Nationaal Lucht- en Ruimtevaartlaboratorium
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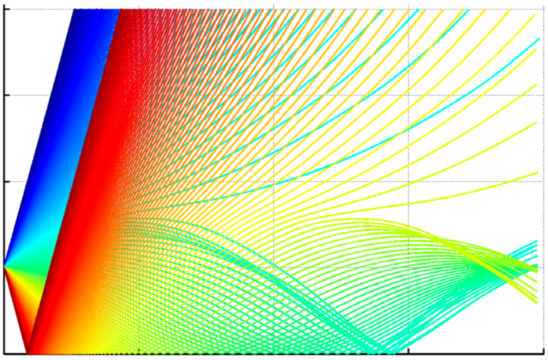
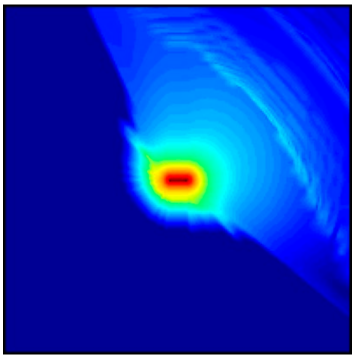
Executive summary

A weather dependent noise contour prediction concept

Combining a standard method with ray tracing





Problem area
Standard noise contour prediction methods make assumptions which results in fast algorithms to calculate the noise exposure around airports. One such assumption is to use average atmospheric conditions for the noise calculations. However, meteorological phenomena play an important role in the propagation of sound through the atmosphere. Not taking the varying atmosphere into account may therefore lead to deviations in the computed noise levels.

More complex and more detailed noise models may be used in situations where this is not acceptable. A major disadvantage however of the more detailed noise simulation models is their computational inefficiency. This drawback makes these models practically unsuitable for computing the cumulative exposure from a high number of flight operations.

This paper presents a hybrid solution, based on components from both types of noise models.

Description of work
From a high-level perspective, the work described in this paper is based on the removal of one of the default components of a noise contour prediction method. At the same time, the model is extended with an interface to an external, so-called excess attenuation model. In such a way, the external model will be able to replace the removed component. With the help of the external model, the noise model is able to account for weather effects.

From a more detailed point of view, the component that is removed from the noise model is the lateral attenuation adjustment. This

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Author(s)
S.J. Heblij
M. Arntzen
D.G. Simons

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component normally adjusts the power- and distance based noise level for several effects. These effects include absorption by the ground surface, refraction and scattering of the sound signal as a result of meteorological conditions.

The external excess attenuation model that takes over the responsibility to correct for these effects is primarily based on acoustical ray tracing. This is a numerical technique to obtain the sound propagation paths from a source to locations on the ground surface. Apart from a ray tracing model, the developed excess attenuation model also recalculates atmospheric absorption along the paths of the rays and applies a ground attenuation model to calculate the overall excess attenuation.

Together, the two models provide a setup that offers some of the capabilities of detailed noise simulation models, without compromising on computational efficiency. In practice, there is a fixed penalty (in terms of computation time) for pre-processing a particular atmospheric situation. However, the impact on the computation time for the noise evaluation process for a particular flight trajectory itself is negligible.

Results and conclusions

Both the results from the validation process as well as the numerical example affirm that propagation based on average conditions (assuming spherical spreading) as used by most of the current noise contour models is not a good assumption in non-standard atmospheric conditions. The setup presented in this paper provides an alternative that allows correcting for non-standard meteorological conditions.

It should be realised however that the validation of the excess attenuation model is currently based on comparisons with theoretical methods only. It is recognized that it would be desirable to also validate the extended version of the noise model using measurements.

Applicability

Although the hybrid model can be used for multiple purposes, it was specifically developed for an application in the area of aircraft trajectory optimisation. Since trajectory optimisation involves the evaluation of a high number of (slightly) alternative trajectories through the same atmosphere, the computational efficiency of the weather-dependent noise model was of primary importance.

Nationaal Lucht- en Ruimtevaartlaboratorium, National Aerospace Laboratory NLR

Anthony Fokkerweg 2, 1059 CM Amsterdam,
P.O. Box 90502, 1006 BM Amsterdam, The Netherlands
Telephone +31 88 511 31 13, Fax +31 88 511 32 10, Web site: www.nlr.nl

Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

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A weather dependent noise contour prediction concept

Combining a standard method with ray tracing

S.J. Heblij, M. Arntzen and D.G. Simons[1]

[1] Delft University of Technology

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A weather dependent noise contour prediction concept: combining a standard method with ray tracing

Sander J. Heblij and Michael Arntzen
Air Transport Division, National Aerospace Laboratory NLR, Amsterdam, the Netherlands.
Dick G. Simons
Faculty of Aerospace Engineering, Delft University of Technology, Delft, the Netherlands.

Summary
Standard noise contour prediction methods make assumptions which results in fast algorithms to calculate noise around airports. One such assumption is to use average atmospheric conditions for the noise calculations. However, the actual noise propagation depends on the actual atmospheric properties. In this paper, a concept to include weather dependent propagation effects is described and evaluated. The concept comprises the replacement of the standard excess attenuation method by a model based on ray tracing. This paper shows it is possible to include the impact of weather conditions on noise propagation in a standard noise prediction method without major impact on computation times. When applying a more realistic weather situation, the noise results for a single flight show remarkable differences compared to the results from the standard methods. Further studies should assess the effects on accumulated yearly noise metrics and contours.

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1. Introduction

Airport noise contour modelling is typically performed using ‘integrated NPD-based models’, where NPD stands for Noise-Power-Distance. A popular example of such a model is the Integrated Noise Model (INM) [1]. INM is the FAA's official methodology for noise impact assessment in the vicinity of civilian airports in the US since 1978. The underlying methodology of the model is in line with noise computation method as described in Doc.29 of the European Civil Aviation Conference (ECAC) [2]. Other, but similar computer model implementations exist as well.
The integrated NPD-based models depend heavily on tabulated data, called the NPD curves. Basically, these curves translate source levels into levels observed at a distance by applying attenuation due to spherical wave spreading and due to standard-day atmospheric absorption and do so for multiple engine settings [2].
Meteorological phenomena play an important role in the propagation of sound through the atmosphere. Not taking the varying atmosphere into account will therefore lead to deviations in the computed noise levels. For more information on this phenomenon, see for example reference [3-4]. Typically, the integrated NPD-based models do not take these varying conditions into consideration. They are designed to estimate long term average noise levels. It is assumed that using a model that is based on the average atmosphere should suffice for computing the long term average noise exposure. At the same time it is recognized that this may sometimes lead to deviations from observed levels. For applications where this is not acceptable, one could use a higher-fidelity model.
These higher-fidelity models typically employ a simulation approach that offers more flexibility for more complex computation. In that case, the noise source itself, for example, can be specified as directional, both in lateral and longitudinal direction. Furthermore, the source can typically be specified using 1/3rd octave bands instead of the A-weighted level and the propagation models used for high-detail noise models can be more complex as well. They generally allow for more acoustical effects (e.g. terrain, Doppler shift) and can cope with non-standard atmospheric conditions, such as temperature inversions. Examples of models that use these more complex noise modelling techniques include NOISIM [4], FLULA [5] and

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ANOPP2 [6]. A major disadvantage however of the more detailed noise simulation models is their computational inefficiency. This makes them less suitable for computing the cumulative exposure from a high number of flight operations.

This paper presents a hybrid solution, based on components from both families of noise models. We will present a Doc.29-based noise model that offers some of the capabilities of detailed noise simulation models, without compromising on computational efficiency. In practice, there is a fixed penalty (in terms of computation time) for pre-processing a particular atmospheric situation. However, the impact on the computation time for the noise evaluation process itself is negligible.

While this hybrid model can be used for multiple purposes, the first foreseen application will be in the area of aircraft trajectory optimisation. Since this involves the evaluation of a high number of (slightly) alternative trajectories through the same atmosphere, computational efficiency is of primary importance for this application.

2. Overall Methodology

The primary component of the NPD-based models is NPD interpolation. Furthermore, there is a major noise level correction mechanism. This mechanism is based on the observation that, generally speaking, there is a difference in sound level directly under the aircraft flight path and locations to the side of the flight track, even when the distance between the aircraft and observer is equal for both situations. This attenuation effect is termed lateral attenuation and is in excess of the attenuation that can be attributed to distance effects, as already accounted for in the NPD data. Lateral attenuation itself is a collective term. The physical mechanisms that are involved in lateral attenuation include: absorption by the ground surface, refraction and scattering of the sound signal as a result of meteorological conditions and engine-installation effects [7].

Especially the refraction effects are influenced by wind and temperature gradients. This means that the default lateral attenuation is not always a good estimate for a particular meteorological condition. To obtain better estimates for these particular cases, a Doc.29-based noise model has been extended with functionality to compute excess attenuation (EA) for any atmosphere using a separate EA-model.

3. Model description

The excess attenuation functionality with respect to the noise model itself comprises a minor adaptation. This adaptation concerns the addition of an interface that allows the noise model to interpolate and apply an EA-correction that is specified in an external database. These databases can be generated using a separate excess attenuation model, called the EA-database generator. The relation between the two models is provided in Figure 1.

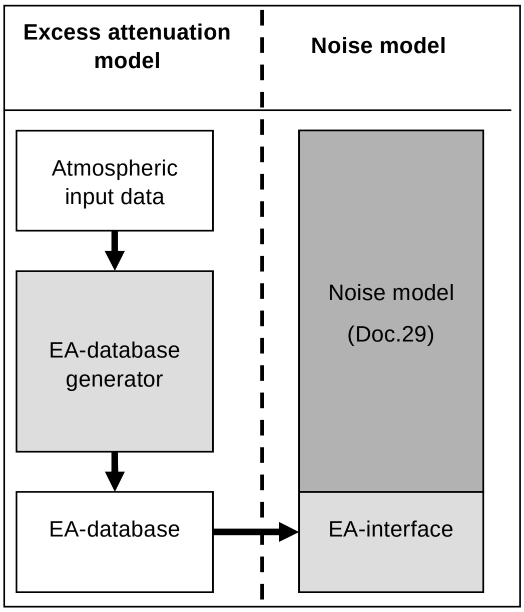

Figure 1. Diagram showing the relation between the excess attenuation model and the noise model

This means that the developments involved two models: the EA-database generator itself and the addition of an interface to the pre-existing, ECAC Doc.29-based noise model.

3.1 Adaptation to the noise model

The EA-correction replaces part of the standard lateral attenuation correction in the noise model (the engine installation effect correction remains unaffected). This updates equation (4-6a) and (4-6b) in the Doc.29 specification document [2]. The lateral attenuation correction term is replaced by an excess attenuation correction term in the model. The value of this component is obtained using 3D linear interpolation on the EA-database values. The three interpolation parameters used are the horizontal and vertical distance between aircraft and observer and the propagation direction (azimuth).

3.2 Development of the EA-database generator

The excess attenuation model is primarily an acoustical ray tracing model. The ray tracing method that was used here to obtain the rays is based on the numerical integration of Snell's law of refraction. This principle is applied to the concept of the effective sound speed. The effective sound speed is a summation of the adiabatic sound speed and the horizontal component of the wind velocity in the travelling direction of the ray [8].

The ray trace model assumes a layered (horizontally stratified) atmosphere where in each layer the atmosphere is constant. By consequent evaluation of Snell's law for small ray segments (e.g. small time steps), a ray path can be traced along which the sound propagates. This is done for a variety of initial travel directions at the source and different source heights. Each ray is traced until it exceeds a predefined time limit, or has bounced a number of times at the ground surface. For this specific model, the ray travelling time limit was set to 60 seconds. For the noise model, this should be well inside the range of interest and basically means that effects that may occur outside this range are ignored.

When all required ray paths are determined, the resulting geometries can be used to compute the intensity relative to the source. This computation is based on the principle of focusing and defocusing: the observation that in a refracting atmosphere, different rays may converge (focusing) or diverge (defocusing) when compared to a non-refracting atmosphere. Actual focusing factors are computed by comparing the mutual distance between two or more adjacent rays near the receiver to their mutual distance at the source [8].

Typical problems with ray tracing are the formation of caustics and shadow zones. Caustics are locations where adjacent rays cross each other. At this location the focusing factor (and the sound pressure level) goes to infinity. In reality however, although the sound pressure level is indeed higher in these areas, it cannot be infinite. This phenomenon is a weakness of geometrical acoustics, for which solutions to the problem, are ranging in complexity. For the solution chosen here, sound pressure levels based on focussing are set to a maximum of 10 dB over the corresponding spherical spreading levels for that same distance.

The second typical ray tracing problem concerns shadow zones. These are regions where, due to upward refraction, no rays can penetrate. According to ray tracing theory, no sound pressure is present in these regions. While it is true that sound pressure levels in reality are significantly lower in these zones, other propagation effects such as diffraction and (turbulence induced) scattering can be expected to carry some of the acoustical energy into the shadow zone. Since ray tracing cannot predict sound levels in the shadow zone, which was considered unacceptable for this application, a different approach had to be selected here.

For the shadow zones, results from a Fast Field Program (FFP) code were used to obtain the sound pressure levels [9]. FFP is an acoustics method that solves the Helmholtz equation, which is the linear wave equation in the frequency domain. Compared to ray tracing, FFP is computationally expensive. Therefore, the FFP code was not included in the EA-database generator. Instead, an FFP tool was used to compute intensities within a shadow zone for different propagation ranges, linear effective sound speed gradients and frequencies. Based on the results, linearised loss rates (dB per meter into the shadow zone) have been obtained as a function of refraction coefficient and frequency. Sound pressure levels are eventually calculated using the ray tracing based level at the nearest shadow zone boundary and the FFP-derived loss rate. The combination of ray tracing and this FFP-derived model will be referred to as the augmented ray tracing method.

The excess attenuation model also applies atmospheric absorption. Atmospheric absorption rates are calculated for all 24 considered 1/3rd octave bands for all local temperature and humidity conditions along the ray using the method described in reference [10].

Finally, the excess attenuation model also uses a ground attenuation model. The ground attenuation depends on the characteristics of the ground and the angle of incidence of the sound wave. The ground characteristics are described using ground impedance determined by the effective flow resistivity of the ground material and the frequency of the sound wave as described in reference [11]. The effective flow resistivity was set to 250 kPa·s/m^2, a typical value for grass covered ground.

Finally, the overall excess attenuation as written to an EA-database is computed by combining all components, as depicted in Figure 2.

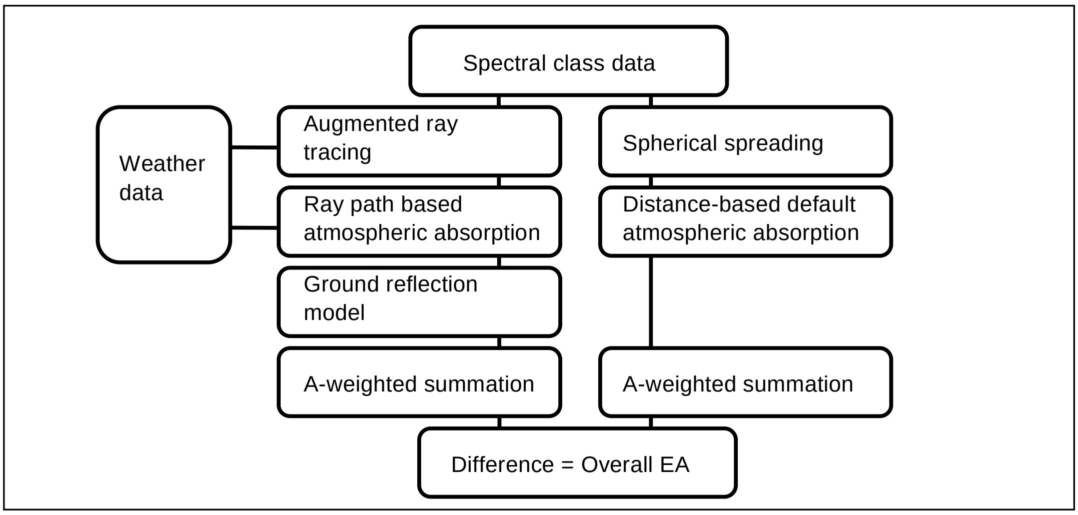

Figure 2. Overview of the computation process of the excess attenuation database generator

Generally speaking, the method to compute the overall excess attenuation follows the method used to correct the NPD curves for non-default atmospheric absorption [2]. Starting from a reference spectrum, nominal and non-nominal propagation are compared and the resulting difference is the excess attenuation as written to the EA-database.

Due to underlying model limitations, there are three exceptions to the overall computation process that should be mentioned here. The first exception is the +10 dB limit that is applied in case of extreme focussing, which has already been mentioned.

Secondly, a -30 dB(A) correction limit has been applied for the overall excess attenuation. Without this limit, correction values lower than -30 dB(A) can be observed at positions deep into the shadow zone, especially because the FFP-based augmentation method is unbounded. It is believed that limiting the overall correction will result in more realistic correction values.

Finally it should be noted that this ray tracing implementation is not intended for sources at relatively low heights. Therefore, the EA-database generator uses the standard lateral attenuation function as used by the standard version of the Doc.29 model to generate excess attenuation values for heights of 50 meters and below. The first ray tracing result is generated for a height of 100 meter. This means that the noise model gradually switches from the standard lateral attenuation to ray tracing excess attenuation for parts of flight trajectories between 50 and 100 meters.

4. Verification and validation

The excess attenuation functionality involves two models: the EA-database generator itself and the addition of an interface to the pre-existing noise model. Both developments have been verified and/or validated.

The EA-interface to the noise model has been verified using comparative analyses. To this end, an EA-database was used that holds values corresponding to the default lateral attenuation function. The results, when compared to the original, default Doc.29 implementation show that for L_{Amax}, the differences are minor and are caused by the introduction of the interpolation process. The same holds for L_{AE} for observer positions below and astride of the flight path. Behind and ahead of the flight path however, the results show significant differences. Further analysis showed that although the interface works as intended, the adoption of simplified geometric definitions that enable the use of this interface does lead to results for L_{AE} that may be less comparable to results that have been generated without using the extension. Acknowlegding this restriction, the results have been accepted.

Validation of the EA-database generator has also been performed using a comparative analysis. Two other propagation techniques, namely spherical spreading and FFP, have been used as reference. The first results are based on an atmosphere with a purely theoretical effective sound speed profile, assuming a fixed rate of $dc/dz = \pm 0.1\ s^{-1}$. The results in terms of transmission loss (excluding effects of atmospheric absorption and ground impedance and at ground level) for the three propagation methods have been analysed for several directions. Figure 3 shows the results for the downwind direction (i.e. dc/dz = 0.1 s^{-1}). The figure shows that both the FFP and ray trace solution identify three zones where the intensity is higher than spherical spreading theory predicts.

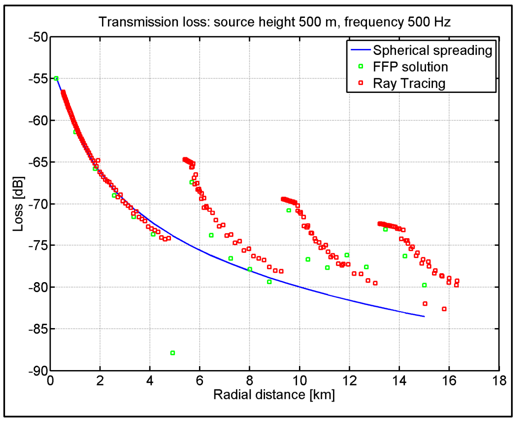

Figure 3. A comparison of spherical spreading, augmented ray tracing and FFP for a theoretical sound speed profile.

A second validation case is not based on a theoretical effective sound speed profile, but is based on a typical result from a weather balloon sounding. Figure 4 shows the results, now for the upwind direction. The shadow zone is clearly visible in the figure.

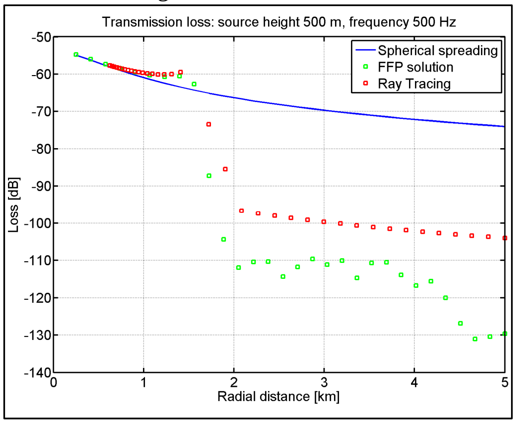

Figure 4. A comparison of spherical spreading, ray tracing and FFP for a typical sound speed profile.

Overall it was concluded that the augmented ray trace method generates results that show fairly good resemblance with the FFP, especially with respect to the localisation of areas with elevated and reduced intensities. Assuming that the FFP provides the best results, the ray trace results are certainly acceptable, especially considering the fact that the ray trace only needs a fraction of the computation time that the FFP requires.

While it is recognized that none of the three methods is flawless in practice, the results in this section also clearly show that spherical spreading as used by popular noise contour models not always seems to be a good assumption.

5. Numerical example

This section shows a result of the EA-database generator and the effects of applying this result on the overall noise level for a simple flight trajectory. The results are based on the same weather balloon sounding data as was used for the second validation case in the previous section. Figure 5 shows the overall EA-correction as stored in the database for a single height (150 meter). A typical database contains correction values for 15 different heights between 100 and 3000 meter.

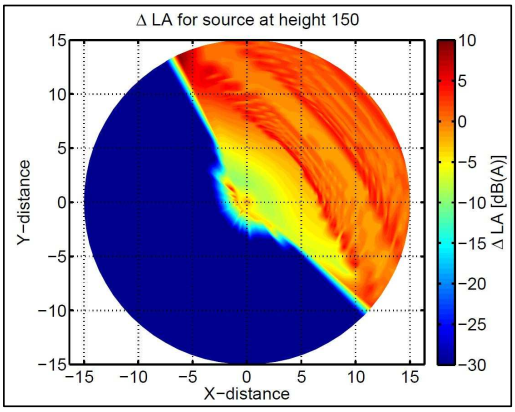

Figure 5. Excess attenuation for all directions, based on a typical atmosphere from weather sounding balloon

From this figure (which includes atmospheric absorption and ground impedance) it is clear that the shadow zone is located south-west (upwind) from the source, while the illuminated zone is on the north-east side (downwind).

When providing this excess attenuation database to the noise model and running the model for a flight trajectory existing of a single, straight segment at constant altitude (150 meter), speed and power settings, the results for L_{Amax} are as shown in Figure 6.

The effects as computed by the excess attenuation database generator are clearly visible in the overall noise result. Especially the asymmetry between the upwind and the downwind direction is remarkable.

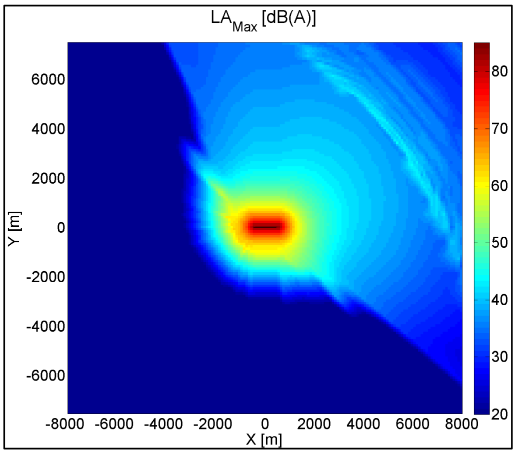

Figure 6. L_{Amax} when using the excess attenuation from Figure 5, for a simple trajectory (black line).

6. Conclusions

This paper presents the development and validation of a pre-existing NPD-based noise model that has been extended with functionality to apply an excess attenuation correction from an external database, instead of applying the default lateral attenuation correction. It also describes the development of a model that can generate the excess attenuation databases for the extended noise model, for any atmosphere as reported by weather sounding balloons. This EA-database generator is primarily based on acoustical ray tracing, augmented with other techniques to overcome ray tracing limitations.

Both the results from the validation process and the numerical example show that propagation based on average conditions (assuming spherical spreading) as used by the current NPD-based noise models appears not to be a good assumption in non-standard atmospheric conditions.

Concerning future work, it should be realised that the validation of the excess attenuation database generator is currently based on comparisons with theoretical methods only. It is recognized that it would be desirable to also validate the extended version of the noise model using measurements. No such validation exercise has been planned at this time, but an opportunity based on measurement data that is already available is being evaluated.

A second direction for future work concerns an application of the model. As mentioned in the introduction, these types of noise models are typically used for calculating noise contours around airports, based on the overall contribution of all flights during a longer period, typically a year. In this case, the overall noise exposure is based on the sum of contributions of all flights. The numerical example in this paper confirms that non-standard conditions can have a significant influence on the result for a single flight. In this light, an interesting research problem would be to investigate whether a computation for a full year using the standard model would yield comparable results to a computation for a full year based on all atmospheric conditions in that year. And furthermore, it would be interesting to determine whether the answer to this question would differ from airport to airport, based on the corresponding weather patterns. Work in this direction has already started.

Acknowledgement

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