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Including atmospheric propagation effects in aircraft take-off noise modeling

Michael Arntzen[1,2]; Martijn Hordijk[2]; Dick G. Simons[2]

[1] National Aerospace Laboratory (NLR), Netherlands

[2] TU Delft, Aerospace Engineering, Aircraft Noise & Climate Effects, Netherlands

ABSTRACT

Aircraft noise is frequently calculated by models using Noise-Power-Distance relations (NPD-tables). Such an approach is common in the Integrated Noise Model (INM) or the method outlined in ECAC Doc. 29. Only a limited correction for atmospheric propagation effects is available through empirical lateral attenuation functions that are intended, as is the model, for multi-event calculations.

A new feature, developed at the NLR, is to include the results of ray tracing in a Doc.29-based calculation. As such, the noise model is augmented by detailed propagation effects on a single-event level.

Results are demonstrated for two different take-off procedures as Sound Exposure Level (SEL) contours. Consequently, the effects of wind on departure procedures are illustrated and further quantified by predicting awakenings in fictitious communities. The results show that the effects of sound refraction are the largest as the aircraft is low. Therefore, a departure procedure featuring a shallow climb angle shows more effects than procedure with a steeper climb. It is shown that wind effects can clearly lead to asymmetrical contours and awakenings. The results show that there is a potential for noise mitigation based on ambient atmospheric conditions.

Keywords: Aircraft Noise, Meteorological effects, Airport Noise
I-INCE Classification of Subjects Number(s): 53.1, 24.6, 52.2

1. INTRODUCTION

Integrated aircraft noise models provide the basis of many aircraft noise mitigation or noise mapping studies. Such models, like the FAA's Integrated Noise Model (INM) [1] or the method described by ECAC in their Doc.29 [2], rely on simplifications to reduce the real-life physical complexities. One of these simplifications is the averaging of atmospheric propagation effects throughout the year. As such, integrated noise models provide results that are intended for yearly averaged noise metrics such as the L_{DEN} or L_{DN}. This particular simplifications regarding atmospheric propagation is under investigation in this paper.

In noise contour algorithms, the so-called 'Lateral Attenuation' (LA) model takes the effects of aircraft shielding and non-standard atmospheric propagation into account. The latter is the Excess Attenuation (EA), i.e. the attenuation in excess of spherical spreading and absorption as is integrated in the Noise-Power-Distance (NPD) relations. It is well known that sound rays are curved by the atmosphere due to wind and temperature gradients.[3-5] These effects are ignored in the NPD relations and amended by the EA model. The EA model is an empirical relation, based on a curve-fit through

[1] Michael.arntzen@nlr.nl

year-long measurements of EA. Therefore, the EA model inherently assumes that these effects average out over a year. Consequently, large differences for single-events may occur.

Quite recently, the NLR's Doc.29 implementation was augmented by the functionality to include these atmospheric propagation effects.[6-7] A ray tracing code was used to predict and use the EA for a single-event instead of the empirical relations. Using this method it is possible to investigate the impact of more detailed atmospheric effects in a standardized noise model. Furthermore, it offers a potential to study if particular aircraft procedures could benefit from atmospheric influences to minimize their noise impact.

The current study attempts to provide insight in the effects of atmospheric propagation for three Noise Abatement Departure Procedures (NADP), including a standardized NADP-1 (ICAO-A) and NADP-2 (ICAO-B) procedure. By investigating the two procedures, the effects of atmospheric propagation on noise contours and awakenings will be discussed. From this discussion, a first indication on the potential of weather based noise mitigation procedures is distilled.

2. NOISE MODEL

2.1 Doc.29

The used noise model is described by ECAC in Doc.29 [2] and, from hereon, referred to as the Doc.29 model. This model is very similar to INM, especially regarding the modeling assumptions. The cornerstone of this method is formed by the NPD relation. Tabulated NPD relations form the basic prediction of the noise level at a specific distance from the aircraft. The tabulated NPD values include the effects of spherical spreading, ground reflection (at 90 deg grazing angle, i.e. aircraft is directly overhead) and atmospheric absorption under standard conditions. The data is typically provided by aircraft manufactures and obtained during the aircraft certification process, or at least under such conditions. By using the NPD relation, the sound level at an observer location is predicted. Applying this NPD relationship for noise footprint calculations is a rather fast method and therefore popular for large (yearlong) scenarios or optimization studies.

To create a multi-event scenario for an entire year involves the specification off annual traffic, routes, runways and procedures. By calculating the noise footprints of individual aircraft, or their noise-representative counterpart, the individual effects of each aircraft are obtained on a calculation grid located around the airport. Each individual flight is subjected to the empirical EA relations, thereby mimicking the averaged atmospheric propagation conditions throughout the year. By summing the individual results, the annual noise exposure level can be computed. It is common to use a noise exposure metric that penalizes evening and/or night flights, such as L_{DEN}.

2.2 Ray tracing augmentation

As mentioned in the previous section, the NPD relation includes propagation effects for a standardized atmosphere. In the standardized atmosphere it is assumed that sound rays follow a straight path and absorption is uniform (height independent). Both assumptions are known to be hampered. A correction based on measurements (EA model) is therefore used. However, the EA model provides results for yearlong averages thereby severely limiting the application of that model to single-event predictions. At the NLR, a ray tracing algorithm was written to calculate the EA for curved paths. Based on Snell's law, a quick computational algorithm is developed that takes the appropriate geometric spreading, path based absorption and ground reflection of an impedance plane into account. [8]

Limitations of ray tracing theory are formed by caustics and shadow zones. A caustic is formed as two consecutive rays cross and leads (mathematically) to a singular (infinitely high) acoustic pressure, which is physically unrealistic. Therefore this behavior is limited to 10 dB over the spherical spreading results. Shadow zones are areas on the ground where no ray coverage is present. Such a situation implies that no sound is propagated towards that area since rays indicate where sound energy is present. However, there is no total silence in shadow zones since diffraction (ignored in ray tracing) occurs. To correct this, an analysis with a Fast Field Program (FFP) [9] was executed to calculate the additional, frequency dependent, losses in shadow zones. On the basis of that analysis a simple correction procedure has been developed and included in the ray tracing algorithm. [7, 8]

Summing all the individual loss factors (spreading, atmospheric absorption, ground reflection) over the ray paths, leads to a total transmission loss on the ground. Since a part of the loss is already included in the NPD relation, the difference is the calculated EA loss that needs to be applied in the model. Hence, if the EA loss is calculated by ray tracing for a particular stratified atmosphere and source spectrum, the results can be used or re-used by the original Doc.29 model. This implies that the computational efficiency of the original model is retained and therefore still allows optimization studies that involve many evaluations of the model.

2.3 Previous results

The augmented Doc.29 model was used to evaluate the validity of the empirical EA relations. By simulating the 2010 weather situation in the Netherlands, using varying atmospheric measurements for daily night and day conditions, single-event results were used to create an annual noise exposure contour. It was shown that the yearly contours predicted by the empirical EA relations, coincide closely with the ray tracing calculated results for the Dutch weather situations studied. At the same time is was acknowledged that in case of strong prevailing winds the conclusions might be different.

Small differences were observed underneath departure routes that could be associated with atmospheric absorption. It was shown that the accumulated effect of non-uniform absorption over a ray path has a relative large effect on the resulting differences, when compared to the effects of wind and ground impedance. Wind effects were just noticeable on a smaller time scale, i.e. monthly contours, and only for the relatively low (48) L_{DEN} contour values. If wind effects are present, they are likely to influence lower contour values since those are formed at more shallow angles from the source compared to higher contour values. Refraction effects, by wind or temperature, are more likely to occur in such a situation. [7]

3. SIMULATION SETUP

3.1 Trajectory

The current study evaluates the effect of atmospheric propagation on departing flights from an airport. In general, two departure procedures are commonly encountered in daily operations and are referred to as ICAO-A and ICAO-B procedure. There is a distinct difference in climb profile as the ICAO A procedure climbs relatively steep at a constant speed until reaching 3000 ft. The ICAO B procedure is reducing its climb rate along the procedure, thereby accelerating and reducing flap settings. Figure 1 show the procedure used in this study, for a Boeing 737-300 aircraft.

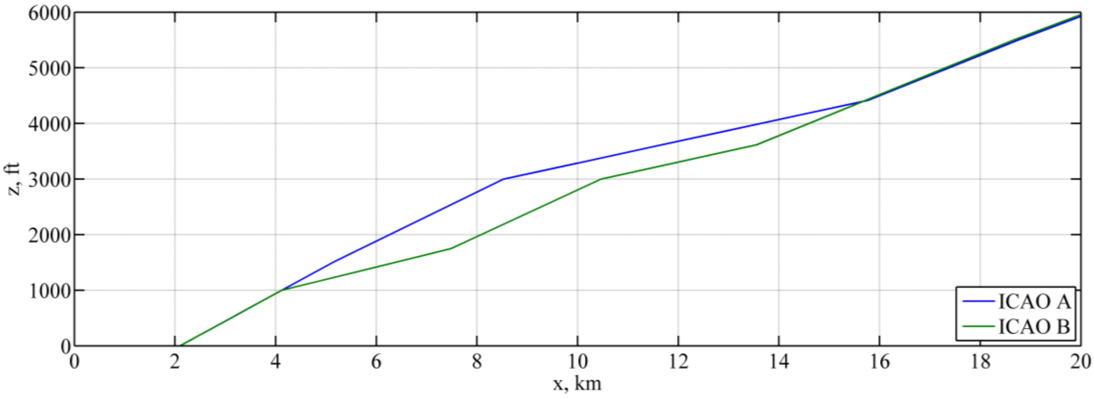

Figure 1 Modeled climb profile for B737

The test case will involve these two procedures and the route, i.e. ground track, is fixed along the extended centerline of the runway. Essentially, this is a 2D problem as no deviation in ground track is allowed. These two profiles and ground tracks are fixed during the simulations. This implies that only effects of atmospheric propagation on noise contours are simulated.

3.2 Atmosphere

To obtain a relevant atmospheric scenario for the simulation, measured atmospheric data[1] was analyzed. This analysis showed that in particular wind conditions, a change of wind direction with altitude is very common. Figure 2 shows this effect.

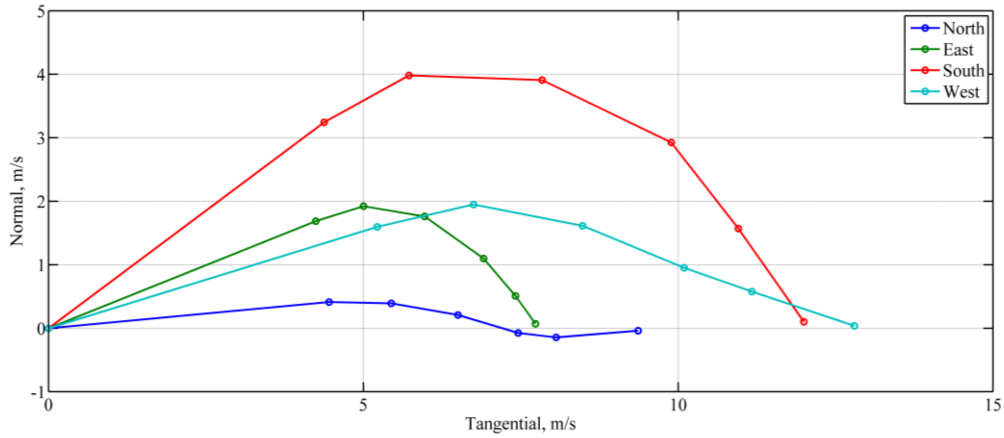

Figure 2 Measured (mean) wind components for wind originating from different wind-rose directions for an entire year. The circular markers show an increasing height at intervals of 0, 10 100, 300, 600 1000 and 2000 m.

Figure 2 shows the normal and tangential wind components, calculated for the mean wind as obtained after the analysis of an entire year. The circular markers show an increasing height at intervals of 0, 10 100, 300, 600 1000 and 2000 m. The wind at the ground surface is (artificially) set to zero. The tangential direction is defined along the cardinal wind direction, the normal direction points 90 degrees to the right of the tangential direction. It is clear that wind originating from a Southern direction shows the largest change in wind direction. Such a change in wind direction can be related to the 'Ekman spiral'. Earlier studies concluded that this phenomenon should not be ignored when calculating aircraft noise contours including propagation phenomena.[10]

Based on this conclusion, NADPs are subjected to four different atmospheric conditions. The first is the ISA condition, including temperature lapse but excluding wind effects. The temperature lapse is the International Standard Atmosphere (ISA) defined standard of -6.5 K/km and the relative humidity is uniform at 70%. This results in, more or less, constant atmospheric absorption at all relevant altitudes. The second condition involves a logarithmic wind profile (8 kts at 10 meters altitude) in a headwind condition on top of the temperature lapse. The third atmospheric condition is similar to the second, but the wind is coming from a South-West direction, i.e. 135 degrees. The final atmospheric condition applies the same wind as the third condition, but the South-West wind direction is modified by a changing wind direction based on Figure 2, i.e. the Ekman wind condition. This results in a changing wind direction from 135 degrees at the ground, to 155 degrees at roughly 200 meters. At higher altitudes, the wind is thus coming from a different direction than the surface wind.

4. RESULTS & DISCUSSION

4.1 Noise contours

Noise contours are created with help of the ray tracing augmented Doc.29 model for the departure procedures illustrated in Figure 1. As a baseline to compare the results to, the model was first applied for ISA conditions (hence, including temperature lapse). The corresponding Sound Exposure Level (SEL) contours for 65 and 55 dB(A) are shown in Figure 3 and Figure 4.

[1] Balloon soundings obtained from the university of Wyoming; http://weather.uwyo.edu/upperair/sounding.html, accessed on 21-07-2014.

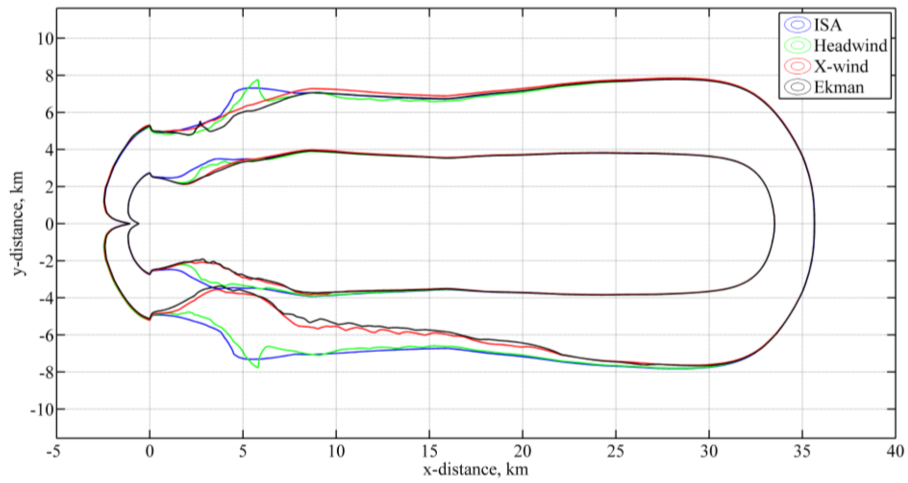

Figure 3 The 65 SEL and 55 SEL contours for the ICAO A procedure.

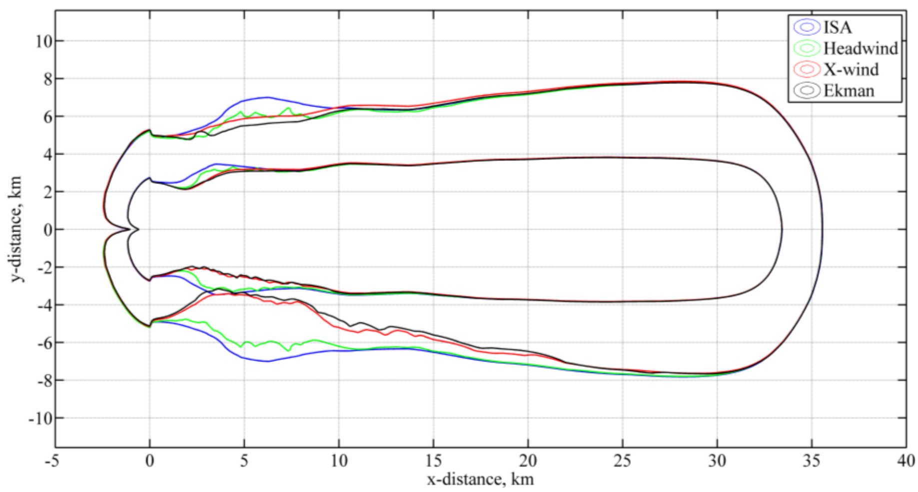

Figure 4 The 65 SEL and 55 SEL contours for the ICAO B procedure.

Comparing the ICAO A to the ICAO B procedure, that is Figure 3 to Figure 4, shows that the ICAO B procedure in general shows slightly smaller contours. Especially in the area where the two flight paths differ (see Figure 1). For both the ICAO A and B procedure, the headwind results in a slightly smaller contour near an x coordinate of 5 km. The contour remains symmetrical around the y-axis since the wind is aligned with that direction, i.e. wind from the East.

If a cross wind (x-wind) is considered, the results become asymmetrical. Notice that a shadow zone is present around an x-coordinate of 5 km at the negative y position. Both the 65 SEL and 55 SEL contour are affected and smaller. Furthermore, the ICAO B shows this behavior more clearly than the ICAO A procedure. Since the aircraft is lower near this x-coordinate, see Figure 1, the effects of refraction are more pronounced. Hence, the potential use of weather effects for noise mitigation is larger for lower flying aircraft. At the opposite side of the cross wind contour, that is the positive y-direction (x = 5 km, y = 6 km), more aircraft noise should be expected due to the downwind conditions.

The results based on the change in wind direction, linked to the Ekman behavior, are labeled 'Ekman' in Figure 3 to Figure 4. The aforementioned shadow zones are now more pronounced due to the wind moving to a more southerly direction. However, the same behavior appears at the downwind area of the contour, i.e. x = 5 km; y = 6km, but only for the 55 SEL contour. This can be linked to downward refracted rays that bounce of the ground and hit the ground outside the relevant contours. As such, there are areas on the grid where less rays are present leading to lower sound levels.

4.2 Awakenings

To evaluate the effects of the atmosphere on a more quantitative scale, awakenings are calculated for fictitious communities. These communities are mirrored around the y = 0 axis. Different noise-response relationships are available to that end; here we've used the FICAN [11] relation and assume a 20 dB(A) transmission loss going from outdoor to indoor sound levels.

On either side of the ground track, along a centerline at y = 4 km or y = -4 km, there are four communities that are directly adjacent of 3 km length in both x and y direction. These communities are referred to as community 1 through 4, see Figure 5.

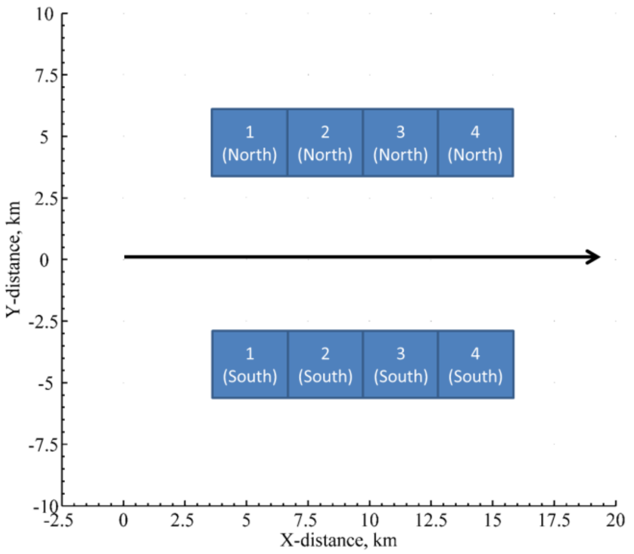

Figure 5 The location of the communities.

By using an assumed and constant density of people in the communities, the number of people awakened by the aircraft can be calculated. The relative amount of awakenings, i.e. referenced to the total number of people awakened in both the North and South side of a community, is shown for the ICAO B results in Table 1. Table 1 should be interpreted in the following way; for ISA conditions, 50% of the total number of people awakened in community 1 (both North and South) lives in the North part and 50% lives in in the South part, i.e. an equal amount of people is awakened on either side of the ground track.

Table 1 Relative amount of awakenings for different wind for the ICAO B departure.

ICAO B		Percentage awakenings, %			
Atmospheric condition	**Community**	**1**	**2**	**3**	**4**
ISA	*North*	50%	50%	50%	50%
	South	50%	50%	50%	50%
Headwind	*North*	50%	50%	50%	50%
	South	50%	50%	50%	50%
X-wind	*North*	76%	63%	53%	52%
	South	24%	37%	47%	48%
Ekman	*North*	77%	64%	54%	52%
	South	23%	36%	46%	48%

Table 1 shows that, as expected, for ISA conditions there is no difference between the communities to the North or South of the ground track. The same holds for headwind conditions, i.e. the wind blows from the East. However, for the cross wind condition, an asymmetry occurs in the number of awakenings between the North and South communities and this effect increases for the condition where the wind direction changes with altitude. Note that this effect is most pronounced for the 1st community and the least for the 4th. This is due to the fact that the 1st community is closer to the runway, at which point the aircraft is not as high as at the 4th community. As such, refractive effects have more influence for the 1st community.

5. CONCLUSIONS

Incorporating actual meteorological effects in a standardized noise contour model is possible using the described method based on ray tracing and Doc.29. As such, effects of multi-event contours have been studied before and atmospheric absorption was shown to have a large effect. In the current study, single-event contours are studied by looking at departure procedures. The SEL noise contours, expressed in 55 dB(A) and 65 dB(A), show noticeable differences if the effect of wind is taken into account. Shadow zones can occur that modify the contour shape. In general, the shallower the grazing angle is with respect to the contour line, the larger the differences due to refraction are. Hence, the ICAO B procedure is more susceptible to this effect than the ICAO A procedure.

Calculating the number of awakening allows quantifying the impact of wind direction. As a result, communities to either side of a ground track were shown to be affected differently. A difference in wind direction, between ground and different altitudes, was shown to have an impact as well. The current study shows that if effects of atmospheric propagation are taken into account, there may be ways to mitigate aircraft noise in communities.

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