UNCERTAINTIES IN THE PREDICTION OF ENVIRONMENTAL NOISE AND IN NOISE MAPPING

W. Probst ACCON GmbH, Acoustic Consulting, Gewerbering 5, 86926 Greifenberg, Germany

1 INTRODUCTION

Quantifying noise effects and/or annoyance by noise as demanded by Directive 2002/49/EC (END)[1] on a large scale needs the knowledge of the noise indicators at the where about of the people living in an area and the relation between these indicators and the harmful effects that shall be avoided or minimized.
If the noise situation in our cities and communities in different countries shall be compared based on the methods described in this directive about environmental noise, it is of great importance that we have some knowledge about the uncertainties that are included in the whole process. We are only able to decide if differences in the determined quantities about noise for different cities are significant, if it can be excluded that they are a result of a stochastic variation.
There are different methods used to describe uncertainties – many expressions like accuracy, uncertainty, errors, deviations and others are used in publications to describe what we need at the end: a quantification of the reliability of the determined quantities.
In International Standardization the concepts of GUM[2] are widely accepted and used in the last few years. This concept is transparent and powerful, because the dispersion of a population of possible results is broken down to the dispersion parameters of the different influences. This allows to rank these influences and to find the best method to improve the accuracy.
In some cases we use the concept of a theoretical “True value” and qualify the possible deviation by “errors”. The GUM – concept recommends to describe dispersed data as population where a single element is defined by it’s value and an uncertainty. This uncertainty is generally expressed as momentum of 2.nd order or standard deviation.
Figure 1 shows an example. If many different persons determine the sound power level of the same machine at different times, we will get different results. If we present the number of values in classes of decibels we get a presentation as shown in figure 1. In this case the mean value is 78 dB(A) and the standard deviation describing the dispersion is 3 dB. If we approximate the values by a Gaussian standard distribution, the level that is not exceeded with a given confidence can be calculated using the coverage factor k

$$L_{limit} = \overline{L} + k \cdot \sigma \quad (1)$$

Referring to a normal distribution the coverage factor is 1,645 for a level of confidence of 95 % (one sided).

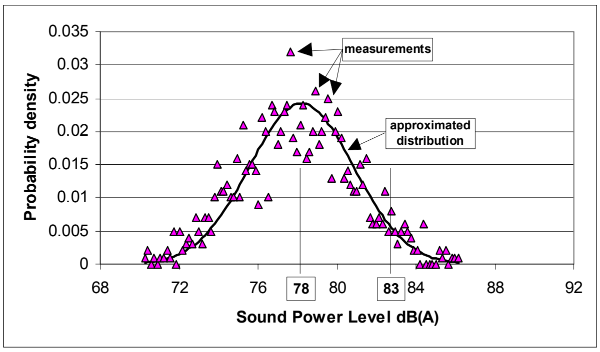

Figure 1 Dispersed results of sound power measurements and approximation by a normal distribution

In our example this level that is not exceeded by a confidence of 95 % is 83 dB(A).
In many cases the level L is not measured – or predicted – directly, but is determined from N other quantities x1, x2, ….,xN through a functional relationship

$$L = f(x_1, x_2, \ldots., x_N) \quad (2)$$

If the uncertainty of these quantities can be characterized by the standard deviations σ1, σ2…σN, the combined uncertainty σc of the level L to be determined can be expressed as

$$\sigma_c{}^2 = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 \sigma^2(x_i) \quad (3)$$

This is true if the input quantities xi are uncorrelated. If some or all of these input quantities are correlated, the appropriate expression is

$$\sigma_c{}^2 = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 \sigma^2(x_i) + 2\sum_{i=1}^{N-1} \sum_{j=i=1}^{N} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} \sigma(x_i, x_j) \quad (4)$$

Here the covariance σ(xi, xj) expresses the correlation between xi and xj.
These are the basics. The combined uncertainty σc as it shall be used in all measurement standards is an excellent concept to quantify the different influences on the uncertainty of the result – there is no reason why the same concept should not be used in the prediction of sound pressure levels.
In prediction we have some – often not very precise – information about the partial steps, but only very rough and often no knowledge about the accuracy of the final result. Taking into account that noise mapping is a financially interesting business, we should not be content if different groups declare their results to be the most accurate ones. A sober analysis based on scientific principles is the best way to tackle the problem.

2 THE CONCEPT OF UNCERTAINTY IN NOISE PREDICTION

If we want to characterize the result of a noise prediction calculation by an uncertainty, we have first to clarify what this end result shall be.
The basic element or "atom" of all predictions is the calculation of the sound pressure level L in a distance d of a simple omni directional and with all energy in one frequency band radiating point source. The result can be expressed as

$$L = f(L_W, A) = L_W - A(d) \quad (5)$$

where LW is the sound power level of the source and A(d) is the combined attenuation caused by many influences. If we know the uncertainty of the source emission σ-source and of the propagation calculation σ-propagation, the combined uncertainty resulting from (3) and (5) is

$$\sigma_L{}^2 = \sigma^2{}_{source} + \sigma^2{}_{propagation} \quad (6)$$

The uncertainty of the sound power level of the source depends on the method used to determine it. In our old – pre-GUM- concept the relevant standards are characterized by the grade 1, 2 or 3 and these grades define the maximal standard deviation of the population of all possible results if this standard is applied.

Table 1 Examples of uncertainties of source emission σ-source

SOURCE OF INFORMATION	UNCERTAINTY stand.dev. in dB
measurement grade 1 (e.g. ISO 3741)	1
measurement grade 2 (e.g. ISO 3744)	2
measurement grade 3 (e.g. ISO 3746)	4
specific literature (related to machine family)	3
general information from collegues	5

The uncertainty in propagation calculation σ-propagation depends on the method used. From comparisons measurement-calculation and based on reports from colleagues we recommend to use as first approximation (as long as there is a lack of more precise knowledge)

$$\sigma_{propagation} = k \cdot \lg\left(\frac{d}{d_0}\right) \text{ for } d > d_0 \quad (7)$$

with d0 10 m and k = 2 dB.

The so defined standard deviation increases from 0 dB at 0 m – 10 m to 2 dB at 100 m and 4 dB at 1000 m. It is only a rough assumption based on the use of traditional models in Europe (e.g. ISO 9613-2) and should be updated and more detailed step by step.

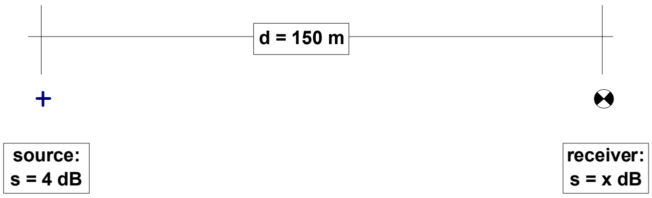

Figure 2 Sound propagation from one elementary point source to receiver

If we calculate the sound pressure level caused by a source with an uncertainty of the assumed emission of 4 dB in a distance of 150 m we get an uncertainty of the predicted sound pressure level of

$$s = \sqrt{4^2 + \left(2\lg\left(\frac{150}{10}\right)\right)^2}\ \mathrm{dB} = 4{,}6\ \mathrm{dB} \tag{8}$$

Generally the calculated sound pressure level at the receiver is the energetic sum of many contributions. If we calculate with frequency spectra or if more sources contribute to the receiver level – in all these cases we can calculate for each contribution the partial level and its uncertainty. Applying (3) on the equation for level summation

$$L = f(L_1, L_2, \ldots, L_N) = 10\lg\left(\sum_{i=1}^{N} 10^{0,1\cdot L_i}\right)\ \mathrm{dB} \tag{9}$$

we get the uncertainty σR of the calculated level at the receiver

$$\sigma_R^{\ 2} = \frac{\sum_i \sigma_{SR,i}^{\ 2} \cdot 10^{0,1\cdot L_{SR,i}}}{\sum_i 10^{0,1\cdot L_{SR,i}}} \tag{10}$$

Equation (10) allows to integrate the concept of uncertainty in prediction calculations and in noise mapping. It is even possible to calculate noise maps with levels of a certain confidence.
The principle is shown in Figure 3.

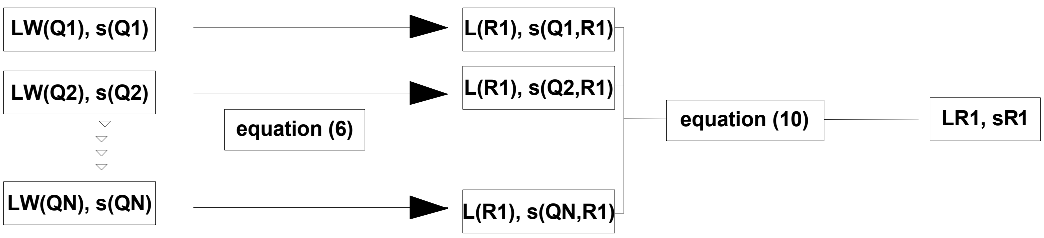

Figure 3 Determination of the uncertainty of the calculated noise level at receiver R1 from sources Q1 – QN

This procedure is an approximation – in reality the propagation uncertainties of all the contributing sources are not completely uncorrelated. But without any further knowledge this is the best assumption.

3 DETERMINATION OF UNCERTAINTIES WITH NOISE MAPS

This procedure cannot only be used for defined receivers, but also for complete noise maps. This is shown with figures 4 – 6. Figure 4 shows the noise map calculated with ISO 9613-2. The sound power level of source Q1 is estimated and therefore the standard uncertainty is assumed to be 4 dB, while this standard deviation may be 3 dB for source Q2. Based on the procedure figure 3, the uncertainty of the whole calculation is determined and presented as “uncertainty map” in figure 5. Adding these two maps figures 4 and 5 with a coverage factor 1,65 for a one sided confidence of 95 %, the map figure 6 was calculated. It shows the levels, that are not exceeded with a probability of 95 %.

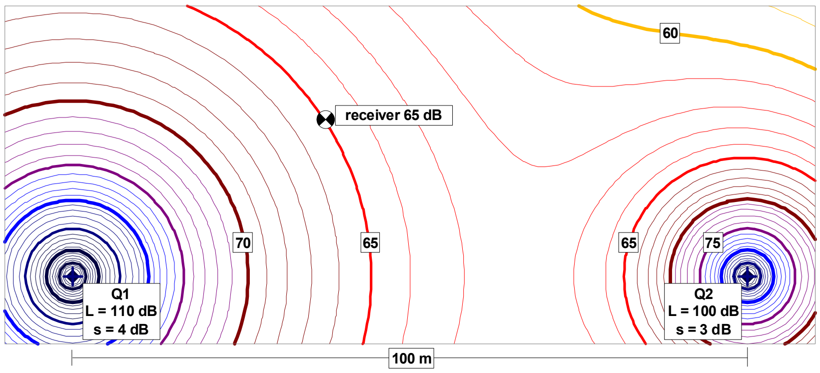

Figure 4 Noise map calculated with ISO 9613-2

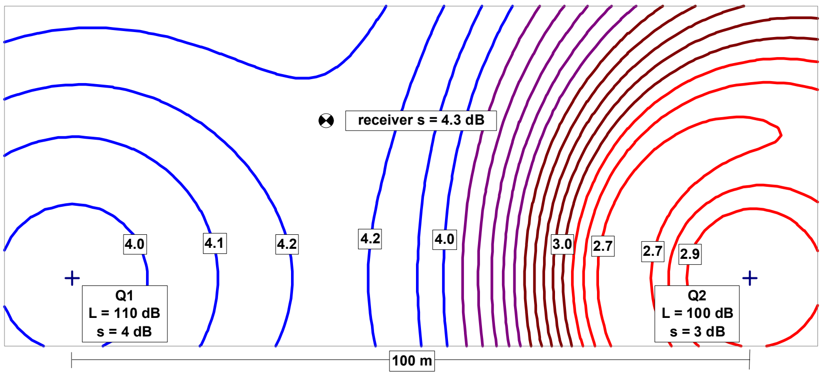

Figure 5 Total uncertainty of the predicted receiver level and it's spatial distribution

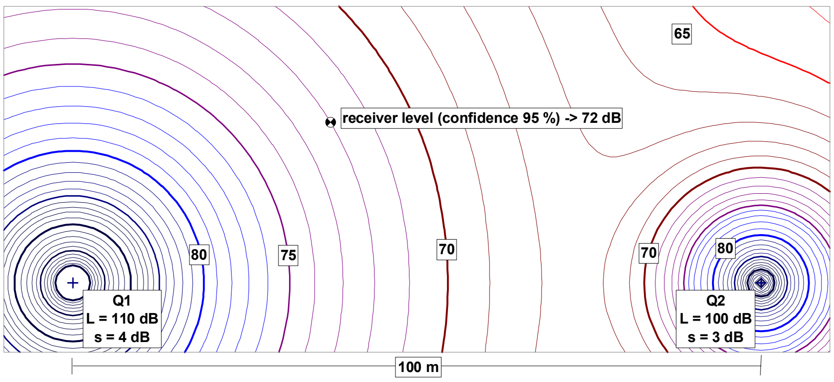

Figure 6 Map of noise levels not to be exceeded with confidence 95 %.

Extended sources are generally split in subparts so small that these can be included in the calculation like point sources. This creates a little problem – if we calculate the uncertainty of the receiver level from one source with emission LW and uncertainty s or we have two sources with emission (LW – 3 dB) and uncertainty s each the uncertainty of the result will be smaller in the latter case. This is because the applied equation (10) is only valid for uncorrelated sources, while the automatically subdivided subparts of an extended source may not be uncorrelated if this source is a road or an area where a noisy device like a fork lift is operating. If the line or area source consists in reality of moving point sources, any assumption about the emission of these point sources is valid for all subparts – the covariance included in equation (4) cannot be neglected. Noise mapping software implying uncertainty determinations as shown in fig. 4 – 6 should take this into account.

4 UNCERTAINTY – WHAT HAS TO BE INCLUDED

It depends strongly on the deliverables of a calculation what influences have to be taken into account when uncertainties shall be estimated. The two terms in the sum equation (6) are sums of the squared standard deviations of various influences and in many cases it is better to split them up to be able to quantify them. In the case of strategic noise mapping based on the END the noise levels are not the end of the game – they are calculated at the most exposed facades of the buildings and according to Annex VI of END the people affected shall be evaluated. Even the distribution of people versus level intervals may only be an interim result – using dose-response relationships the total annoyance of all people in a city[3] may be the metric that shall be used to rank a situation.

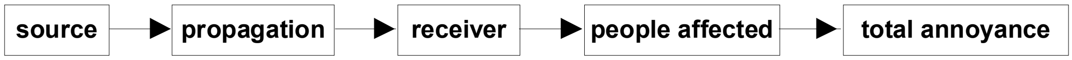

Figure 7 Steps where uncertainties have to be taken into account in EU-Noise-Mapping

If we calculate the strategic noise map, the distribution of people affected and a total annoyance score of all people as a single number we may ask about the uncertainty of this final result. Millions of complex calculations are included to come from the digital model of a city to this final result, and it is only possible in realistic times because we accept a lot of approximations and even assumptions in modelling and calculation. In such cases where the whole process may be improved with more detailed modelling and calculation, but where time or financial budgets define the insurmountable limits, a very thorough balancing of the accuracy of each step is necessary to minimize the uncertainty of the end result. If we invest calculation time and other restricted resources in steps that contribute only little to the result the uncertainty of this result will be increased (always taking into account that restricted budgets define limits).

4.1 Source modelling

In simple cases sources can be modelled as omni directional radiating point sources with A-weighted sound power level. In many cases of industrial noise where hundreds of such sources contribute, this is the best solution. The fewer dominating sources define the noise at the receiver position, the more it is necessary to take into account frequency distribution and directivity of the radiation. Larger sources like machines, trucks and railways may even be modelled as structural extended objects with many sources distributed on their surface. But as mentioned above – detailed modelling needs more data and reduces transparency and understandability. If the directivity of sources is negligible, we reduce the accuracy of the result if we force people to enter hundreds of additional unnecessary numbers.
For sources with sound power levels that have been determined on the basis of the ISO 3740 series the source related uncertainty can be oriented at the values given in table 1.

4.2 Propagation calculation

With road, railway and aircraft noise the source description as well as propagation calculation is generally part of national or international standards. In many countries it is mandatory what standard has to be used when calculating noise levels to prove the compatibility with legal requirements. This is a typical case where the result of a correct calculation using the standardized routines is the "true value", and each deviating value – even if it fits better with measurements – has to be treated as an error.
If the same situation is to be modelled and the levels at the same positions shall be calculated by different people where only the standard is the given frame we will get results that are dispersed. We can distinguish three types of deviations.

- Type A: real errors in the software realization of equations described in the standard. These are bugs and the best way to find and minimize them is to publish with each of these standards a set of test problems with step to step results. These can also be used to certify the correctness of software when the standardized methodology is applied.
- Type B: deviations that are caused by not precise or ambiguously formulated procedures. Many of these cases occur because most standards deal only with simple situations, and it is obvious that we get different results if different developers try to comply with such a problem. These differences are part of the "natural" uncertainty of results using this standard.

- Type C: deviations that are caused because situations that occur in reality and in the model are not covered by the standardized methodology.

Some authors try to show that software packages are erroneous by using different programs for the same problem and yamming about dispersing results. It is recommended to classify the problem what type it is related to the classification above – if it is type 2 or 3, it can only be treated as a motivation to improve the standard.

Many experts claim since years that existing “traditional” models are inaccurate and that meteorological effect should be included more detailed. Much money has been invested in Europe to improve this situation and to develop better models for the near future.

Meteorological influences may increase with larger distances. All our comparisons measured-calculated levels show that differences are small nearby but grow with distance. To study the possible influence of an improvement of the calculation methodology the digital model of the city of Augsburg has been used. It comprises 147 km² agglomeration with 79416 buildings, 704 km acoustically relevant roads and 271725 inhabitants.

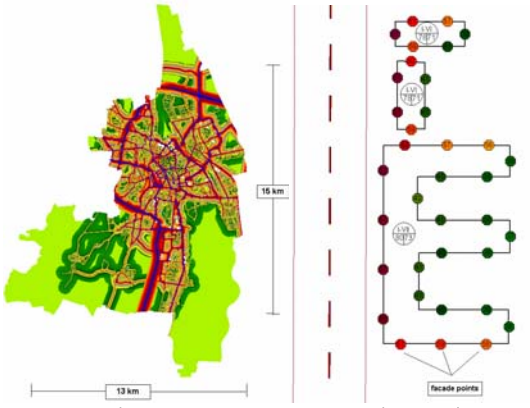

Figure 8 Noise map of Augsburg: 10 m grid (left) and facade levels (right)

The two types of calculation applied are shown in figure 8. The whole project file with all objects, the 10 m grid and the façade levels for all buildings comprises 233 MB. With the two types of map calculated the number of people exposed distributed in level intervals and the total annoyance score [3] have been determined.

With a special compilation of the used program CadnaA it is possible to sum up only those contributions at the receivers that are produced by rays shorter than a defined maximum length – this length restriction is even used for angled reflected ray paths. For maximal lengths of rays of 50 m, 100 m, 200 m, 300 m and with all rays the complete noise maps of Augsburg, the level at the most exposed facades and from these the number of people exposed have been repeatedly determined. Each point in the diagrams figure 9 is a new calculation for the complete city and an evaluation of exposed people based on the L_{den}.

These results figure 9 prove, that the long distance propagation and the meteorological influences are not important for strategic noise mapping in agglomerations. The distances 0 to 150 m determine the uncertainty of the end result, and expenditures to improve the methodologies of the calculation of sound propagation will not change any of the results found with the existing conventional methods. It is rather to fear that the disadvantages of more complex and not simple controllable methods will increase the uncertainty of the final result.

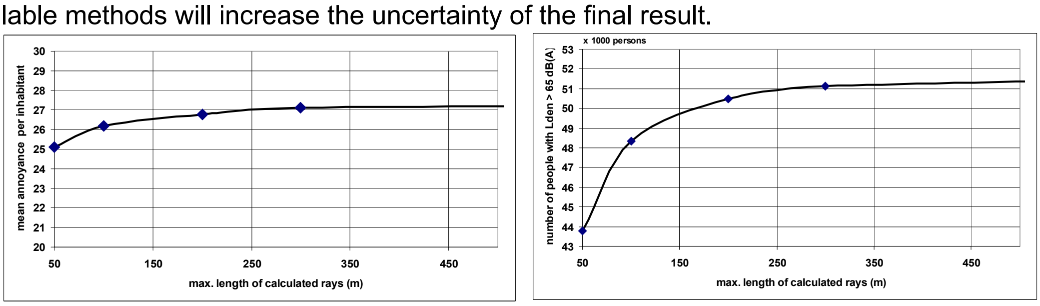

Figure 9 People exposed with L_{den} > 65 dB(A) (left) and mean annoyance score per inhabitant in dependence of maximal ray length calculated

The same way we can investigate the influence of each parameter on the result. Our experience is that it is important to define this end result clearly before the contribution of uncertainties of parameters is investigated. If the "total annoyance score" of a city shall be minimized, then rather simple and crude methods are sufficient. Traffic rearrangements and improvement of road surfaces influence the noise levels on larger areas, and the decision is influenced by mean levels and not by noise levels at defined positions.
This "punctual" uncertainty is important if legal requirements have to be met and this should be proved by a calculation in the planning phase.
Some uncertainties are introduced by the numeric methods used – they have nothing to do with physics and are therefore nearly undetected by users of software tools. The following is only a brief summary with some of these aspects.
All software for noise mapping can be classified in one of the two groups "angle scanning (AS)" and "ray tracing (RT)".
With AS the calculation starts from the receiver point and follows straight lines arranged in definable angle steps. Only those objects are seen and taken into account, that are crossed by these rays. The resolution of the method decreases linear with increasing distance – if narrow angle steps are used to get an acceptable accuracy, the calculation times increase unacceptable with large mapping projects. Another problem with AS is that reflectors near the source are not detected if many objects like buildings or barriers are between source and receiver.
The advantage of the AS method is that calculation of high reflection orders at facades at buildings facing the road can be very quick, because in that case the time consuming calculation of reflected rays coming from outside the "road-space" can easily be suppressed. Even if the uncertainty of each single ray-calculation may be large - if there are reflecting buildings at both sides, many reflections contribute to the result and the uncertainty of each single contribution is not important.
The RT method can be very precise in detail, because the possible rays are constructed in a deterministic way. This high accuracy has it's price – the number of possible rays explodes with increasing reflection order. This is no problem in large scale noise mapping, because with both methods only first order reflections are included generally. But multi reflection influences in narrow roads must be included by an additional correction with RT methods.
But as both strategies have their pros and cons, it is the optimal solution to use a software where this strategy can be selected.
In that case it is recommended to inspect carefully to the patterns of calculated noise contours. These are a very sensitive instrument to detect and quantify errors and uncertainties. If noise contours flounce and show irregular and unexpected patterns, this is not an esthetical problem, but proves that errors depending from the position of the receiver point are produced. The same errors occur if the levels are calculated at defined points. It is recommended to use test samples with very precise defined situations where the correct result is well known to investigate these deviations produced by program strategies. In the examples figure 10 it is obvious that the projection method increases the accuracy.

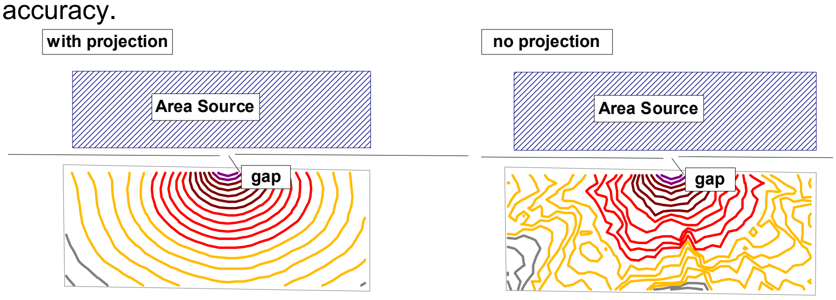

Figure 10 Noise contours produced with projection on and off – projection off with larger uncertainty

4.3 Receiver and people affected

The END requires to produce the distribution of people affected by noise in intervals of L_{den}. This L_{den} shall be determined at the most exposed façade.
As shown in figure 8, the L_{den} at the most exposed façade of a building can be found by calculating these levels directly distributed around the façade and taking the maximum. The same procedure shall be repeated exclusively for buildings with a "quiet" façade. Unfortunately the level at the quiet

façade has to be determined in a distance of 2 m from this façade – this would require two complete calculations of the building noise map.
It would be advantageous to use the same small distance at both sides, but this needs an investigation about the uncertainty that is introduced by that deviation from the END requirement.
This was done using again the city model of Augsburg. To find the influence of the distance of the receiver point that determines the quiet façade, the complete calculation and analysis as defined in Annex VI of END was done with varying distance of the calculation point.

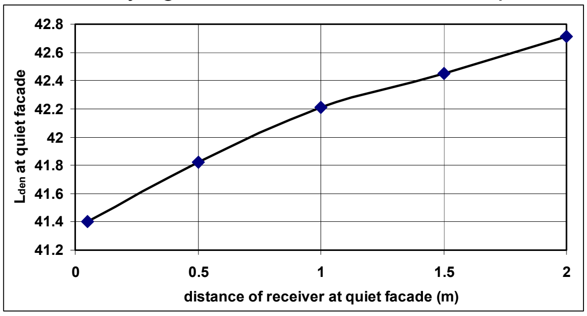

Figure 11 Level at the quiet façade (mean of about 6000 buildings) versus distance

About 6000 buildings in Augsburg can be qualified as buildings with a quiet façade. Figure 11 is based on 5 calculations of this city model and it shows, that there is only a difference of about 1 dB calculating with 0.05 m or with 2 m distance. This cannot justify to double the calculation time: based on these results it can be recommended to calculate with uniform small distance from the façade. To get comparable results for all cities a building should be qualified as a building with a quiet façade if the maximal and minimal façade levels differ by 21 dB or more.
These few examples show that a careful and responsible analysis of uncertainties in noise prediction is complex and covers many influences. The simple question: "How accurate is a noise map?" cannot be answered by one number the time being. It is highly recommended to combine with any further development a very thorough inspection of the possible improvement for the end result on the basis of uncertainty measures. Unfortunately the existence of powerful software for noise prediction encourages many experts to modify existing methodologies more and more – the result are methods where the user must trust his software and where even plausibility-checks are extremely time consuming or even impossible. In some of these cases it can be stated: Lesser is often better.

5 REFERENCES

1. **Directive 2002/49/EC** of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise.
2. **ISO Guide to the expression of uncertainty in measurement**, International Organisation for Standardisation, ISBN 92-67-10188-9, 1993.
3. H.C. Borst, H.M.E. Miedema: **Comparison of Noise Impact Indicators, Calculated on the Basis of Noise Maps of DENL**, ACTA ACOUSTICA Vol. 91, p. 378 – 385, 2005.