Angular and distance dependence of the standard deviation of maximum sound level for aircraft noise

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ABSTRACT

The current method to calculate number above threshold (NAT) in Sweden does not take into account the natural variation of sound level arising from variations in the sound emission and sound propagation. This leads to unrealistic discontinuities in the calculated noise contours as all movements of a specific aircraft type with a specific procedure are assumed to generate the same maximum sound level. Using long term measurements, the standard deviations of maximum sound levels are analyzed after dividing the airspace around the microphones into sections depending on the elevation angle and distance from aircraft to microphone. The standard deviation in each section is determined by calculating the standard deviation of each aircraft type that passes through that section and combining the aircraft type specific results into one figure. The standard deviation varies from about 1 dB to 3 dB with generally higher values the greater the slant distance and the smaller the elevation angle. The found standard deviations are presented in polar diagrams and are implemented in NAT calculations. The resulting noise contours are not only smoother and without discontinuities, but they are also a better representation of what NAT stands for.

Keywords: Aircraft noise, NAT, standard deviation
I-INCE Classification of Subjects Number(s): 13.1.1, 76.1.3

1. INTRODUCTION

In recent years there has been a shift from primarily using equivalent levels such as L_{den} to just as often use number above threshold (NAT) calculations when assessing the environmental impact of the airports in Sweden. The drawback of this is that the method for calculating the maximum sound levels needed does not take into account the natural variation of sound level arising from variations in the sound emission and sound propagation. This variation is becoming more and more an intensely debated subject. The underlying document that governs the noise calculations in Sweden is the ECAC doc. 29 [1] which briefly discusses this issue, only giving the general recommendation that the maximum sound levels could be seen as normally distributed and that a common standard deviation is approximately 2 dB. The German AzB 2008 [2] method, on the other hand, recommends the usage of a standard deviation of 3 dB for most aircrafts in most operational modes. Only a few military aircrafts are recommended a standard deviation of 2 dB. While the usage of variable maximum sound levels is commendable, the assumption that the standard deviation is always the same value can lead to poor calculations. This report aims therefore to construct a model of the standard deviation that depends on the elevation angle, distance from aircraft to receiver point as well as operational mode.

2. MEASUREMENTS

There are four noise monitoring terminals (NMT) around the two airports in Stockholm, Arlanda (ESSA) and Bromma (ESSB), see table 1. The terminals are made by Brüel & Kjear and are of type 2250 and conform to the IEC 61672-1 class 1 specifications. All maximum noise level measurements are A-weighted and measured with time constant slow.

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Table 1 – NMT positions and altitude

NMT number	Airport	Latitude WGS84	Longitude WGS84	Altitude [ft MSL]	Description
1	ESSB	59.36741263	17.90593436	174	1.7 km north west of RWY 12/30
2	ESSA	59.66527617	17.96407502	140	2.0 km north of RWY 3 (19L, 01R) 0.35 km north of the middle of RWY 2 (08/26)
3	ESSA	59.59045781	17.93720267	87	4.0 km south of RWY 3 (19L, 01R)
4	ESSA	59.58155572	17.89289765	119	6.3 km south of RWY 1 (19R, 01L)

The radar track data was supplied from LFV[5] with a point every fourth second and a total of 455 795 measurements together with their radar tracks were analyzed for this report.

3. ANALYSIS

3.1 Dividing the airspace

The airspace around the microphones was divided into sections depending on the elevation angle and the slant distance. The angle was divided in steps of 7.5º, from 0º-7.5º to 82.5º-90º, where the latter range represents planes that pass directly over the measurement position. The distance was divided with an increasing step size that was chosen to make the sections as square as possible. The closest point of approach was calculated for each aircraft and all measurements were grouped into measurement sets. A measurement set is therefore the collection of all measurements of one aircraft type (ICAO code), in one section at one operational mode, e.g. B738, 7.5º-15º, 1550 m-1753 m, departures.

The temporal resolution of the radar tracks is limited and there is only information about the position of the aircraft every fourth second. This resolution is far too low to be directly useable when finding the angle and distance of the closest point of approach. To resolve this, the tracks were linearly interpolated between the radar points which allows for a more accurate angle and distance calculation.

The aircrafts' closest points of approach of all measurements are found in figure 1 and 2. The measurements that are outside of the sections in the figures are analyzed but the sections that those measurements are in were discarded as per the process described in section 3.2.

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[5] The LFV Group is a state enterprise that operates air navigation services for civil and military customers in Sweden.

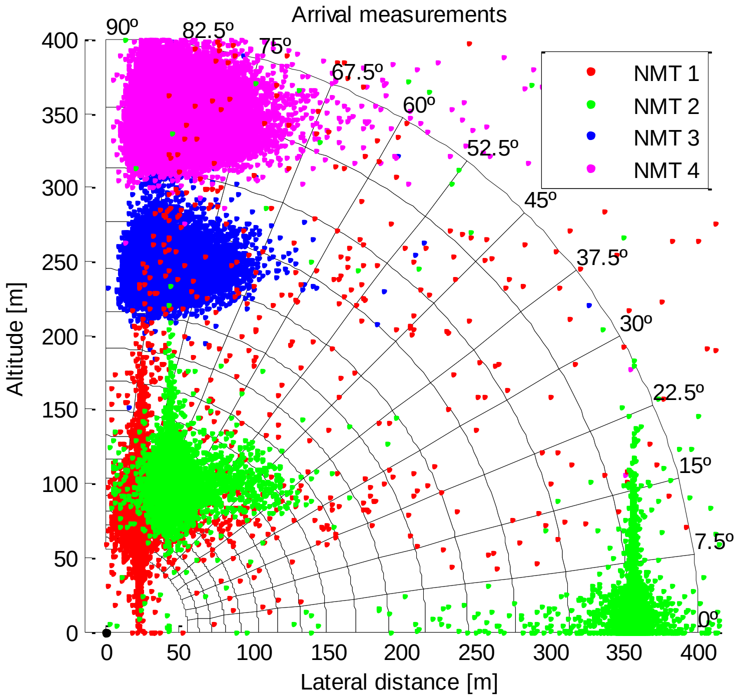

Figure 1 – Distribution of approach measurements.

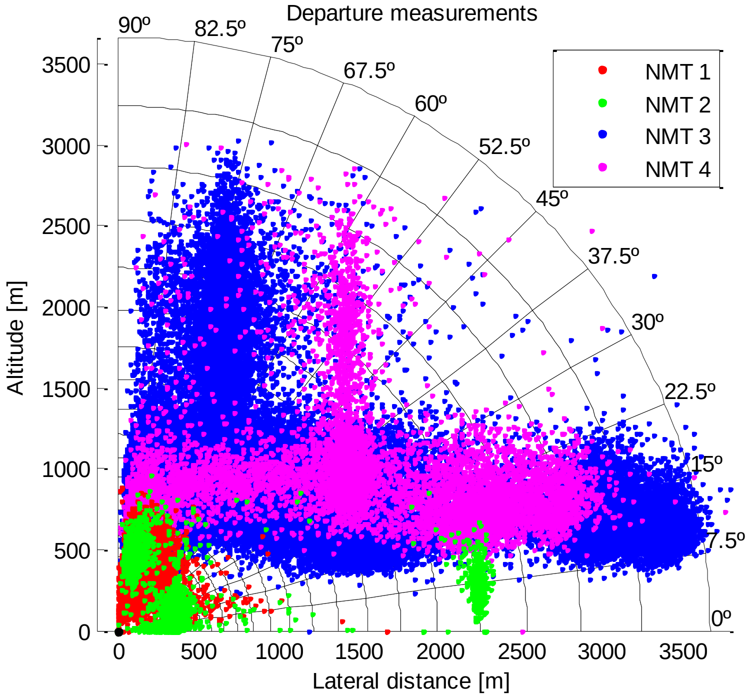

Figure 2 – Distribution of departure measurements.

3.2 Data treatment

3.2.1 Normalization of measurements

While the sections are small, there are sound level differences in the sections that already are described in the current calculation methodology. These differences, namely lateral damping and the difference arising from different slant distances, would increase the standard deviations if they were not adjusted for. The differences in sound level arising from the lateral damping was therefore negated by adjusting the sound levels with the model documented in SAE AIR 5662 [3] and the differences arising from the different slant distances were taken care of by assuming spherical wave conditions. Engine installation effects were not adjusted for but this effect is minimal compared to the lateral damping.

3.2.2 Rejection of measurements due to weather

Using the criteria described in ISO 20906:2009 [4] all measurements done at a temperature below -10 ºC and above 50 ºC (although there were none) as well as those measurements done when the wind speed was above 10 m/s or while there were registered precipitation were discarded as the measurements could be flawed. In addition to this, all measurements done at relative humidity in excess of 94 % were discarded to prevent condensation to influence the results. A total of 82 787 measurements were rejected based on adverse weather conditions.

3.2.3 Rejection of outliers

As the total number of measurements is almost half a million, some measurements are probably incorrect. There could have been an instrument malfunction, an unusual background noise source or an incorrect correlation between aircraft and measurement. Although sound recordings are available for the majority of the measurements, it was deemed an impossible task to listen to them one by one or even to listen to the ones most likely to be flawed. To rule out the outliers the Thompson tau [5] method was used. This method identifies outliers by looking at the extreme values one by one and if the extreme value is greater than the standard deviation multiplied with a critical factor determined from the Students t-distribution, then the value is deemed to be an outlier. This methodology will invariably decrease the overall standard deviations but is a statistical necessity since not all measurements could be studied individually. The most common confidence interval used is 95 % but this will lead to the removal of all measurements that are further away from the mean than 1.96σ which would decrease the standard deviation even if the population of measurements would be perfectly normally distributed. A confidence interval of 99 % was instead used which is less conservative and more in line with previous experiences which is that only a small fraction of the measurements are unusable. A total of 9 175 measurements were rejected using the Thompson tau method.

3.2.4 Rejection of non-normal distributions

Measurements of aircraft noise are often assumed to be normally distributed but this hypothesis is not always tested as the standard deviation can be calculated without explicitly knowing that the measurements are normally distributed. In this case, the standard deviations will be used to calculate NAT using the normal cumulative distribution function and if the measurements would have different distributions, the final results will not be usable. The Lilliefors test [6] with a confidence interval of 99 % was used to reject sets of measurements. The Lilliefors test cannot be performed on measurement sets with less than four data points and all sets with fewer points were discarded. The test for normality is especially important for the outermost sections where the measured maximum sound levels are not much above the threshold level for the measurement equipment. The Lilliefors test will not be passed if a significant portion of the measurements are not available because their level was below the threshold. Of the 25 319 available measurement sets, 7 238 sets totaling 142 137 measurements were rejected and although the majority of these rejected sets had very few elements, there were some that had many elements and the maximum was 16 890. This set consisted of approach measurements for B738 in the section 0º-7.5º, 354 m-400 m. Manual inspection of the larger rejected measurement sets showed that they were rejected because they were too heavy-tailed, i.e. the central part of the distribution had a normal appearance but the ends did not fall off in the expected manner. This could be due to the fact that the measurements were grouped into sets based on ICAO code. Two aircrafts with the same ICAO code can have different engines and the procedures could differ as well if they are flown by different operators which would make the resulting distribution the sum of two or more distributions.

3.2.5 Pooling the standard deviations

After all above rejection tests were passed the unbiased standard deviation was calculated for every remaining measurement set. As the measurement sets in a section could have vastly different number of measurements the standard deviations were pooled to create one single deviation. The pooling process ensures (1) that all single measurements are given the same importance in the end.

$$s^2 = \sum_{i=1}^{k} (n_i - 1){s_i}^2 \Big/ \sum_{i=1}^{k} (n_i - 1) \qquad (1)$$

3.2.6 Limiting the confidence interval

The final rejection was done to only present results that had a 95 % double sided confidence interval less than 1 dB. The confidence interval depends on the standard deviation as well as the number of measurements and was calculated for each section based on the equation (2). Sections with a confidence interval larger than 1 dB were discarded and are left blank in the figures below. The calculated confidence endpoints are shown in figure 5 and 6.

$$\sigma^2 \approx \left[s^2 - 1.96\frac{\sqrt{2}}{\sqrt{n}}s^2, s^2 + 1.96\frac{\sqrt{2}}{\sqrt{n}}s^2 \right] \qquad (2)$$

4. RESULTS

4.1 Standard deviations of maximum sound levels for approaches

The standard deviation for maximum noise levels for approach operations is presented in figure 3 and range from 1.3 to 2.7 dB. The minimum distance with results is 56 m and the maximum distance is 401 m. Due to the positioning of the measurement sites and since the dispersion of tracks is limited since both the airports have ILS instruments installed, the majority of operations passed over the microphone with an elevation angle larger than 70°. There is a group of measurements at around 350 m and 0-15° and this group also has the largest deviations from the mean. However, there are no sections with measurements from 15° to 67.5°. This means that the model constructed from these results will not be based on any results within this interval.

The standard deviation for the airplanes that passed directly overhead is not particularly large. This implies that all aircrafts of the same type is flown with the same, or very similar, configuration at the same altitude.

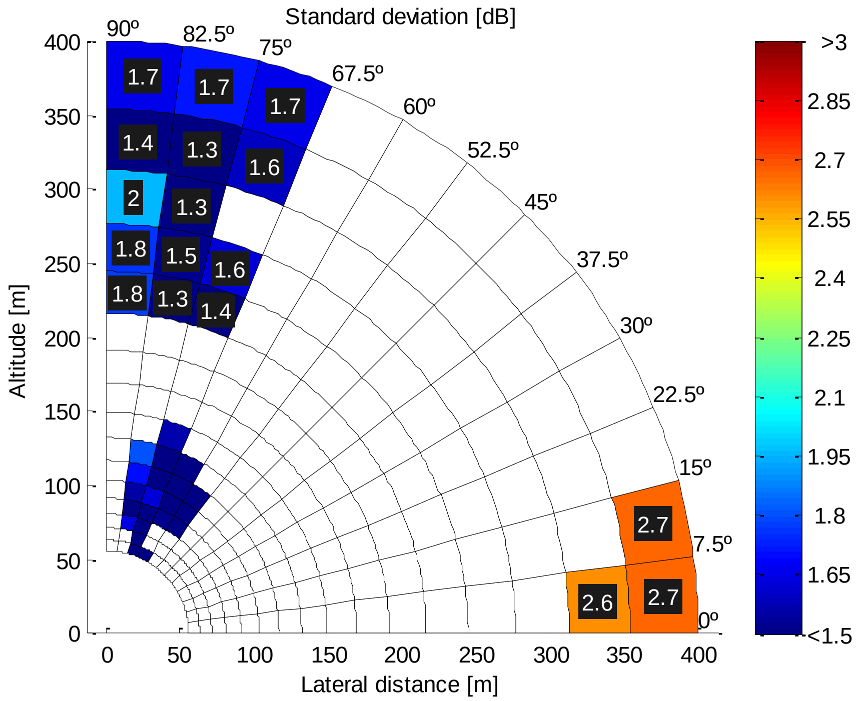

Figure 3 – The standard deviations of approach measurements. Both the number and the color show the standard deviation.

4.2 Standard deviations of maximum sound levels for departures

The standard deviation for maximum noise levels for departing operations is presented in figure 4 and range from 1.2 dB to 3.4 dB. The minimum distance with results is 192 m and the maximum distance is 3667 m. As there are more deviations from the routes when departing compared to approaching there is data for each angle. The maximum results are found at the lowest elevation angles and at the longest distances. There is a slight discrepancy to this trend in the results in the range of 7.5°-22.5°. For these angles the maximum standard deviation is found at 2500 m and decreases slightly for greater distances. The measurements at the maximum deviation were done by NMT 2 and the measurements at greater distances were from NMT 3. NMT 2 (at that angle and distance) recorded aircrafts that have just taken off on runway 01L on Arlanda whereas NMT 3 (at that angle and distance) recorded departing aircraft on runway 19L or 19R. Since NMT 3 is further away from the threshold than NMT 2, the results at greater distances are from heavily laden or aircraft with otherwise poor performance and those aircrafts seem to have less standard deviation than the ones that have just taken off.

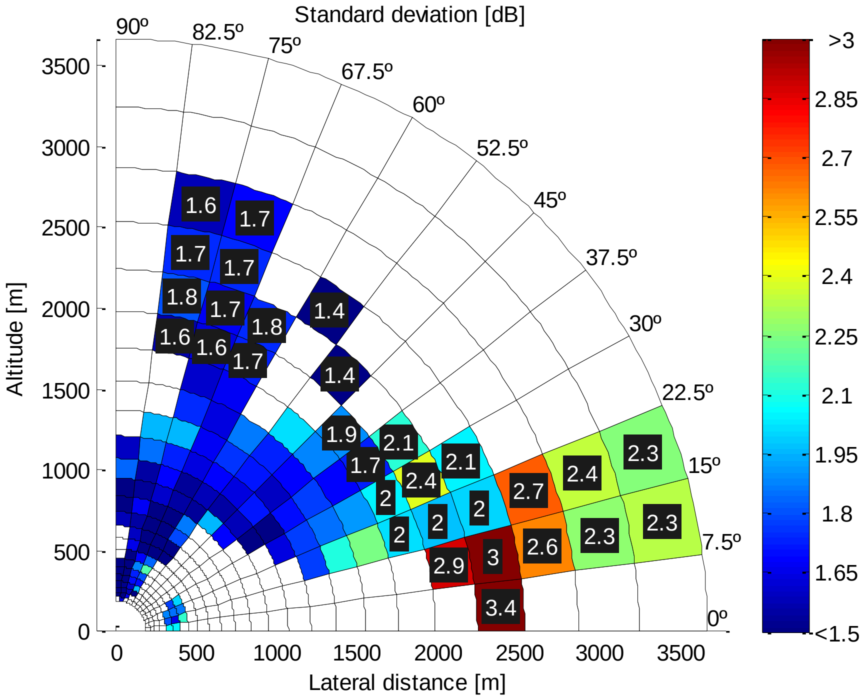

Figure 4 – The standard deviations of departure measurements. Both the number and the color show the standard deviation.

4.3 Constructing a formula

From observing the results in figure 3 and 4 it is apparent that the standard deviation increases with slant distance and decreases as the elevation angle becomes higher. To construct an equation that will describe this it was assumed that the form of this equation would be similar to the equation used to calculate the lateral damping with the difference that the distance dependence is linear and not exponential. While it is quite possible that there could be an exponentially decaying distance dependency, otherwise the standard deviation would increase indefinitely when the distance is increasing, the results at hand does not explicitly show this.

$$\sigma = \alpha r + \beta r e^{-\gamma\theta} + \delta \qquad (3)$$

The coefficients are determined from the center point of each section based on the principle of least square error and the following equations were found where θ is the elevation angle measured in degrees and r is the closest distance between aircraft and receiver point measured in meters.

App.: $$\sigma = 4.81 \cdot 10^{-4} r + 3.67 \cdot 10^{-3} r e^{-0.0373\theta} + 1.39 \quad [dB] \quad \text{for} \quad 59\,m \leq r \leq 377\,m \qquad (4)$$

Dep.: $$\sigma = 3.84 \cdot 10^{-5} r + 7.94 \cdot 10^{-4} r e^{-0.0698\theta} + 1.58 \quad [dB] \quad \text{for} \quad 204\,m \leq r \leq 3455\,m \qquad (5)$$

The coefficient of determination (R^2) was 0.79 for the approach data and 0.62 for the departure data. The above equations (4), (5) are only valid when $3.75° \leq \theta \leq 86.25°$. While there is no harm to extrapolate above the maximum angle, the exponential nature of the equations might overestimate the standard deviations for very low elevations angles and the validity of the equations is therefore limited to this range.

4.4 Measurement and analysis uncertainty

As this report does not concern the absolute maximum sound levels, any static difference from the true maximum sound level would not matter. The only measurement errors that are important are any errors that are varying over time, e.g. the measurement equipment’s sensitivity to fluctuating temperatures. Note that the varying sound levels due to different atmospheric conditions are not an error in this case but rather is what is trying to be explained.

The contributions to the measurement uncertainty from the measurement equipment that are described in ISO 20906:2009 are not all applicable in this case. The directional response does not matter since the measurements are grouped in 7.5º sets. The rest of the tolerances are applicable and the combined standard uncertainty becomes σ_{slm}=0.63 dB. The residual sound contribution to the maximum sound levels are not taken into account for several reasons with the primary reason being that the residual sound level was not recorded for each measurement. However, the distribution of measured maximum sound levels will not be normal if they are just slightly above the background sound level and the Lilliefors test for normality will therefore remove any such measurement sets.

It is important to remember that the standard measurement uncertainty is a maximum value based on the tolerances specified in IEC 61672-1. The true contribution to the calculated standard deviations in figure 3 and 4 from the measurement tolerances might be substantially less than 0.63 dB. Confidence intervals for each section is calculated with equation (2) and the results are shown in figure 5 for approaches and in figure 6 for departures. The values in these figures are consequently only the confidence endpoints for the statistical sample and not the measurement uncertainty. The values in figure 3-6 might as a consequence be slightly overestimated and could be lower if the measurement uncertainty was adjusted for.

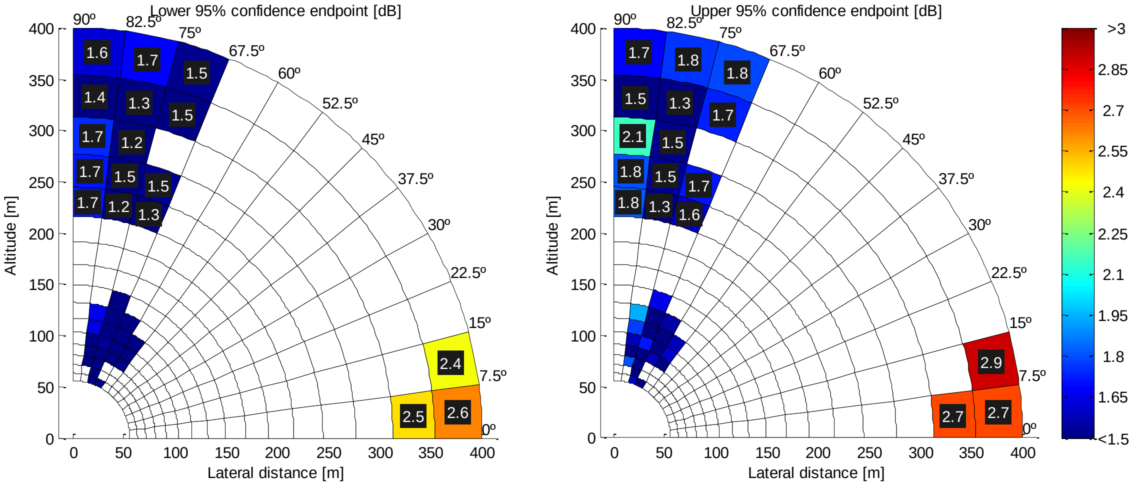

Figure 5a & 5b – Confidence interval of the standard deviation, approach.

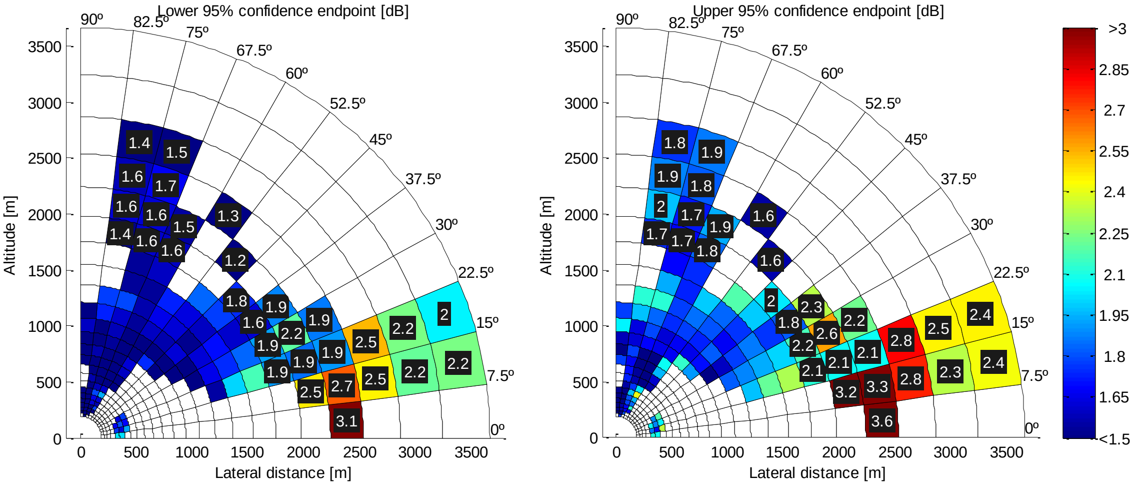

Figure 6a, 6b – Confidence interval of the standard deviation, departure.

5. Using the standard deviations in calculations

The NAT contour will be overestimated if the standard deviation is directly applied to the calculated sound levels due to the fact that the ANP database [7] contains the logarithmic average of the measured sound levels. The AzB 2008 standard acknowledges this fact but still proposes to do the calculations without adjusting the calculated levels. The ECAC doc 29 suggests adjusting the calculated values before applying the standard deviation but does not specify by which amount. Following the recommendation by AzB 2008 the calculated values are not adjusted and the presented noise contour below might therefore be slightly larger than needed. An estimation of the error is that it is most likely lower than the square of the standard deviations found in the figures 3 and 4 multiplied with a factor (eq. 6) – from [ref 1].

$$\delta L < 0.115\sigma^2 \; [dB] \tag{6}$$

The day/evening NAT was calculated for Arlanda Airport for the year 2013. The day/evening metric contains all movements from 06:00 to 22:00 and the selected threshold limits were three and sixteen times above 70 dB(A). The calculation was performed with INM 7.0d with a grid spacing of 100 m x 100 m and the flight paths were modeled with five normally distributed dispersion tracks. The resulting grid file was then imported in Matlab and using the equations (4) and (5) the contribution to the total NAT was calculated from each movement. The standard deviation was obtained from the closest available value for slant distances and elevation angles that were outside of the defined ranges.

As seen in figure 7 the calculation with level distribution is smoother and, although not very apparent in this contour, the jagged edges that can result from using only five dispersion tracks disappear.

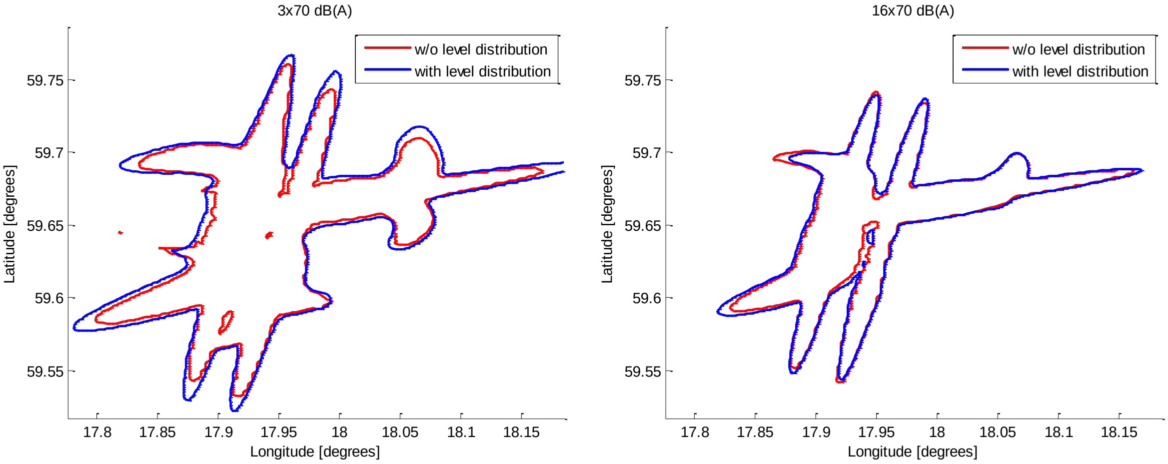

Figure 7 – Calculated noise contours without and with level distribution for three and sixteen times above 70 dB(A).

6. Conclusions

Using long term measurements the standard deviation was shown to vary from about 1 dB to 3.4 dB with generally higher values the greater the slant distance and the smaller the elevation angle. Equations are constructed using the standard deviations and implemented in noise contour calculations. The resulting noise contours are not only smoother and without discontinuities but they are also a better representation of what NAT stands for compared to not using normally distributed maximum sound levels.

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