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Validation of the Aircraft Noise and Performance Database Source Spectra

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Accurate modelling of aircraft noise in different weather conditions is crucial for the reliability of noise predictions and their application worldwide. In best-practice aircraft noise models, such as Doc.29, the change in expected sound level on the ground due to changing atmosphere is modelled with a simplified propagation calculation. The Aircraft Noise and Performance (ANP) database contains several standardised source spectra, known as spectral classes, which are used for these calculations to account for the frequency dependence of the atmospheric effects. The spectral classes consist of Pressure Band Levels (PBL) of 24 1/3rd octave bands. This research focuses on the agreement of these spectral classes with measurements, taken around Amsterdam Schiphol Airport, and quantifies the effect of differences in these spectra for the Doc.29 weather correction. The measurements, taken by an acoustic array close to the runway and by continuous single microphone noise measurement stations (NOMOS) at long range, are propagated to the standard distance of 1000 ft (for which the ANP spectral classes are given) taking into account the geometrical spreading and the actual atmospheric absorption. For the B737-800 and A330, differences in shape are found between the two measured spectra and the spectral class. This is partly due to the low signal-to-noise ratio for the high frequencies in case of large distances between the aircraft and the measurement system. The effect of the application of the measured spectra on the Doc.29 weather correction is found to be smaller than 0.5 dBA for the NOMOS positions, indicating the suitability of the current ANP spectral classes for the weather correction.

I. Introduction

The aviation industry is growing and with it the noise nuisance at communities around large airports. To regulate the flights and design noise abatement procedures, the expected inflicted noise on the ground is calculated using aircraft noise models. The most common noise models are empirical models such as the European Doc.29 standard [1–3] and the Dutch calculation model (NRM) [4]. These so-called best-practice models make use of empirical relations gathered in Noise-Power-Distance (NPD) tables. These tables give the A-weighted noise level for a specific power setting of the aircraft engines and a specific distance of the aircraft to the observer on the ground. The simplicity of this modelling technique allows us to compute a large number of flights in a short time. The disadvantage is that a number of assumptions are made. These NPD tables are made for standard conditions, such as standard atmospheric conditions (i.e. 15 deg °C, 10235 Pa, 80% relative humidity). For situations deferring from these standard atmospheric conditions, a weather correction is used. Any deviations in local weather affect the absorption of aircraft noise in the atmosphere through a change in the absorption coefficient. The absorption coefficient is frequency dependent, thus to find the contribution of this effect, an emission spectrum is needed. These spectra are typically used for a large variety of aircraft and are denoted as spectral classes. In total 18 departure and 23 approach spectral classes exist in the Aircraft Noise and Performance (ANP) database*, of which 4 are for commercial 2-engine turbofan aircraft. This aircraft type is most common in large hub airports such as Schiphol.

The use of spectral classes is a modelling assumption as actually, each aircraft type has its own characteristics in its emitted noise spectrum. In this research, the agreement of these spectral classes with measurements taken around Schiphol airport is investigated as well as the effect deviations have on the modelling results. The focus is on the B737NG and A330 aircraft types. The spectra are determined using close-range and long-range measurements of which the set-up and processing are explained in section II. The acquired spectra are compared to each other and the

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[*] `https://www.aircraftnoisemodel.org/`

corresponding spectral class. The differences are analysed in section III. The application of the measured spectra in the Doc.29 best practice noise model shows the influence of differences in the standard and measured spectra to be small, which is further discussed in section IV.

II. Methods

In Doc.29 [2] a method to apply a weather correction is given. This weather correction is used to take the change in atmospheric absorption of sound with changing atmosphere into account. This correction factor is applied by calculating $\Delta L_A(T, p_a, h_{rel}, d_i)$ for every distance d_i in the NPD table and adding those values to the existing table. ΔL_A is the difference in absorption in actual atmosphere $L_{A,atm}$ and in the standard atmosphere $L_{A,ref}$ (101325 Pa, 15 °C, 80% relative humidity). This factor is calculated by removing the standard atmospheric absorption $\alpha_{n,ref}$ and calculating the new α_n for every frequency band n using temperature T, atmospheric pressure p_a and relative humidity h_{rel} according to the SAE-ARP5534 method [5]. This is done by using the given engine spectrum from the ANP database $L_{n,ref}$, which contains the expected sound levels of 24 1/3rd octave frequency bands at 1000 ft (d_{ref}) from the aircraft as seen in Table 1. The centre frequencies of the 1/3rd octave bands run from 50 Hz to 10,000 Hz corresponding to band numbers 17 and 40, respectively. The weather correction factor is calculated through

$$\begin{aligned}\Delta L_A(T, p_a, h_{rel}, d_i) &= L_{A,atm}(T, p_a, h_{rel}, d_i) - L_{A,ref}(d_i) \\ &= 10log \sum_{n=17}^{40} 10^{(L_{n,ref}+\alpha_{n,ref}d_{ref}-\alpha_n d_i - A_n)/10} \\ &- 10log \sum_{n=17}^{40} 10^{(L_{n,ref}+\alpha_{n,ref}d_{ref}-\alpha_{n,ref} d_i - A_n)/10}.\end{aligned} \tag{1}$$

The correction is thus accounting for the frequency dependence of the spectrum. As the spectral classes are given in dB and the NPD tables in dBA, the spectra are A-weighted using A_n before summation.

To investigate the validity of the spectral classes, noise events of departing and landing aircraft are measured and the resulting spectra are compared to their respective spectral class in the ANP database. For this research, two measurement set-ups, presented in section II.A, are used containing close and long-range measurements. In section II.B the processing of the measurements into the required data is discussed.

Table 1 Spectral classes and their associated Pressure Band Levels [dB] assigned to the B737-800.

Spectral Class ID	Op Type	Center Frequency [Hz]											
		50	**63**	**80**	**100**	**125**	**160**	**200**	**250**	**315**	**400**	**500**	**630**
104	Departure	57.3	56.3	61.5	67.7	71.4	73.7	67.0	72.1	73.8	74.1	71.3	70.4
206	Approach	63.3	65.4	64.1	63.2	66.0	66.6	69.6	70.1	71.5	67.1	71.0	70.4
		800	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**	**6300**	**8000**	**10000**
104	Departure	70.9	70.0	68.2	67.3	63.4	60.9	56.6	53.2	47.8	40.5	31.7	27.9
206	Approach	71.8	70.0	69.6	66.6	62.9	62.0	62.7	59.1	58.8	53.3	50.2	40.6

A. Experimental set-up

A single spectral class is given for the full departure or arrival operation. To check the validity of the spectral classes for all flight phases in the operation, measurements are performed close to the runway (i.e. during final approach and take-off) and measurements are taken at a longer range, typically 500-2000 meters (i.e. during phases such as climb-out or glide descent).

The first set of measurements, close to the runway, is performed using an acoustic array at the north side of the Zwanenburgbaan at Schiphol Airport. The array set-up can be seen in Figure 1. As this research is focused on measuring spectra, the array is not used for noise source localisation. The spectra of the middle 8 microphones are averaged. The exact measurement setup and processing are explained in Vieira et. al. [6, 7] For this research, a data set consisting of

10 take-off and 10 landing measurements for the B737-800 and 10 take-off and 5 landing measurements for the A330, acquired during three different days of the measurement campaign, is used. During these measurements, the aircraft flew straight over the array at an altitude of around 100-300 meters.

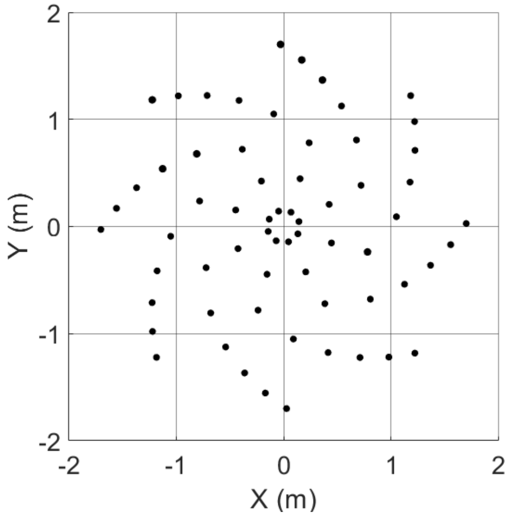


Fig. 1 Acoustic array configuration

The second set of measurements is taken at a longer range by the continuous unmonitored noise measurement system NOMOS, which consists of 41 Noise Measurement Towers (NMTs). These NMTs are placed on 10 meter poles in the neighbourhood of Schiphol and equipped with class 1 microphones which have an uncertainty of 0.7-0.9 dB [8]. For this research, NMTs 10, 14 and 21 are used for landing measurements (number of flights # per aircraft: $\#_{B738}$ = 1288, $\#_{A330}$ = 171) and NMTs 14, 30, 34, 40, 41 and 94 for take-off measurements ($\#_{B738}$ = 1179, $\#_{A330}$ = 105). The data collected from these NMTs contains Pressure Band Levels (PBL) for all 24 frequency bands for each second of the recorded noise event. Additionally, audio files of each noise event are saved with a sampling frequency f_s of 8000 Hz, meaning spectral information above 4000 Hz is not available for this data set. As these NMTs are not in a controlled environment, only measurements adhering to the ISO 20906 requirements [9] are selected to provide the most accurate readings (i.e. during the measurement it is not raining, wind speed is less than 10 m/s and the elevation angle β of the aircraft is larger than 60°). Next to noise data, operational data in the form of ADS-B and RADAR data is available.

B. Measurement processing

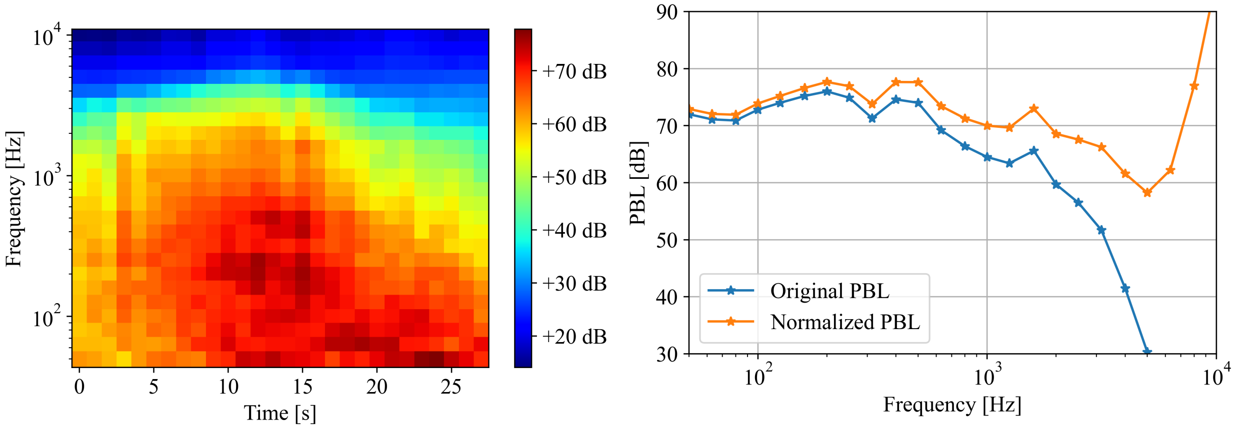
The measurements from both data sets are taken under different weather circumstances and at different distances. To be able to compare the measurements with the ANP spectral class, the measured spectra are standardised as well. For each Pressure Band Level (PBL) the level is adjusted for the difference in absorption and geometrical spreading according to

$$PBL_{d_{ref}}[dB] = PBL_{d_m} - a_{n,ref}d_{ref} + a_n d_m + 20log_{10}(d_m/d_{ref}) \tag{2}$$

The absorption rates a_n are calculated with data from a nearby KNMI weather station that gathers temperature, pressure and relative humidity for the day and time of the recorded flights.[†] The distance between the aircraft and the measurement location d_m is taken from RADAR and ADS-B data for the NOMOS measurements and array measurements, respectively. The reference distance d_{ref} is set to 1000 ft in accordance with the spectral class data. It is assumed that the aircraft is a point source and the emitted spectrum is omnidirectional, so any change in the spectrum over lateral or longitudinal axes is not taken into account. The spectral classes in the ANP database are "... for historical reasons, normalized to 70 dB at 1000 Hz." [2] All spectral classes are thus shifted so the PBL of the 1000 Hz band equals 70 dB. This means that the spectral classes offer only information regarding the shape of the spectrum and not the overall sound pressure level of the source. This latter information is incorporated into the NPD table. For this research, both measured levels and normalised data are shown. For each frequency band, the normalized PBLs of all measurements are averaged and the standard deviation σ is calculated. This is done separately for arrival and departure operations for both aircraft.

[†] `https://www.knmi.nl/nederland-nu/klimatologie/uurgegevens`

Figure 2 shows an example of measurements taken by the NOMOS system. Figure 2a presents the PBLs (not normalized) as a function of time. In Figure 2b the measurement at the instant of maximum A-weighted sound level is shown (blue), together with the resulting normalized PBL corresponding to a 1000 ft source-receiver distance and 70 dB at 1000 Hz. The normalized PBLs become unrealistically high for the higher frequencies. This is most probably due to other contributions to the measured noise levels that are dominant compared to the noise of the aircraft. For this reason, the PBLs above 5 kHz gathered from the NOMOS measurements are disregarded.



(a) Spectrogram of an example noise event of the A330

(b) PBL of noise event at time of $L_{A,max}$ calculated at source level

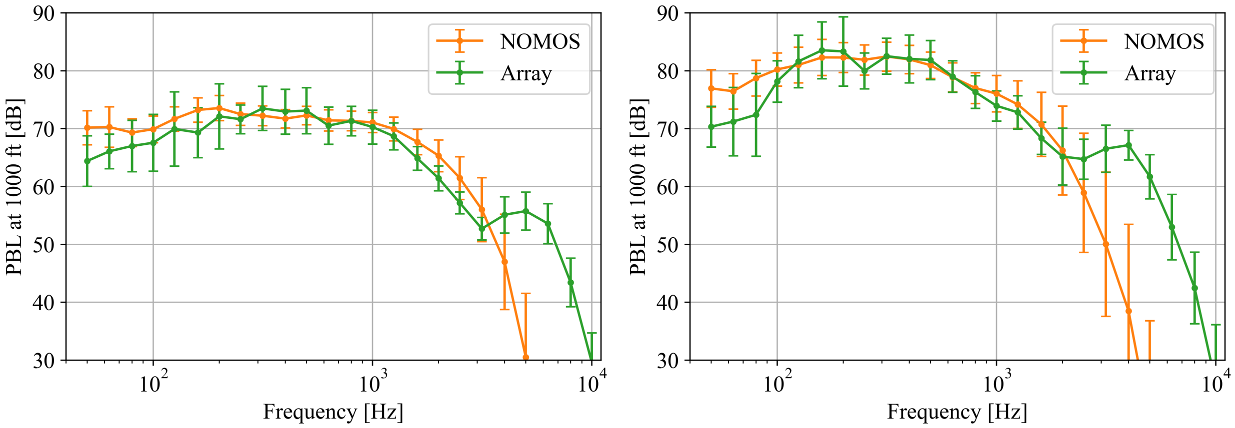
Fig. 2 Example measured noise event of the A330 at microphone and calculated at source level.

Finally, in the aviation industry, it is standard to calculate the noise levels with A-weighting. The NPD tables given in the ANP database are also A-weighted, but the spectral class is given in dB. The A-weighting is, however, accounted for in the correction conform Equation 1.

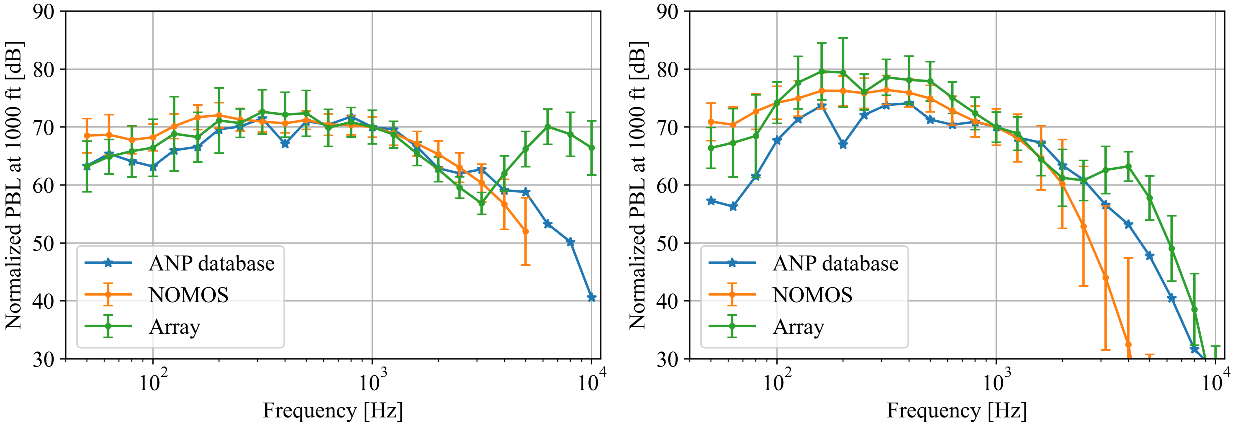
III. Results

A. Measured spectra

The close and long-range spectral measurements are processed and the outcomes are presented in this section. For the B737-800, the averaged measured spectra and their corresponding standard deviation are shown in Figures 3a and 3b in orange and green for the NOMOS and array measurements, respectively. In accordance with standard practice, the measurements are then normalized to be compared to their respective spectral class (Table 1) shown in blue (Figures 3c and 3d).



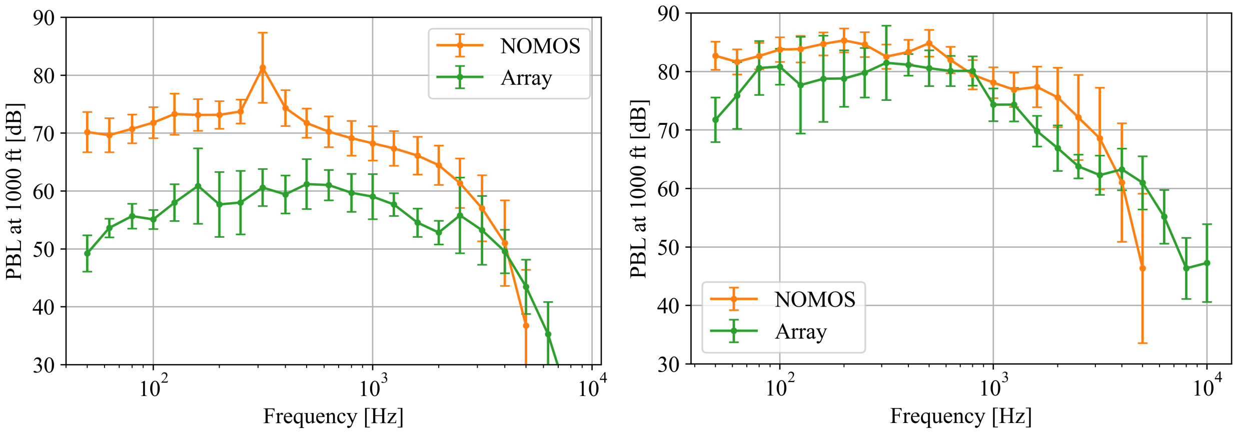
(a) Measured arrival PBLs propagated to 1000 ft. **(b) Measured departure PBLs propagated to 1000 ft.**



(c) Normalized arrival PBLs. **(d) Normalized departure PBLs.**

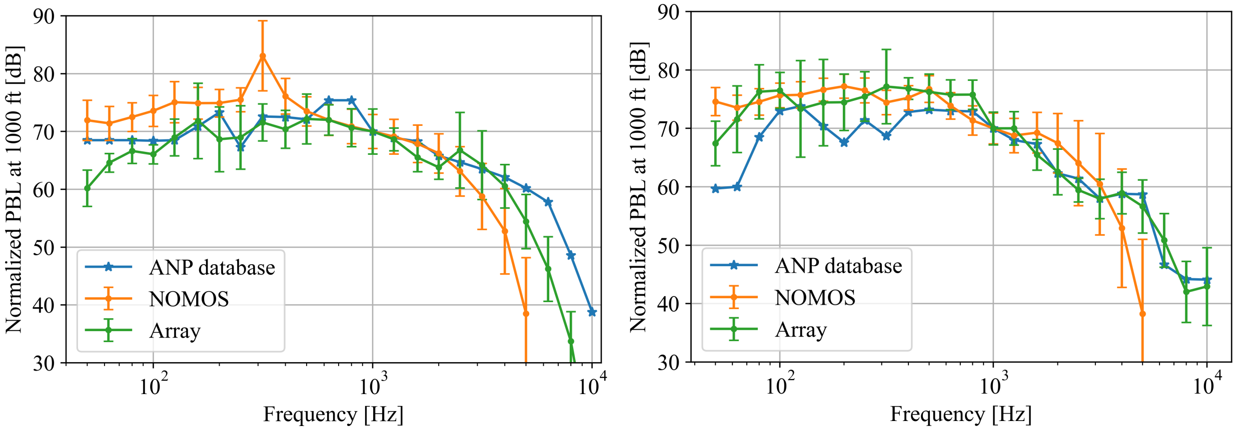
Fig. 3 Averaged measured B737-800 PBLs and their standard deviation compared to the standard ANP spectral class before and after standardisation.

For the A330, with spectral classes 102 and 202 for departure and arrival, respectively, the average measurements and their standard deviation per PBL are shown in Figure 4.



(a) Measured arrival PBLs propagated to 1000 ft.

(b) Measured departure PBLs propagated to 1000 ft.



(c) Normalized arrival PBLs.

(d) Normalized departure PBLs.

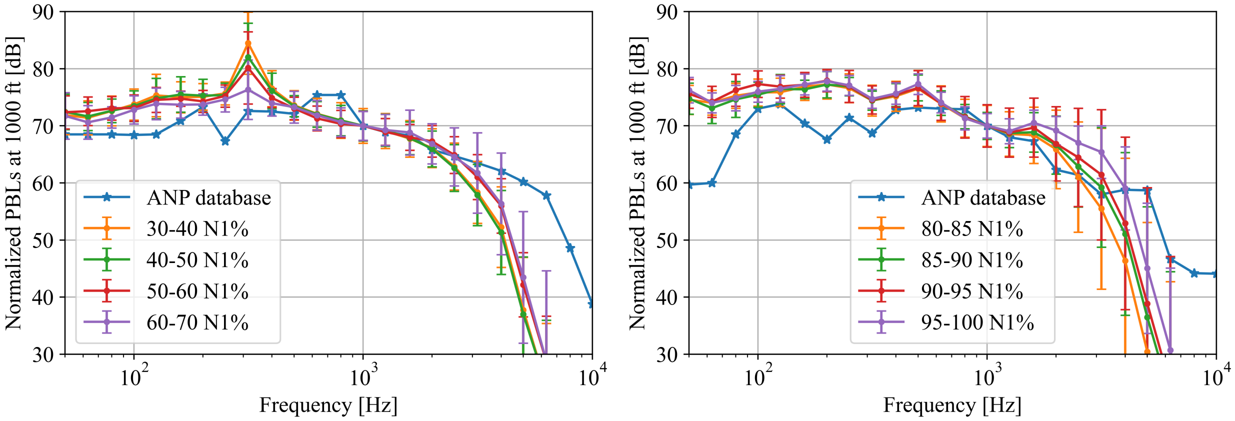
Fig. 4 Averaged measured A330 PBLs and their standard deviation compared to the standard ANP spectral class before and after standardisation.

When looking at the averaged measured PBLs of the close and long-range measurements before normalization in (a) and (b), a few things are noted. For the B737, the PBLs in the mid-frequency range show a close match between the NOMOS and array measurements. This is not the case for the A330 where the close-range array measurements show lower PBLs than the long-range NOMOS measurements when both propagated to 1000 ft. For both aircraft, the departure measurements are less consistent than arrivals i.e. a larger standard deviation is seen in the PBLs of both array and NOMOS measurements. Departure operations commonly have more irregular flight paths, weight and thrust profiles than arrival operations which follow a fixed descent angle. These deviations in operational conditions can cause a larger variation in measured noise levels. Specifically in the NOMOS measurements, the standard deviation of the PBLs grows with increasing frequency. This is likely due to the low signal-to-noise ratios for long distances.

For comparison of the two measured spectral shapes with each other and the ANP spectral classes, the measured data is normalized as seen in (c) and (d). For the B737-800, the array measurements show, for both operations, a drop followed by peak around 3500 Hz. This could be due to engine liners as this is the first harmonic of a typical blade passing frequency (BPF) of the CFM56-7B engines.When looking at the overall trend of the array and NOMOS departure measurements, it seems that the lower frequency band levels are underestimated by the ANP spectral class. This is in line with research results where semi-empirical models under-predicted the noise levels at low frequencies [7].

For the A330 measurements, very different shapes of spectra are found for the two measurements and the ANP database. The arrival NOMOS measurements show a sharp peak at 300 Hz, while the array measurements and ANP database show a small peak at around 200 Hz. At higher frequencies, both measured spectra are significantly lower than the ANP database. For the departure measurements, the array measurements show, especially for frequencies above 1000 Hz, a good agreement with the spectral class of the ANP database. Similarly to the B737, the PBLs at low frequency are underestimated by the ANP database.

An analysis to find the potential origin of the differences is performed. From the NOMOS audio files, the BPF could be found and used to analyse the engine setting $N1\%$. The method of extracting $N1\%$ from NOMOS audio files is explained in Merino-Martinez et. al. [10] To find the influence of this engine setting on the measured spectrum, the PBLs are sorted by $N1\%$ in Figure 5. Two things can be seen. During arrival operations, visible in Figure 5a, the peak around 300 Hz flattens out at a higher engine setting while at higher frequencies (around 3 - 4 kHz) these higher engine settings produce more noise. For the departure noise measurements, visible in Figure 5b, the PBLs of the lower frequencies are not affected by a change in engine setting. Similarly to the arrival measurements, higher engine settings produce more noise for frequencies larger than 2 kHz. Given the limited effect of $N1\%$, there must be other factors than $N1\%$ that cause the mismatch between spectral class and the measured spectra.



(a) Normalized arrival PBLs of the A330 split into engine setting.

(b) Normalized arrival PBLs of the A330 split into engine setting.

Fig. 5 Measured and normalized PBLs from the NOMOS system split out by engine setting.

B. Effect on Doc.29 predictions

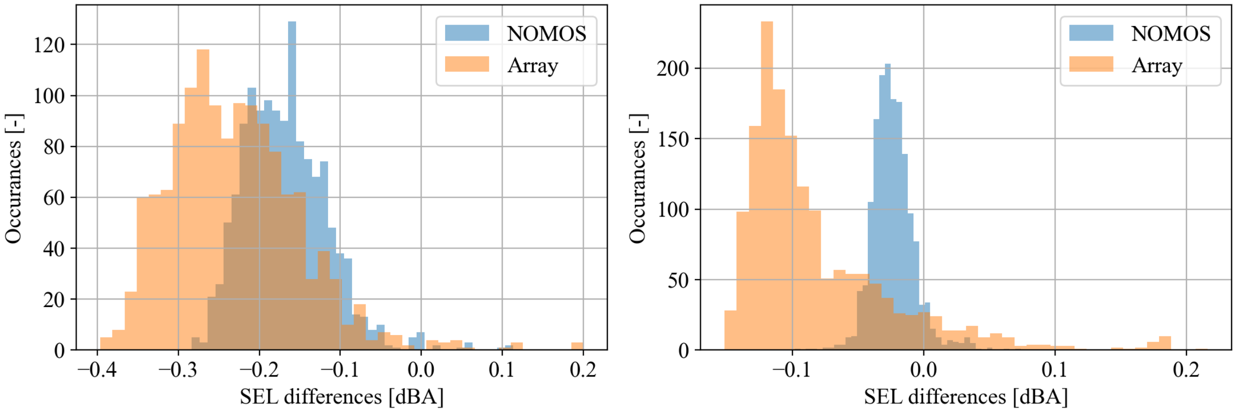
The Doc.29 model is used to predict noise levels of aircraft flyover events on the ground. Outputs are the maximum A-weighted noise level $L_{A,max}$ and the Sound Exposure Level (SEL). To analyse the effect the spectral class has on the weather correction, the measured (and normalized) PBLs are implemented as a new spectral class in Doc.29 (replacing $L_{n,ref}$ in Equation 1) to predict a new $L_{A,max}$ and SEL. These values are compared to the ANP spectral class based values. The difference in SEL values is plotted in Figure 6 and Figure 7 according to

$$\Delta \hat{L_A} = L_{A_{measurement}} - L_{A_{ANP}} \tag{3}$$

where $L_{A_{measurement}}$ is the A-weighted noise level ($L_{A,max}$ and SEL) predicted by Doc.29 using the normalized measured spectrum. $\Delta \hat{L_A}$ quantifies the effect of using a different spectrum, where ΔL_A (Equation 1) is the weather correction.

When comparing the data sets of around 1000 B737-800 flights and 170 A330 flights modelled with the standard and measured spectra, a slight shift in the levels is observed. For both aircraft, a primarily negative ΔL_A is seen caused by a larger absorption when using the measured spectra. The shapes of the NOMOS and array histogram of differences are similar although shifted.

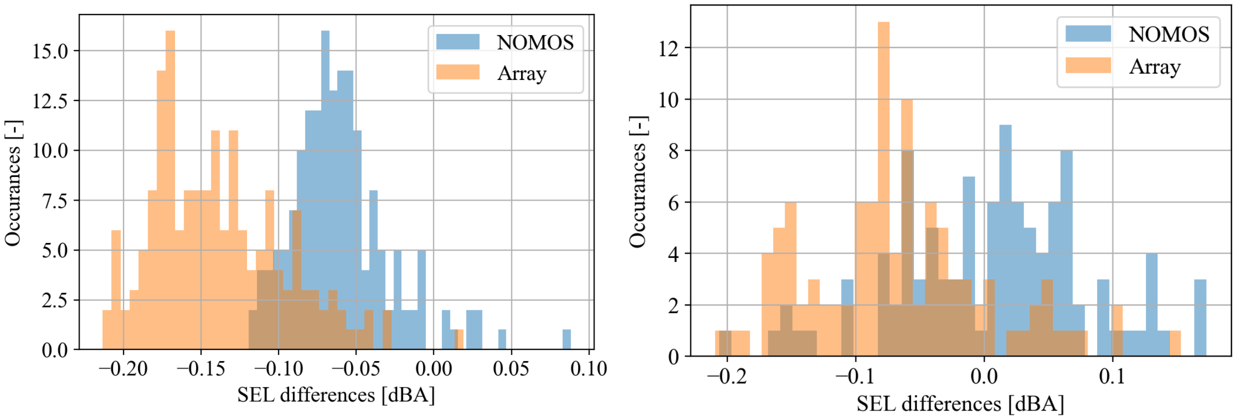
As a final step, the noise predictions are also compared to the $L_{A,max}$ and SEL measured by NOMOS. Although the average of the modelled $L_{A,max}$ and SEL values changes, the differences between modelled and measured values remain similar. The standard deviation of these differences is unaffected by the use of updated spectral classes. This analysis is not shown in this contribution.



(a) Arrival operations modelled with NOMOS and array-derived spectra.

(b) Departure operations modelled with NOMOS and array-derived spectra.

Fig. 6 Effect of applying measured spectra of B737NG on Doc.29 SEL predictions.

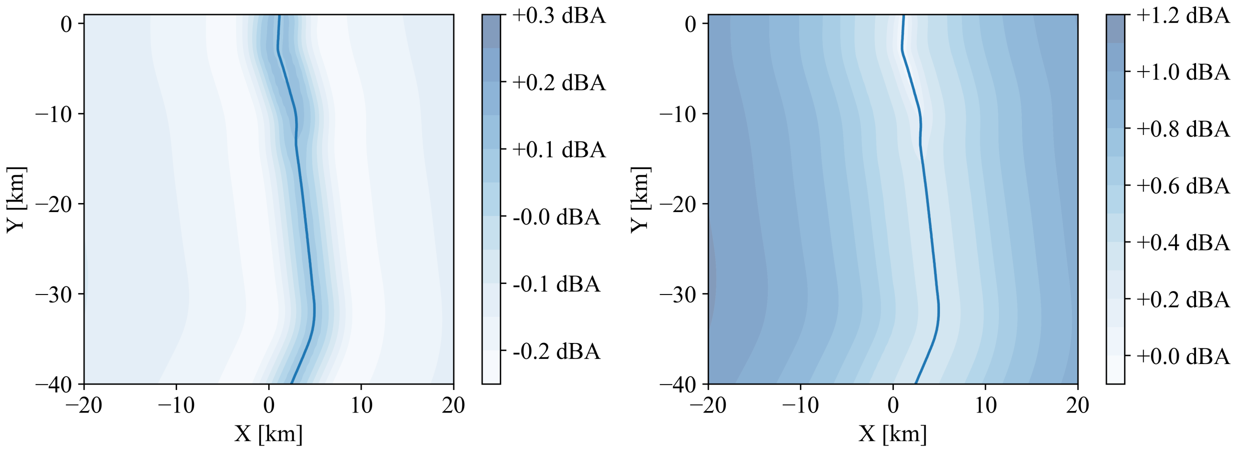


(a) Arrival operations modelled with NOMOS and array-derived spectra.

(b) Departure operations modelled with NOMOS and array-derived spectra.

Fig. 7 Effect of applying measured spectra of A330 on Doc.29 SEL predictions.

Best-practice models, such as Doc.29, are often used to model the impact of aircraft noise over large areas using contours. To analyse the effect of a change in ANP spectral class on these contours, the measured spectra are used to model the noise of a departure operation at Schiphol Airport. In Figure 8, the change in noise level predicted on the ground is shown when the measured spectra are used instead of the ANP spectral class. The weather condition during this simulation is a winter day; 4 °C, 100670 Pa and 95% relative humidity. The effect of the close-range array measured spectrum is small, around ± 0.2 dBA. The effect of the long-range NOMOS measured spectrum is larger, up to 1.2 dBA. Note that these values are not encountered in Figures 6 and 7 due to the smaller distances between the NOMOS NMTs and the aircraft considered during the measurements in Figures 6 and 7. These results are similar to what is seen in Figure 6b, where the use of the NOMOS-derived spectrum has a larger effect than the array-derived spectrum. This is likely due to the higher NOMOS PBLs in the lower frequency bands which are hardly absorbed.



(a) Contours of the differences in modelled SEL value when using Array measurements vs ANP spectral class.

(b) Contours of the differences in modelled SEL value when using NOMOS measurements vs ANP spectral class.

Fig. 8 Changes in modelled footprints of SEL values of a departing flight of the B737-800. (Note the deviating colour axis)

IV. Discussion

The measured source PBLs are found to differ from the standard spectral class. Also, a difference is found between the close-range (array) measurements and long-range (NOMOS) measurements. An important cause for these differences is probably that these measurements are taken at different flight phases. In addition, even though the NOMOS NMTs are equipped with a class 1 microphone, the measurement conditions (unmonitored with possible background noise and/or reflections) are less favourable. Nevertheless, they allow for building a large dataset and can give insight into the differences in the spectra for changing operating conditions such as engine settings.

For both analysed aircraft, changing the standard spectral class to the measured ones had a limited effect on the modelled SEL of flights around Schiphol airport. The influence of the used spectral class on the modelled noise levels can be significant for very short distances but dampens out quickly. The changes in contour caused by differences in the lower frequency PBLs, tend to influence the larger distances. Although the changes in modelled level become significant (up to 1.2 dBA), the total noise level at these locations is low (<40 dBA) and outside of the scope of best-practice noise modelling. Thus the current method of using the ANP spectral classes is deemed accurate enough for the Doc.29 model.

As a final step, we investigate the effect of assuming a flat spectrum. This assumption is sometimes made in literature. A uniform spectrum with PBLs of 70 dB for every frequency band is used to model the contour in Figure 9. The effect of using a uniform spectrum on the weather correction is higher than when the measured spectra are used especially close to the runway and at a large distance (>20 km). Close to the runway, at the top of Figure 9, SEL differences of more than 3.5 dBA are found. This is due to the high PBLs (70 dB) at high frequencies compared to the PBLs in the ANP database (see Table 1). Further away from the runway, the high frequencies dampen out and the contour looks similar to Figure 8b.

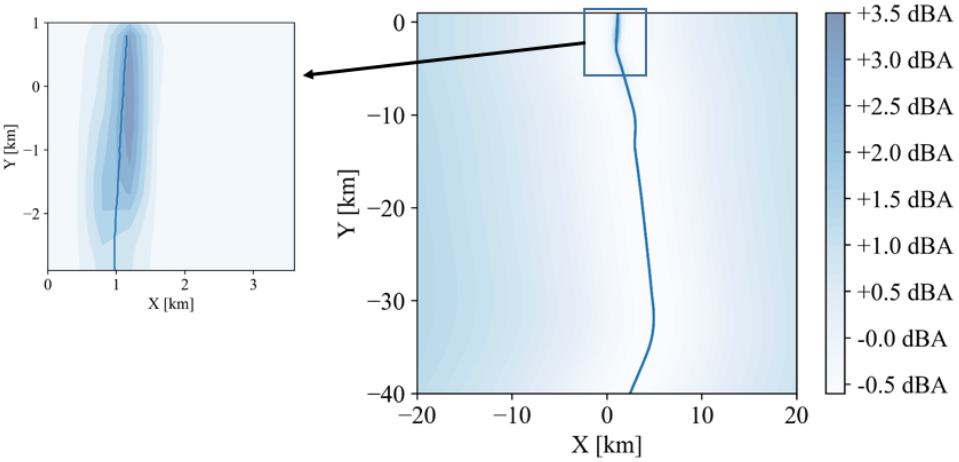


Fig. 9 Changes in SEL footprint when a uniform spectrum is used for a departing flight of the B737-800.

V. Conclusion

All aircraft have different noise emission characteristics. These differences are visible in the acoustic spectrum and influence the propagation of sound through the atmosphere. With changing weather situations and thus changing sound propagation, knowledge about the emitted noise spectra of each aircraft is important to accurately quantify the effect of the changing atmosphere on the received levels. In this research, the noise spectra of the B737-800 and the A330 are measured and compared to their respective standard spectral class from the Aircraft Noise and Performance (ANP) database. Two types of measurements are used i.e. at close range (200-500 ft), using an acoustic array, and at long range (500-3000 ft), using the NOMOS measurement system. The measured spectra are then applied to the Doc.29 aircraft noise model for the calculation of the weather correction.

Differences between the two measurement types and the aircraft's respective spectral class are found. Despite that, differences in Doc.29 calculated Sound Exposure Levels (SEL) are limited to 0.2 dBA for arrivals and 0.1 dBA for departures on average for the predictions of the NMT stations considered. For larger distances from the track, larger differences are found, especially when using the NOMOS-derived spectra. However, total noise levels are low for these larger distances. For the situations considered in this contribution, it can be conducted that the spectral class from the ANP database can be applied.

Acknowledgements

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