# Dynamic Noise Mapping based on Fixed and Mobile Sound Measurements

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**Summary**
This work introduces an approach for calculating dynamic noise maps on the basis of fixed as well as mobile sound measurements. The proposed approach extends the temporal and spatial resolution of the traditional noise map that is based on long-term equivalent levels, and is therefore well suited for the prediction of indicators that are more closely related to the perception of the acoustic quality of the urban environment. The approach uses a model based interpolation technique, and accounts for the presence of sources that are generally not considered in noise maps. On the one hand, data from fixed noise measurement stations is used to continuously adapt the parameters underlying the map to temporal changes due to variations in source strength and propagation conditions. On the other hand, data from mobile noise measurements is used to increase the spatial resolution of the map. As an illustration of this approach, the construction of a dynamic map of the 13th district of Paris is presented. A network of twenty-four fixed, intelligent sound measurement devices is installed in the area. Next to this, mobile sound measurements are performed at regular periods inside the case study area. For this, five measurement devices are carried by researchers performing walks through the area, logging instantaneous 1/3-octave band levels as well as GPS data, such that trajectories can be fully reconstructed afterwards.

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## 1. Introduction

The European Environmental Noise Directive [1] has led to the implementation of strategic noise mapping in many European cities since 2002. Strategic noise maps have become an important noise policy instrument for identifying black spots, and for the assessment of the effects of urban noise exposure on inhabitants [2]. Nevertheless, measurement campaigns often show significant discrepancies between calculated and measured acoustical indicators, in particular at highly shielded urban zones, mainly due to simplifying assumptions made within the applied source and propagation models. Moreover, although strategic noise maps certainly have their merits, they fail to capture sounds that are less easy to predict, and the temporal dynamics of the sound environment is not at all included. The latter might be quite important to evaluate sleep disturbance and noise annoyance [3].

The increasing availability of low-cost computing devices, microphones, and (wireless) internet access forms a technological push for the use of distributed sound measurement networks. Consequently, the latter are increasingly being applied to validate and improve the accuracy of traditional, purely calculated noise maps that are based on long-term equivalent levels. In addition, acoustic sensor networks can be useful to improve the spatial and temporal resolution of such noise maps. If real-time measurement data is available from a relatively dense network of sound measurement stations, one can use this data to create so called *dynamic noise maps*, which are periodically updated (e.g. every 10 minutes). In previous efforts in creating such dynamic noise maps, it was assumed that the propagation of sound is independent of time, and that the time-varying sound level at the receiver location can be obtained by only updating source powers [4]. Another method consisted of interpolating between the noise levels measured instantaneously at many immission points using mobile measurement stations [5, 6]. The accuracy of these methods strongly depends on the density of the measurement network, and because errors in the propagation model (e.g. due to meteorological effects) are not accounted for, the spatial accuracy is usually poor.

In this paper, a general model-based interpolation technique for calculating dynamic noise maps is presented, in which source and propagation parameters are tuned simultaneously. The approach makes use of a combination of fixed as well as mobile sound measurements, to increase the temporal and spatial resolution of a basic noise map. The proposed method is an extension of earlier work [7, 8] in which only fixed measurement stations were used. In Section 2, the general methodology is presented. In Section 3, a case study that will illustrate the proposed approach is presented. This case study is currently still being carried out in the 13th district of the city of Paris, in the framework of the GRAFIC project.

## 2. Methodology

### 2.1. Sound level estimation

The proposed methodology for dynamic noise mapping relies on a sound source emission and propagation model that is periodically updated based on sound level measurements, which can be performed both by fixed or by mobile measurement stations. Figure 1 shows an overview of the proposed methodology. In general, the model estimates the equivalent sound pressure level at a particular location $\mathbf{x}$ and at time $t$, for each 1/3-octave band with center frequency $f$, by summing the contributions $L_{f,i,j}(\mathbf{x},t)$ of all modelled sources $i = 1,\ldots,N_s$ through all propagation paths $j = 1,\ldots,N_{h,i}$ between source $i$ and location $\mathbf{x}$:

$$L_{eq,f}(\mathbf{x},t) = 10\log_{10}\sum_{i}^{N_s}\sum_{j}^{N_{h,i}} 10^{[L_{f,i,j}(\mathbf{x},t)]/10} \quad (1)$$

The contribution at $\mathbf{x}$ of source $i$ through propagation path $j$ is calculated on the basis of an estimate of the sound emission of the source and an estimate of the attenuation along the propagation path,

$$L_{f,i,j}(\mathbf{x},t) = L'_{W,f,i}(t) - A'_{f,i,j}(\mathbf{x},t) \quad (2)$$

The estimates of sound emission and attenuation are each composed of two parts: a part that is obtained

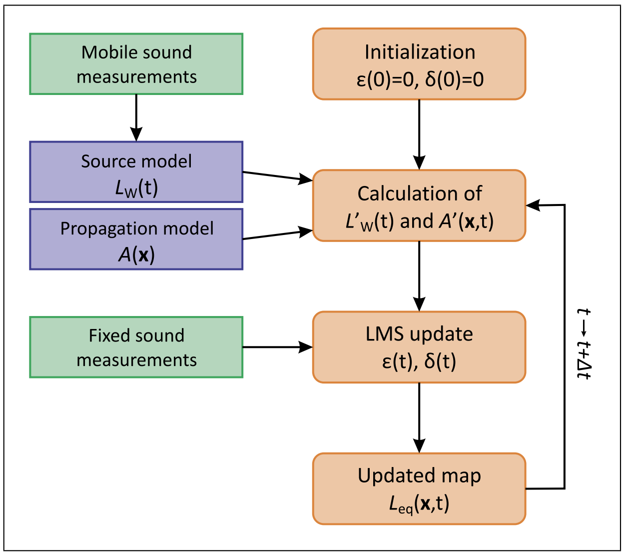


Figure 1. General overview of the proposed methodology. For simplicity, indices $f$, $i$ and $j$ have been removed.

through sound source and propagation modelling [7], and a relatively small time-varying correction that incorporates all factors that are not taken into account in the model, and thus makes up for the difference between model and measurement:

$$L'_{W,f,i}(t) = L_{W,f,i}(t) + \epsilon_{f,i}(t-1) \quad (3)$$

$$A'_{f,i,j}(\mathbf{x},t) = A_{f,i,j}(\mathbf{x}) + \delta_{f,i,j}(t-1) \quad (4)$$

Modelled values for the sound emission $L_{W,f,i}(t)$ could simply be long-term average values. However, diurnal pattern effects on sound source emissions can be taken into account; therefore the time dependence is explicitly noted. Values can be spatially adjusted based on detailed mobile sound measurements (see Section 2.3), or could even be obtained from a detailed temporal simulation model for particular sound sources, such as a microscopic traffic simulation model coupled with an emission model for the case of urban road traffic noise [9].

Modelled values for the propagation attenuations $A_{f,i,j}(\mathbf{x})$ are to be pre-calculated using a propagation model, which should include the direct path between source and receiver, as well as paths including reflections and diffractions, and should account for the effect of atmospheric turbulence [7]. Within the current implementation, this propagation calculation is time-independent, but in future, temporal atmospheric effects on sound propagation, e.g. obtained through meteo measurements or a meteo model, could be accounted for.

Both corrections $\epsilon$ and $\delta$ can be functions of frequency and time. Values are obtained by minimizing the squared error between estimated sound pressure levels and measured values $L_{eq,f}(\mathbf{x}_{meas},t)$, obtained through a number of fixed measurement stations. Inspired by the least mean squares (LMS) algorithm that is popular in signal processing, the minimization is not resolved explicitly at every time step, but on average over a longer time period, hereby assuming that $\epsilon$ and $\delta$ change only slowly with time over the course of a day.

It should be obvious that a model that aims to predict instantaneous sound pressure levels, e.g. on a second-by-second basis, will most likely fail. A suitable aggregation period has to be chosen, which balances stability and repeatability with a sufficient degree of dynamics. For this work, a 10-minute temporal interval was chosen. The equivalent sound pressure level $L_{\text{Aeq,10min}}$ includes the total sound energy received at a measurement location; every sound source contributes to this quantity independently.

### 2.2. Reducing degrees of freedom

As model parameters are to be tuned based on measurements, the number of degrees of freedom that can be resolved is determined by the number of measurement stations and the assumptions on temporal coherence on the time scale considered in the model. From equations 3 and 4, it is clear that, for each frequency band and for each receiver, the number of unknown $\epsilon$ equals $N_s$, and the number of unknown $\delta$ equals $\sum_{i=1}^{N_s} N_{h,i}$. This makes that the system of equations obtained from matching calculations with a limited number of observations will be strongly under-determined. Moreover, many sources and propagation paths have only little influence on a particular immission point, which makes the system also ill-conditioned. Drastically reducing the number of degrees of freedom is therefore necessary.

Inspired by land-use regression modelling, sources are categorized according to their type, and a single correction $\epsilon$ is applied to the emission of all sources within the same category. To be able to resolve the solution of $\epsilon$, the number of source categories should therefore typically be less than the number of measurement locations. Road traffic sound sources can for example be grouped by road (section), and grouped further according to vehicle category, traffic intensity, or the speed limit. If long-term measurements are available, e.g. from fixed measurement stations located within the study area, an alternative statistical approach can be used, whereby road sections are clustered based on sound level indicators (equivalent levels, percentile levels, average spectrum etc.), for example using Kohonen maps [11, 10].

To be able to resolve the solution of $\delta$, propagation paths are grouped into three categories: (i) the 2D path, consisting of direct line-of-sight propagation and reflections or diffractions in the horizontal plane; (ii) the diffraction path over roof tops, and (iii) the scattered path, i.e. the contribution to the immission due to turbulence scattering, mainly important in shielded areas. It is expected that the 2D path estimate is relatively accurate, whereas the diffraction path might be slightly inaccurate but time-independent, and the scattered path may change significantly over time. Therefore, it is important to keep these three corrections separate. Paths within the same category are then adjusted by a single value of $\delta$.

Although in principle, there are no fundamental constraints in performing the fit to measurements on a per frequency basis, this additional degree of freedom jeopardizes the uniqueness of the solution and could easily lead to over-fitting. Therefore, in the current implementation, the corrections $\epsilon$ and $\delta$ are still performed independent of frequency.

### 2.3. Temporal and spatial resolution

The use of both fixed and mobile sound measurements allows to extend the temporal and spatial resolution of the noise map based on long-term equivalent levels. On the one hand, fixed measurement stations that are placed at strategic locations within a study area [12] allow to periodically correct for temporal changes in source emissions and propagation attenuations, according to the methodology described above, thus resulting in a dynamic noise map. The larger the number of fixed measurement stations, the larger the number of temporal effects that can be accounted for. On the other hand, mobile sound measurements, for which the goal is to cover the complete study area with good spatial resolution, allow to better characterize the spatial distribution of the various sound sources within the study area. For example, mobile sound measurements can be carried out along the different roads within a study area, with the goal of better characterizing the spatial properties of the emission of road traffic. This would e.g. allow to account for the influence of vehicle stop-and-go behaviour on sound levels near intersections [13]. The measurement duration needed to characterize the emission of road traffic at a particular location for different times of the day will obviously depend on the the traffic intensity [14].

## 3. Paris case study

### 3.1. Study area

The 13th district of Paris is situated to the south of the city center, on the left bank of the River Seine, centered around the Place d'Italie roundabout. It has an area of about 7.15 km$^2$, and has about 180.000 inhabitants, part of which live in dwellings inside high-rise appartment buildings. Figure 2 shows a noise map ($L_{\text{den}}$) of the area (courtesy of the city of Paris). Most exposed façade noise levels exceed 55 dB(A) for the vast majority of dwellings inside the study area. However, inner courtyards, which provide lower noise levels, are available for at least part of the dwellings inside the area, thanks to the typical rowhouse architectural style.


Figure 2. Static noise map (distribution of $L_{\mathrm{den}}$) of the study area. The boundary of the study area is highlighted in blue.

Figure 3. Example of a fixed measurement station, placed on the windowsill of a dwelling.

### 3.2. Fixed measurement stations

The environmental sound inside the study area is monitored using 24 cost-effective ASASENSE measurement stations, placed at the façade of the dwellings of volunteers living in the area. Figure 3 shows an example of such a measurement station, placed on the windowsill. These devices consist of a single board computer, equiped with a CF card, a sound card, an ethernet card and a microphone, all put inside a weatherproof housing. The devices are fully *plug-and-measure*: installation only involves connecting the device to the power outlet and to the internet (the volunteers agreed to make their internet connection available); there are no buttons or displays on the measurement station.

The measurement stations log 1/3-octave band levels with a temporal resolution of 125 ms. Data is sent over the internet to the server infrastructure located in Ghent, Belgium, where the data is further processed. The data communication has some robustness built-in: if the internet connection fails, the devices save their data internally, and send the data in one batch once the internet connection is back online. Further processing of recorded sound levels is carried out using a server-side agent-based approach. For all data available at each location, a range of acoustical indicators is calculated on a 10-minute basis. These indicators include $L_{\mathrm{Aeq,10min}}$, needed for the dynamic mapping introduced in Section 2, as well as percentile levels, the number of sound events, indicators for the temporal and spectral structure of the sound [16], psychoacoustic indicators, etc. More details on the general sensor network architecture can be found in [12, 15].

Recruitment of participants within the 13th district of Paris was carried out by Bruitparif. Figure 4 shows an overview of the locations of the fixed measurement stations (blue stars), scattered over the study area. As of March 1, 2015, the measurement stations have already been active for about 6 months, resulting in about 120.000 hours of sound level data. The GRAFIC project aims to gather at least one full year of measurement data for dynamic mapping purposes.

### 3.3. Mobile measurement stations

Continuous, mobile sound level measurements are performed using five dedicated measurement stations,

Figure 4. Overview of the locations of the 24 fixed measurement stations, each marked with a blue star. The colored lines show the preliminary measurement results ($L_{\mathrm{Aeq,10s}}$) for the mobile measurements. The color scale is the same as in Figure 2.

carried by researchers performing walks through the study area. The devices are specially tailored for mobile measurements: they are mounted in a backpack, and are powered by a battery pack [17, 18]. Instantaneous 1/3-octave band levels are logged in the same way as with the fixed measurement stations. In addition, instantaneous GPS data is logged, such that the walks can be fully reconstructed afterwards. While measuring, participating researchers carrying the backpacks are asked not to disturb the acoustic environment; care is taken not to record footsteps and other undesirable sounds. As such, the mobile meaurements allow to perform a detailed spatial characterization of the various sound sources within the study area, increasing the spatial resolution of the noise map as described in Section 2.

Mobile sound measurements are still being carried out; to date about half of the study area has been covered, and about 24 h of mobile data has been gathered. Figure 4 shows an overview of the preliminary mobile measurement results. In order to smooth out the measurement data and to compensate for jitter in the GPS signal, results (sound levels and GPS locations) are aggregated over 10-second intervals.

## 4. Conclusion and perspectives

In this paper, a method to dynamically update noise maps based on fixed and mobile measurements is proposed. The model starts from reasonable good sound source and propagation models. Within the proposed approach, mobile measurements covering the full study area are used to increase the spatial resolution of the base map, whereas the data from a network of fixed measurement stations is used to create a dynamic noise map, which is periodically updated. The least mean squares method is applied for continuously tuning model parameters. To avoid an underdetermined system, the number of degrees of freedom is reduced by grouping the sources and propagation paths into broad categories. Source power and propagation attenuation are hereby corrected per category through a small offset that is dynamically adjusted.

The efficiency of the proposed method is currently being evaluated through a case study in the 13th district of Paris, France, carried out in the framework of the GRAFIC project. On the one hand, a network of twenty-four fixed sound measurement devices is installed in the area. On the other hand, mobile sound measurements using five portable measurement devices are being performed at regular times inside the study area, logging instantaneous 1/3-octave band levels as well as GPS data. Measurement data collection is still ongoing; once sufficient data is available, the next step will be to group modelled sound sources into broad categories. Road segments, to which road traffic noise sources are mapped, will be grouped based on an a priori classification of roads, but the use of automated clustering algorithms based on noise indicators measured along the road will be investigated, in order to obtain a categorization that fits more closely to the emission properties along the roads inside the study area.

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