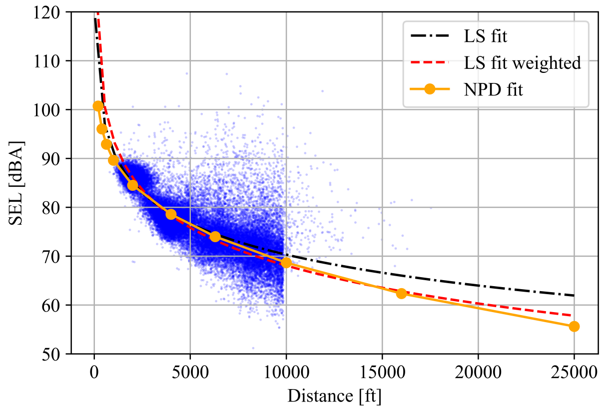

Figure 4. Measurements of the A320-NEO with weighted and unweighted LS based on found NPD curve.

With the parameters found from the weighted LS, all expected noise levels can be calculated for the undetected flights. To validate the LS parameters found, the data set is split, where the operations and measurements from 2019 until 2024 are used to find the LS fit, and the measurements from 2017 and 2018 are used for validation. This results in a test dataset of about 25% of all measurements.

The above grouping results in 256 different LS fits using a total of more than 6 million measurements for training and 2 million for testing. For each group, the estimated measurements are compared with the real ones and a difference ΔSEL, defined as $SEL_{LS} - SEL_{measured}$ is found. Per group, an average deviation μ and a standard deviation σ can be determined. Here, a negative μ indicates an underestimation of the noise levels. A large μ in the validation data set can point to large differences between the data sets or insufficient data. A large σ indicates that there is high variability in the data that cannot be explained by the current LS fit. Consequently, an R^2-test is performed to check the goodness-of-fit. For this study, an R^2-value larger than 0.5 is deemed acceptable.

4. RESULTS

The measurements are summed and compared to the modelled L_{Night} and L_{DEN} for all NMTs of all eight years. First, an analysis of which flights are often not measured was done in Section 4.1. The results of the LS fit of the different groups are shown in Section 4.2. The LS fits are then used in Section 4.3

to quantify the effects on the total measured L_{Night} and L_{DEN}. Although the results differ per year, 2023 is used as an example to present more detailed results.

4.1 Undetected flights

An analysis of the measured flights and flights that have not been acoustically detected showed clear patterns. As already seen in Fig. 2, a relation between the percentage of undetected flights within 25,000 ft and the average yearly L_{DEN} is visible. As Schiphol Airport uses a fixed amount of arrival and departure routes, the slant distance at PCA is often centred around a certain value for arrivals and departures. For NMT 18, this results in the fly-overs as seen in Fig. 5. NMT 18 is a low-noise region NMT with measurements around the 8000 ft during PCA. In general, fly-overs under this distance are often measured, however, this number reduces around 10,000 ft (around 3 km). Interestingly, multiple fly-overs relatively close by are not measured.

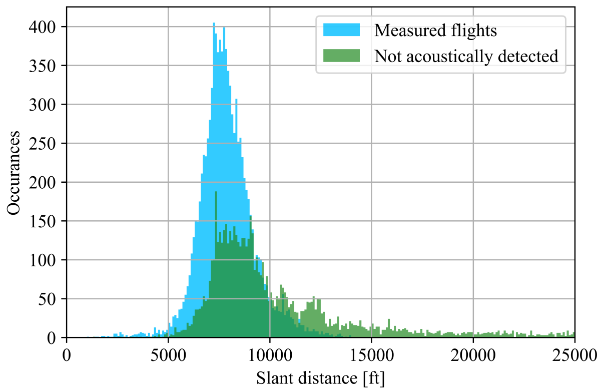

Figure 5. Slant distances of measured and unmeasured flights over NMT 18 during the year 2024.

In addition to the NMT location and slant distance, the aircraft type also influences whether an aircraft is measured. Most flyovers that are not detected acoustically can be attributed to the B737-800, which is not surprising as this is the most common type flying at Schiphol. Looking at the relative numbers i.e., the number of non-detected flights in comparison to the total number of flights each year, the results are quite different. The A320-NEO family becomes the most frequently unmeasured aircraft type, with over 40% of its flyovers within 8,000 feet going unrecorded. The runner-up, the E295, with 39% undetected flyovers, shows that newer, quieter [2] aircraft are a large proportion of the total undetected flights. This indicates that the noise levels of these events are likely lower than the NMT thresholds.

[2] Quiet aircraft are defined as aircraft adhering to Chapter 14 of the EASA certification noise levels

4.2 Least-squares results

To quantify the effect of the undetected flights on the total measured L_{DEN}, their influence is estimated with LS for 256 different groups as defined in Section 3. The results for the validation data are shown in Fig. 6, presenting the mean μ and standard deviation σ of the differences between the estimated and measured SEL. Validation groups with less than 30 flights are removed due to their low significance. The mean overall deviation is slightly positive, with a few outliers present. The positive μ is caused by an underestimation of the LS estimates. The NPD influence on the weighted LS is causing lower estimated SEL values at larger distances than what is measured by the NMTs as seen in Fig. 4. A different trend is visible in the differences of the standard deviation. The variation seen in the estimates of the arrival operations, in blue squares, is higher than that seen in the departure operations, in orange triangles.

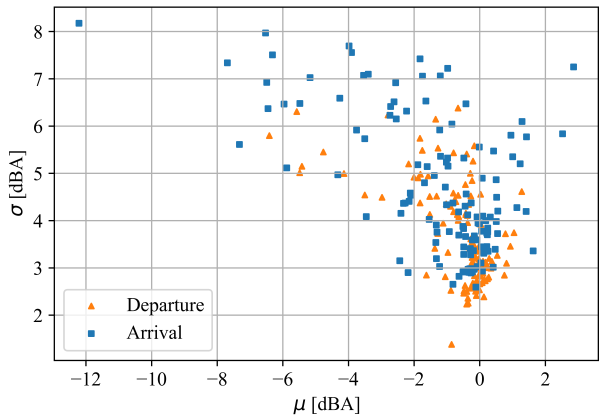

Figure 6. Mean and standard deviation of the differences in estimated and measured SEL for all groups.

In Fig. 7 and Fig. 8, the R^2 scores of the validation data set are shown for the high- and low-noise region LS estimates, respectively. In general, the R^2 values for departures are higher than for arrivals, indicating that the LS estimates found better suited the departure measurements.

The second observation of the R^2 values is that for low-noise NMTs, the values are generally lower than for high-noise NMTs. This results in values lower than 0.5 and thus not sufficient. Some R^2-values are not shown as they turned negative. A negative R^2 value indicates that the current fit is worse than a horizontal line (i.e. the prediction is worse than the average value of the data). This can be caused by using an inappropriate model structure and/or unreliable measurements at these NMTs. Further research is necessary to determine the quality of these measurements. For high-noise regions, over 90% of all flights measured have an R^2-score of 0.5 or higher.

The third observation is that for smaller aircraft, class 004 and weight classes 1 and 2, the R^2-values are lower than 0.5 for arrivals and departures. The same is visible in the newer, quiet aircraft such as the A20N and E295. For heavier and louder aircraft, such as the B744, the R^2-values are good, around 0.8 for in the high-noise regions and 0.6 in the low-noise regions. As heavier aircraft are generally louder, measurements surpass the thresholds and background noise levels more often, thus creating more reliable noise measurements.

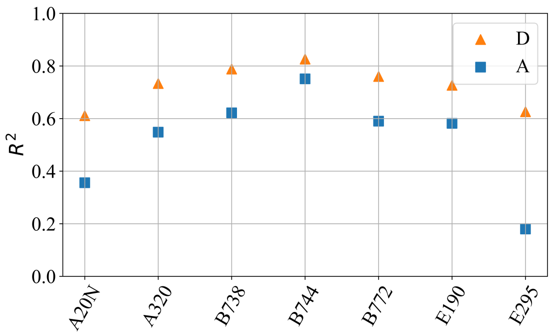

Figure 7. R^2-values of the different LS results of the validation data set in the high-noise region for a select number of aircraft types.

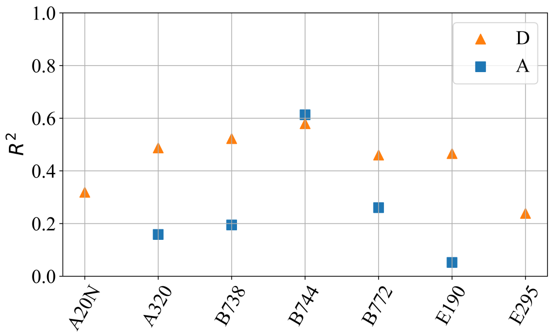

Figure 8. R^2-values of the different LS results of the validation data set in the low-noise region for a select number of aircraft types.

All of the above observations are likely affected by the high uncertainty of the noise measurements at large distances from the NMTs. As seen in Section 3.2, the measured noise levels decrease with distance but seem to reach a plateau around the threshold levels (± 70 dBA SEL), which is around 8,000 to 10,000 ft depending on the aircraft type. Measurements at large distances have larger variations, which results in unstable predictions with the LS estimates. This mainly affects the low-noise regions and quieter aircraft. For that reason, the noise estimates obtained through the weighted LS are only used up to 8,000 ft for this research and other undetected flights are ignored.

4.3 Comparison of L_{Night} and L_{DEN}

The measured and modelled L_{Night} and L_{DEN} are calculated per NMT per year. An example of the L_{DEN} of one year, 2023, is shown in Fig. 9. Although the results differ per NMT, the general correlation between measurement and model is good, and the average ΔL_{DEN} is close to 0. When adding the estimated SEL of the undetected flights, the measured L_{DEN} changes to the values as seen in Fig. 10. The effect of these undetected flights is largest in the NMTs in low-noise regions such as NMTs 4 and 31, while there is little effect on the measured L_{DEN} in NMTs 10 and 40. This results in larger model underestimations up to 1.0 dBA further away from the airport but overall a better correlation between measured and modelled levels.

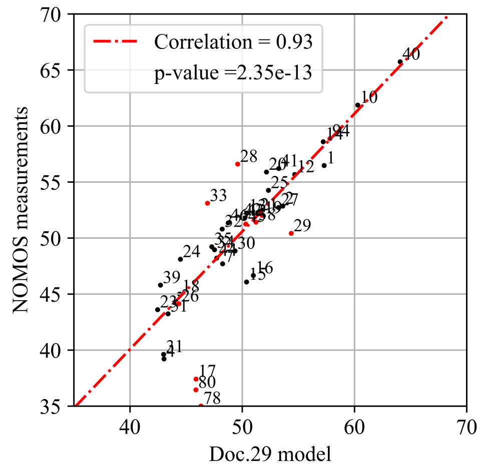

Figure 9. Measured and modelled L_{DEN} of all NMTs for the year 2023.

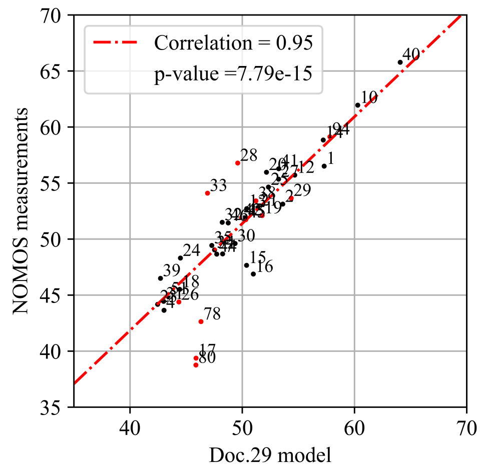

Figure 10. Measured and modelled L_{DEN} with the addition of undetected flights of all NMTs for the year 2023.

The measured and modelled L_{Night} and L_{DEN} values were compared for the years 2017 to 2024. First, the average L_{Night} across all NMTs, along with the standard deviation, are presented in Fig. 11. The Doc 29 model overestimates the measured

L_{Night} by an average of 1 dBA for all years, although fluctuations are visible. When the estimated SEL values of the undetected flights are added, this overestimation is diminished, improving the agreement between measured and modelled L_{Night} values.

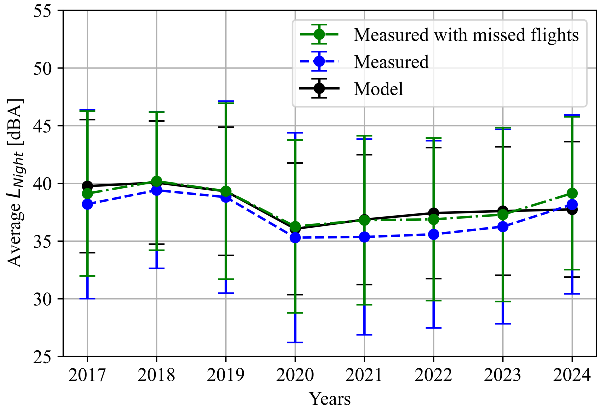

Figure 11. Average modelled and measured L_{night} over all NMTs and their corresponding standard deviation.

Contrary to the L_{Night}, the modelled L_{DEN} showed an average underestimation of 0.67 dBA, as seen in Fig. 12. This falls within the expected 1-2 dBA uncertainty range of best-practice noise models. The average differences between measured and modelled results increase by approximately 0.6 dBA when undetected flights are included. While this represents a significant increase, care should be taken when interpreting these results. As discussed in Section 2, uncertainties in aircraft noise event detection may have led to an overestimation of the impact of undetected flights. However, when undetected flights are considered, the correlation grows as well as is seen in Fig. 13. This proves a better match between measured and modelled levels.

Analysing the trends of L_{DEN} over the years also showed a high dependence on NMT location. For example, in Fig. 14, the values are shown for NMT 2 where an almost perfect match between measured and modelled noise is visible.

The vast difference between the relative measured noise levels of L_{Night} and L_{DEN} is hypothesised to two factors. During night-time operations, a different set of arrival and departure routes is used. Different modelling assumptions could be the cause of these differences. More likely is that the lower measured noise levels could indicate that the influence of background noise during daytime measurements is significant. In future research, the influence of background noise on measured SEL should be studied. For this research, the L_{Night} results are deemed more reliable.

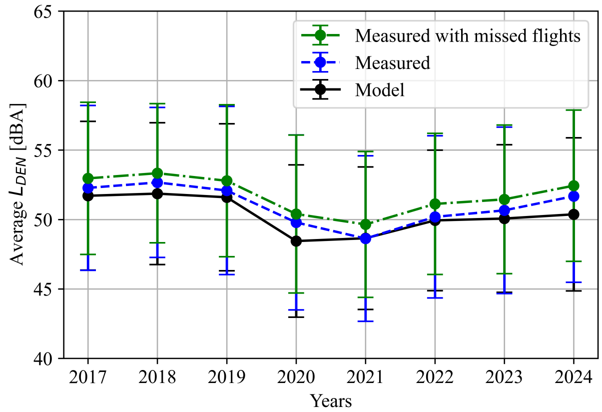

Figure 12. Average modelled and measured L_{DEN} over all NMTs and their corresponding standard deviation.

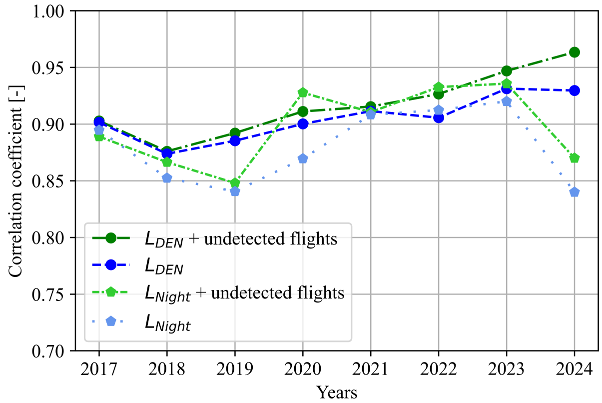

Figure 13. Correlation coefficients between the measured and modelled L_{Night} and L_{DEN} with and without the addition of undetected flights.

5. CONCLUSION

From 2017 to 2024, the NOMOS measurement system has been continuously monitoring noise levels around Amsterdam Airport Schiphol. These measurements were compared to yearly L_{Night} and L_{DEN} values modelled by the Doc 29 aircraft noise model.

While the measured L_{DEN} values represent a summation of all recorded measurements, not all flights were captured due to NMT thresholds.This research focused on estimating the effect of these undetected flights on measured L_{Night} and L_{DEN}. The research showed that aircraft often go undetected at distances larger than 10,000 ft but also the aircraft type is of importance. For the newest, quiet aircraft, more than 40% of the flights within this distance are not measured.

By categorizing existing measurements based on aircraft type, operation type, and NMT location (high-noise or low-noise

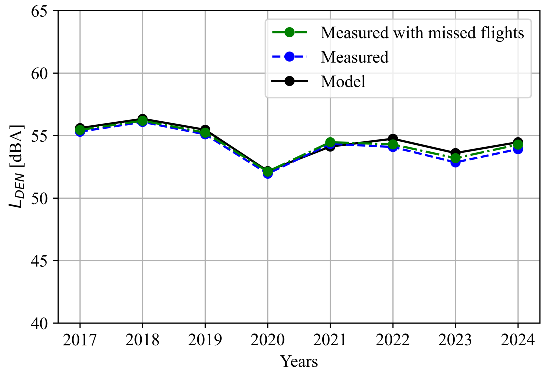

Figure 14. Modelled and measured L_{DEN} of NMT 2.

regions), 256 different weighted least-squares (LS) fits were identified. These estimations allowed for the approximation of noise levels for undetected flights.

Although measurements in high-noise regions provided reliable results, those taken further from the airport showed significant variation, leading to unstable LS estimations. This instability suggests that either the LS model is not a suitable approximation or the measurements in the low-noise regions are of poor quality. Further research is needed to assess the measurement quality in distant areas.

The comparison between the total measured L_{Night} and L_{DEN} and the Doc 29 model showed good agreement, with the model overestimating on average 1 dBA for L_{Night} and underestimating the L_{DEN} by an average of 0.67 dBA over all years. Incorporating the effect of the undetected flights had an average 1.0 dBA increase of the measured levels in the low-noise regions and minimal effect in the high-noise regions for both L_{Night} and L_{DEN}. For L_{DEN}, this effect increased the average difference between measured and modelled noise levels, which could be due to either model underestimation or increased influence of background noise in the low-noise areas. When adding the effects of the undetected flights to the measured L_{Nights}, where generally lower background noise levels are measured, the overestimation of the model disappeared, and a good match between model and measurement was found.

Finally, for both L_{Night} and L_{DEN}, the correlation between the model and measurements was strong. Adding the LS-estimated noise levels, the correlation improved significantly. This indicated that taking into account the undetected flights improves the comparison of measured and modelled yearly average noise levels.

6. ACKNOWLEDGMENTS

The authors would like to thank the Royal Schiphol Group for the use of the modelling and measurement data for this research. Further, we would like to thank the Knowledge and Development Centre (KDC) Mainport Schiphol for their funding.

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