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Spatial interpolation contribution to noise maps uncertainty

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Abstract
Noise maps results are usually presented as contour graphs or isophone curves, which describe the sound levels as functions of spatial location. These maps are added to Geographic Information Systems (GIS), allowing sound level evaluation as a function of the continuous coordinates x and y, for a given height above ground. Although the outcome of the system is a continuous variable, the calculations that allow its evaluation are obtained in discrete points that form a calculation grid, which is created by the application of spatial sampling techniques. Using spatial interpolation tools, values are assigned to the locations in which measures or calculations have not been performed.
The application of sampling and interpolation techniques (the type of grid, its density, the interpolation algorithms…) contributes to the uncertainty of the results.
This paper describes a calculation method to quantify the uncertainty associated to the spatial sampling and interpolation process.
We also propose a revision of the classical meaning of noise mapping uncertainty, taking into account the final application of the results.

Keywords: noise map, uncertainty, interpolation, sampling grids, simulation

1 Introduction

Outdoors noise simulation models have become the most widely used tool for environmental noise assessment. Several models have been developed to estimate noise pollution produced by road traffic, trains, aircrafts and industrial noise sources. All of these models calculate the sound levels at specific locations defined by a grid of receivers. These discrete results are then interpolated to provide a continuous spatial representation of sound levels, referred to as a noise map.
The accuracy of the individual simulation receiver's results is related to the quality of input data (ground, traffic intensity, speed, etc.), the accuracy of the noise model, uncertainty propagations within the model and the function of the chosen software. If the model and the software package are selected by the acoustic consultant and the input data are established, the results for each receiver are fixed and so is the receivers' uncertainty. Main references use this approach to refer noise maps uncertainty (1-6).

Aside from the receiver's uncertainty, the overall uncertainty of the map is also related to the grid size/density, interpolation method and map ranges for representation.
Frequently a 5dB map range classification is used. Therefore, it is commonly assumed that other contributions to uncertainty will be masked by this classification process. However, in order to evaluate the quality of a map, one needs only to check if the isolines are located in the correct position. If all of the areas of the map are classified correctly, the map is perfect, no matter the range of each class. It follows that the limit between areas are the isolines, which are the supporting objects in a map.
The accuracy of the isolines is extremely important, as they are used for limiting noise areas, establishing action plans, defining land use and so on. Therefore, they are very important in social and economic terms.
Isolines are the only positions on the noise map where the results are expressed as exact values, instead of ranges. It can be concluded that the ranges do not affect the map's quality. "Ranges" can be related to "scales" on a topographic map. Scaling the map provides more details but does not necessarily contribute to improving the accuracy.
Often, the impact of the interpolation process on noise map accuracy is overlooked. The process is usually based on setting the minimum necessary requirements based on the grid of receivers. The finer the grid, the better the results. While this is true, it is not complete. As the density of receivers increases, the accuracy of the map will be improved, but the computational costs will also increase exponentially. Furthermore, most of the receivers do not contribute to the optimization of the map quality.
In this paper, we describe a method to estimate the quality of a map in relation to the grid type, the grid size and the interpolation process.

2 METHODOLOGY

2.1 Definitions

Noise map: A noise map is a spatial representation of the noise levels within an area. The measurand is the sound level (Ld, Ln, etc.) that is spatially distributed in a continuous 2D surface at a fixed height above the ground.
It is widely accepted that a noise map can be based from measurements (large spatial and time samplings) or from simulation tools (using parameterized sound sources and propagation models). Simulation tools are preferred because they optimize costs, generalize results for the long-term and can be used for evaluating different scenarios.
In both cases, it is necessary to define a discrete grid of receivers, in which results must be calculated or measured. The grid results must be interpolated to a noise map. The map is typically represented in classes of 5dB, using a contour or isoline map. Figure 1 shows schematically the steps that must be followed in creating a noise map.
Uncertainty: As defined in (7), the result of a measurement or simulation is an estimation of the value of the measurand, and thus is only complete when accompanied by a statement of the uncertainty of that estimate. As follows, uncertainty characterizes the dispersion of the values that can reasonably be attributed to the measurand.
Acoustic noise model: The acoustic noise model contains equations and algorithms to calculate the noise levels at specific receivers from a set of input data. The difference between the true noise levels (Figure 1a) and the calculated noise levels (Figure 1c) characterize errors in the models.

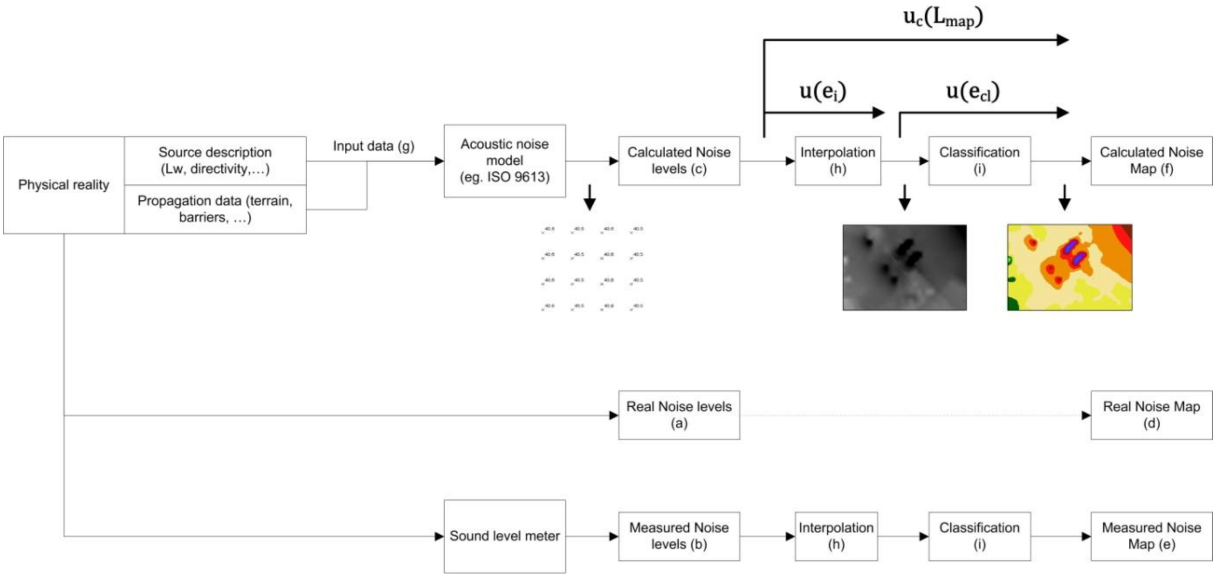

Figure 1 – Process of elaboration of a noise map.

The characterization of real noise levels will be made by measurements (Figure 1b). However, the precision of acoustic models is out of the scope of this paper.

Noise mapping uncertainty: When applied to a noise map, an overall uncertainty value of U (dB) means that the real value of sound level ($t_{true\ value}$, dB) at most points on the map is expected to be within the a percentage defined confidence interval, Equation (1).

$$\left|L_{true\ value} - L_{map\ reading}\right| \leq U \tag{1}$$

Therefore, the accuracy of the map is related to the deviation between the map readings and true values.

The estimation of uncertainty of a noise map is based on the idea that the more accurate the results for the receivers in the grid are (Figure 1c), the more accurate the map is (Figure 1f). Consequently, the uncertainty can be calculated for specific points through statistics (4,5). This estimation of the receivers' uncertainty is related to the uncertainty of input data (Figure 1g), the uncertainty propagation through the model, and the uncertainty of evaluation data (2, 9, 10).

2.2 Uncertainty due to map representation

A noise map is not usually defined by a discrete set of receivers' results. Subsequently, interpolation (Figure 1h) and classification (Figure1i) tasks also need to be considered in the estimation of a map's uncertainty.

The interpolation process converts the set of discrete receivers to a continuous surface. Afterwards, it is frequently required to represent the results in classified ranges (usually as wide as 5dB). This classification process improves the trueness of the map by converting deviated values into proper values. In the classification task, there are only areas correctly classified and areas misclassified – there are no deviated values. Thus, if no area in a map is misclassified, the map is absolutely accurate, regardless of how many classes are defined or the width of the ranges.

For example, if the true value at a point is 48.5dBA, then a calculated value of 46.0dBA has a deviation of 2.5dBA. After classification, both values are assigned the same 5dB class, 45-50dBA, and the same colour in visualization. Consequently, there is no error in the results.

However, when applying this example to a location near an isoline of the map, the same deviation may denote an incorrect classification (50-55dBA instead of 45-50dBA), meaning that the isolines are not properly located. Subsequently, the trueness of the map is dependent on the correct location of the isolines that separate two successive ranges. It is less important what happens between two consecutive lines because the accuracy of the map is based solely on the location of the isolines.
Noise map uncertainty characterizes the dispersion of the error at any point of the noise isolines with a confidence level of 95%.
This new approach allows the effect of interpolation on a noise map uncertainty estimation, which is not usually considered, to be included. Consequently, the approach also takes into account the effect of the calculation grid (3,11).

2.3 Grid uncertainty estimation

This paper focuses on the contributions of the calculation grid size and interpolation method to the uncertainty of a noise map. For this reason, the input data variability, its propagation, and all other contributions to the uncertainty have been neglected. It is assumed that values calculated at the grid points are true values and their uncertainty contribution is 0dB.
After calculations of the noise model at the grid points, the discrete results are interpolated to obtain a continuous spatial distribution of noise levels, which is called a noise map.
The techniques for spatial interpolation can be divided into two main groups; deterministic and geostatistical interpolators (12). Deterministic interpolators create a surface from measurements based on the extent of similarity (inverse distance weighted) or the degree of smoothing (radial basis functions) of the data. Geostatistical interpolators (kriging) create a statistical model for the measured points and lead to better results when applied to noise mapping.
Other acoustic considerations can be taken to improve the local performance of the interpolation process, for instance near barriers, or near sound sources (3).
Calculation of the map's uncertainty is carried out following the methods described in (7).
The analysis of variability all over the noise map, is made by a simplified model. Equation 2 shows the model applied for the estimation of uncertainty in a noise map.

$$L_{map,j} = L_j + E_{i,j} + E_{cl,j} = L_j + E_{i,j} \tag{2}$$

The terms used in this equation are described in Table1.

	Variable	Estimation of variable	Arithmetic mean	Estimation of variance	Standard uncertainty	Combined uncertainty
Sound Level shown in the map for location j	$L_{map,j}$					$u_c(L_{map})$
Deviation produced by interpolation	$E_{i,j}$	$e_{i,j}$	$\overline{e_{i,j}}$	$s^2(e_{i,j})$	$u(e_{i,j})$	
Deviation produced by classification	$E_{cl,j}$	$e_{cl,j}$	$\overline{e_{cl,j}}$	$s^2(e_{cl,j})$	$u(e_{cl,j})$	
True value at point (j)	L_j					

$L_{map,j}$ is the sound level observed at location j, which depends on three factors: the true value at that location, the effect of the interpolation process and the effect of the classification process.

As mentioned, it is assumed that the true value at that location (Lj) can be gathered just running the noise model for that location.

As far as we propose to estimate uncertainty only at the isolines, the deviation caused by classification process can be neglected, as it is only derived from the interpolator's resolution.

In general terms, the deviation produced by the interpolation process depends on the grid of results used at the input of the interpolator (Figure 1c). So there is an interaction between these two factors. But, in this analysis the input at the interpolator is fixed, because we pretend to estimate the uncertainty in this precise situation. Consequently we are excluding the interaction from the analysis, breaking the dependencies between these two factors. As a result, the interpolation uncertainty (form c to f in Figure 1) can be considered as an independent variable, and can be simply added to the previous contributions in the process (from g to c in Figure 1), to calculate the overall combined uncertainty in this precise map under consideration.

If the grid of receivers or any input or parameter of the noise model changed, the interpolation uncertainty should be recalculated.

The combined standard uncertainty of sound levels in the map, $u_c(L_{map})$ is calculated from the standard uncertainty of the interpolation error, $u(e_i)$. Therefore, it is necessary to measure the error at the lines. This is done by setting several receivers on the lines (Figure 2),and performing new calculations. For each line, a set of “old” interpolated values and a new set, which has been calculated using the noise model, will be available. The new set is considered free of errors.

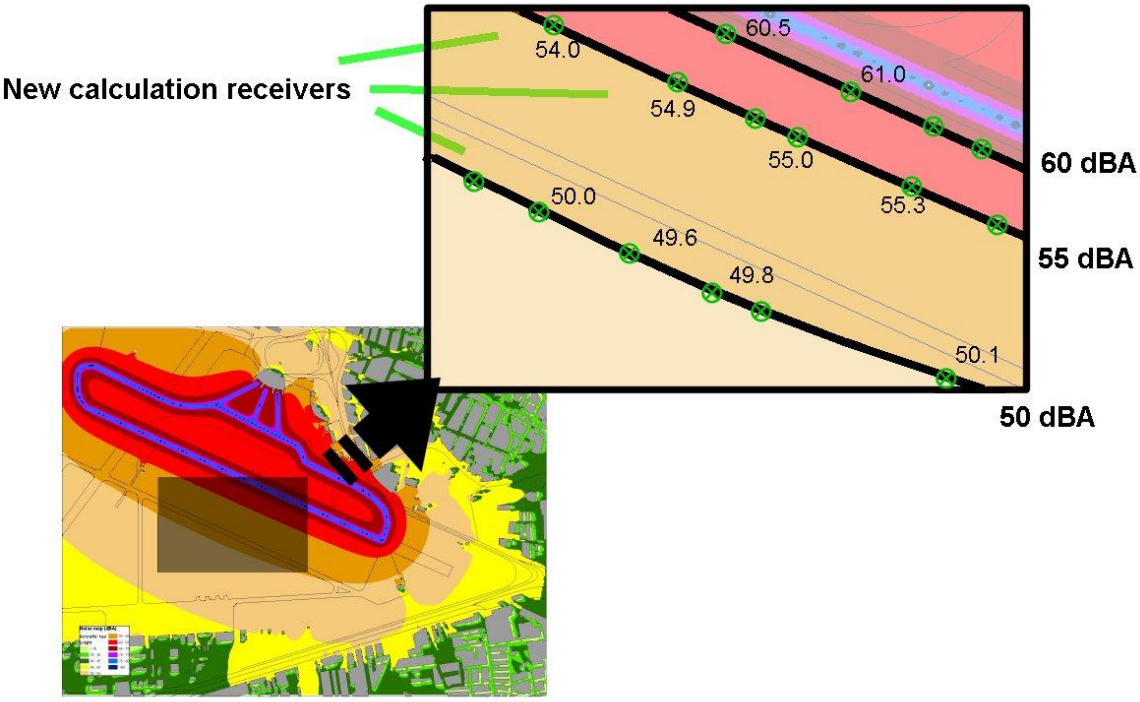

Figure 2 – Uncertainty receivers’ position.

As all the points, *j,* are located on the same isoline, *Lj* will be a constant. The dispersion of the data can only be attributed to interpolation error, whose best estimate is the arithmetic mean of the *n* observations:

$$\overline{e_i} = \frac{\sum_j e_{i,j}}{n} \qquad j \in 1..n \tag{3}$$

The variance of the observations will be estimated by equation 4:

$$s^2(e_{ik}) = \frac{1}{n-1} \sum_{j=1}^{n} \left(e_{i,j} - \overline{e_i}\right)^2 \qquad j \in 1..n \tag{4}$$

And the best estimate of the variance of the error mean, is given by

$$s^2(\overline{e_i}) = \frac{s^2(e_{ik})}{n} \quad (5)$$

The standard uncertainty of the interpolation error is defined as follows:

$$u(e_i) = \sqrt{s^2(\overline{e_i}) + \bar{e}_i^{\,2}} \quad (6)$$

The calculation of the combined and expanded uncertainty of sound levels in the map, which includes the rest of the components, is out of the scope of this paper.

3 Conclusions

A new approach for defining of a noise map's uncertainty, which includes uncertainties caused by visualization ranges and interpolation processes, has been proposed. The focus of this approach is set precisely on the interpolator's contribution to uncertainty, including the effect of the calculation grid as an input.
The method for calculating this uncertainty has been described. This method allows for the estimation at the supporting objects of the map (isolines) and does not depend on the interpolation method or the calculation grid.

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