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English summary

This short report is concerned with two related subtopics in long-range acoustical noise prediction: Atmospheric modelling and parametric uncertainty. It consists of summaries of recent research articles from the outdoor acoustics literature. Our motivation is to provide background material for ongoing work on noise prediction from military practice ranges.

Sammendrag

Denne korte rapporten omhandler to relaterte temaer innenfor prediksjon av langt-rekkende akustisk støy: Atmosfære-modellering og parameter-usikkerhet. Notatet består av sammendrag av artikler fra forskningslitteraturen om utendørsakustikk. Motivasjonen vår er å skaffe bakgrunnsmateriale for pågående arbeid med støyprediksjon fra militære øvingsfelt.

Contents

1 Introduction

We are currently investigating a new model for acoustic noise propagation from Military practice ranges. The aim is to improve accuracy for low frequencies and long ranges. The chosen model, a so called Parabolic Equation (PE) model, will enable us to incorporate quite general data, including range- and height dependent sound speed profiles, topography and range-dependent ground impedance. Obtaining adequate input data to the PE model is the topic of this note.

Atmospheric conditions are difficult to measure and predict, hence atmospheric modelling is a critical part of noise prediction. In this note, we survey literature on the topic from the perspective of long-range sound propagation. In fact, modern research in outdoor acoustics to a large extent consists of describing the environment, i.e. sound speed variation and ground properties. In addition, describing the sensitivity of sound levels to environmental parameters is important. With regards to acoustic ground effects, basic physical modelling is also an active research field. Two general references on outdoor sound propagation are the textbooks [1] and [34]. For more recent developments, a review is given in [49].

1.1 Scope

The purpose of this note is to summarise recent research papers relevant to two closely related topics:

1. The characterisation of weather on the scales that pertain to long-range sound propagation.
2. Uncertainty quantification and sensitivity analysis of long-range noise prediction.

The discussion is for the most part limited to the literature on outdoor acoustics. Ground effect is an additional significant source of uncertainty, hence a brief summary of ground effect modelling is included.

1.2 Definitions

Some notions and symbols are useful to define before starting the discussion. We denote the perturbation to ambient pressure by p. We work in Fourier space, so that p is a complex valued function of spatial location and frequency f. The relative sound pressure level is given in dB by

$$\Delta L = 10 \log_{10} \frac{|p|^2}{|p_{\text{free}}|^2}, \tag{1.1}$$

where p_{free} is the complex pressure in a homogeneous atmosphere unaffected by ground. By mean sound level in dB we refer to 10 times the logarithm of the mean square of p. It is common in computations to assume radial symmetry around a point source. The spatial coordinates then reduce to the vertical height z and horizontal range r. Sound speed is denoted by c and wave number by $k = 2\pi f/c$. Weather conditions affect sound level because c increases with temperature. Sound waves move at a speed $\mathbf{u} + c$, where $\mathbf{u}$ is the directional wind. Both wind and temperature are therefore crucial input parameters.

2 Parametric variability and uncertainty

A significant part of uncertainty in outdoor sound propagation is parametric, meaning that we are unable to know the exact input values, but we believe the model is otherwise accurate. For weather this is largely the case. There is parametric uncertainty in the ground models also, while the accuracy of the ground models themselves can be uncertain. Other example parameters are sound source location and topographical data. Source strength is independent of linear propagation and hence not discussed here.

In this section, we cover research articles that deal broadly with parametric variability in sound prediction. The core problem of sound level estimation is the (time-consuming) evaluation of a mapping $X \to \Delta L$, where X denotes the input parameters. If X can be assigned a probability distribution, then so can the sound level ΔL. The mapping from X to sound level ΔL (at a specific geographical location) can be referred to as a 'response surface'.

Typically, there are so many uncertain parameters that Monte Carlo sampling is the only viable computational method. In [48], for some scenarios Latin Hypercube Sampling (LHS) was reported to improve accuracy. For that work, there were six stochastically independent parameters representing uncertain data, and in addition there was a large parameter space describing the turbulent fluctuations in c. The same authors have suggested a systematic method for global sensitivity analysis based on LHS samples from a uniform distribution in [31]. They found that sensitivities differed a lot between upwind and downwind conditions. A technique known as cluster weighted modelling was used to characterise the response surface based on the LHS samples. A singular value decomposition of the sound level output samples was first performed to significantly reduce dimensionality. Fifty LHS samples were used, but the authors do not conclude clearly whether this was a sufficient number. As a quantification of sensitivity, derivatives with respect to the input parameters were estimated. Sensitivities for each of six input parameters (two for ground, four for weather) were plotted in (r, z)-space. The authors believed this approach to be more 'accurate and robust' than a competing method, a neural network algorithm.

The neural network algorithm in question was explored in [27] for flat terrain over ranges up to 900 m, and a frequency range of 2-200 Hz. The authors reported 'near instantaneous' evaluation of sound level given a source and receiver geometry. Ten input parameters were considered including a Monin-Obukhov vertical profile. Training the network with 27.000 PE calculations resulted in a RMS error of 2.42 dB (compared to a corresponding PE calculation). Atmospheric turbulence was included in [42], and there exists further work on the neural network algorithm in e.g. [26].

Alternatives to random sampling have been considered in the literature. A polynomial chaos method for the parabolic model was derived but not implemented and tested in [7]. A moment method was derived and tested in [46] for turbulence effects. It consists of solving a parabolic equation for the second order moment $\mathrm{E}[p(r,z)\overline{p}(r,z')]$. The equation was derived in [51]. The moment method converged faster than Monte Carlo but gave poor results for low sample counts. The authors concluded that it outperformed random sampling at low frequencies when accuracies better than about 0.3 dB were desired. This type of model was also studied in [5], where applied specifically to shadow zones.

If the parametric space is not too large, the response surface $X \to \Delta L$ can be characterised by evaluating on a grid and interpolating. This is known as a stochastic collocation method in the probabilistic setting. It was the basic strategy of [22]. The authors considered three parameters: Ground resistivity and two describing a log-lin sound speed profile. The approximate response surface was referred to as a 'metamodel', and had the advantage of being quickly evaluated. The sampling strategy was Cartesian with 1521 sample points for non-turbulent propagation. They also evaluated at 13 sample points (based on a 'Doehlert design') with turbulence, where the turbulence was modelled with costly Monte Carlo sampling. The 'metamodel' was used to provide various statistics and to calibrate the model parameters based on sound level measurements. The choice of the two weather parameters was found to yield over-fitting. The paper also proposes kriging (a statistical interpolation technique) as an interpolation method, specifically to interpolate the difference between measured and simulated data. Kriging was used similarly in [4]. Temporal covariation in measured sound signals was quantified in [3], with day- and night-time conditions studied separately.

3 Ground interaction

A thorough overview of acoustic ground models can be found in [1]. The most widely used ground model in outdoor acoustics is a rigid frame porous medium. Among those, the impedance model of Delany and Bazley ([6]) has been particularly successful, but several others are in use. The impedance model of [36] applies to lower frequencies than the Delany-Bazley model. It was used in [35].

These models assume that the ground is vertically homogeneous. In addition, the 'local reaction' assumption is typically used, which implies that the ground interaction reduces to the impedance boundary condition

$$p_z = -\frac{ik_a}{Z}p. \tag{3.1}$$

Hence, the sound waves in the ground do not have to be simulated. The specific impedance Z in (3.1) is a function of frequency and ground properties. As a next step, the ground can be described as a rigid porous layer of given thickness above a hard (fully reflecting) layer. An impedance boundary can be derived by using the grazing angle limit value of Z (see e.g. [18, 37]).

Another generalisation of (3.1) is to include elastic effects. In [24, 21] a layered poroelastic ground model is described and tested. The result is an impedance value Z that depends on both frequency and propagation angle (of a planar wave). There can be strong effects when sound speed coincides with the Rayleigh wave velocity. Effects of ground surface roughness and vegetation are also being researched. Generally speaking, ground roughness reduces sound level, and models exist that try to incorporate this effect in the impedance value Z (e.g. [1]).

The effect of a random impedance surface was considered in [29]. The impedance model had two random inputs. Spatial variation was not considered, with lack of data on spatial correlations given as a reason. They concluded that the problem could not in general be reduced to a deterministic problem.

4 Atmospheric refraction

For long range propagation, variation in atmospheric conditions cause sound level variations up to tens of dB. Fluctuations induced by shear and thermal instability can cause large variations over short time periods of seemingly constant weather conditions. At the other end of the temporal scale range, there are diurnal and seasonal variations. Typically, mean sound levels are sought. This topic can to some extent be considered a subset of micro- and mesoscale meteorology, but we have mostly restricted our attention to the acoustics research literature for this study. The section is divided into six subtopics. Note that research papers often address several of these subtopics.

4.1 Measurements

The Norwegian Trials were a series of measurements performed in the nineties in inland Southern Norway. The campaigns at Finnskogen in September 1994 and February 1996 stand out in the literature due to the presence of topography and the long ranges considered. Dense forest was the dominant vegetation. The September campaign experienced cloudy weather mixed with clear weather and moderate winds. Morning temperature inversions were observed on clear days. The February campaign was performed mostly during a cold period dominated by temperature inversion. Weather was measured with tethersondes and weather towers. Simultaneously, ground conditions and noise from controlled detonations were measured.

The weather data gathered during the Norwegian Trials are summarised in [15]. Several interesting observations are made. During the winter trials, conditions were found to be highly homogeneous in the horizontal directions. Simultaneous tethersonde experiments 12.5 km apart going up to 1300 m height are plotted. A jet seen at 700 m altitude was even found to be strongly correlated. In addition, from the summer trials, a time series from two weather stations 12 km apart and with an altitude difference of 20 m are shown to be near identical. The only exception was during night-time/morning inversions, when temperature sank more for the station lying in a depression. Even wind direction was strongly correlated.

The micro-meteorological effects of the forest was investigated with weather towers. The canopy appeared dense enough to capture a lot of the solar insolation, resulting in different temperature gradients below and directly above the tree top layer. During the September Finnskogen trial an interesting time series was measured by tethersonde consisting of a 300 m deep morning inversion as it is breaking up.

Comparison between noise measurements and FFP (a computational method) noise predictions were made for winter Haslemoen data in [17, 12]. The summer Haslemoen trials were considered in [16], where a poroelastic ground model was included. Noise prediction methods have been applied to the Finnskogen September trial data in [35]. Several algorithms were tested, including a Parabolic Equation method. One conclusion was that all methods overpredicted levels for low frequencies, especially below 10 Hz. Otherwise prediction accuracy varied from case to case, with some improvement observed from including terrain in the model.

A large scale measurement campaign of simultaneous sound and weather measurements is summarised in [25]. Sound signals from a controlled source were propagated over a flat and fairly homogeneous terrain and measured at 3 km range. The location was in interior Northern Finland. These measurements were performed every hour over a contiguous 20 month period. Extensive weather data were gathered with SODAR, weather balloons, a meteorological tower equipped with anemometers and synoptic observations. Ground impedance values are also given, one set for summer and one set for winter. Correlations between pairs of weather/ground parameters are given, as well as correlations between each single weather/ground parameter and noise response. Nine different regression models were considered for each parameter. Which parameter had the strongest correlation with noise, depended on frequency. Time of day and Pasquill category were generally important parameters. The median noise level for each Pasquill category varied with about 20 dB. Variability also changed markedly with Pasquill category at 80 Hz and higher. There was a distinct difference in median sound level of about 10 dB between day and night, at least at higher frequencies. At 80 Hz, and to some extent 160 Hz, this tendency was less clear, though, and variability was larger at night than in daytime. For higher frequencies on the other hand, variability was a bit larger during daytime. Histograms for sound levels in dB are shown for 40, 80, 160 Hz and higher. They look approximately normal with standard deviations about 9 dB. Histogram peaks are generally shifted slightly towards high noise level, though.

Low frequency propagation over a ’gently sloped’ range of 1300 m is reported in [43]. A 60 m weather tower measuring continuously is reported to have provided useful input to a PE simulation for 50 Hz, while tethersonde data were too erratic. At 150 Hz, the PE simulations were less successful. Scatterplots of sound level versus sound speed gradients demonstrate great variability. The experiments were performed at night during a temperature inversion and varying wind direction.

An interesting measurement campaign is described in [38]. Blast noise was measured over distances up to 16 km. Weather towers were employed, one along each of the three propagation paths considered. Two measurement series each were performed in flat desert terrain, and in temperate, ’hilly’ forest terrain. Different times of year were considered. A total of about 900 shots were fired during the campaign. Large variability was observed from 2 km, but variability does not appear to increase from 2 km. Typical diurnal variation patterns in sound level was not found, for which the absence of ’settled weather systems’ is given as an explanation.

A phenomenon termed ’the quiet height’ has been discussed in [41]. In simulations of strong downward refraction over soft ground there is a large vertical gradient in the sound level near ground. In particular, there is a certain height of a few meters at which sound level is 10-15 dB lower than at the ground. Flat topography and the frequency range 100-500 Hz was considered in [41]. The 'quiet height' then only appears after a range of a few hundred meters. For wide frequency bands it gets smoothed out. At large range an expression for the height that only depends on the sound speed profile is given, while the ground impedance value can be ignored. The authors give an argument that the quiet height is stable to sound speed fluctuations using an analytical model (which had no range dependence). An experiment involving a four meter vertical receiver array at 1.8 km range verified the theoretical model for the quiet height.

4.2 Analytical profiles

The Monin-Obukhov similarity theory provides a model for ensemble mean vertical weather profiles in the surface layer. The thickness of the surface layer can be up to 200 m, and varies a lot with the type of weather. This theory assumes flat and homogeneous terrain, hence it is difficult to apply to typical Norwegian conditions. It allows reconstruction of the sound speed profile from a few ground-based observations of mean quantities (but note that more data than a standard weather station provides are required to get at vertical fluxes). Discussions within the context of noise prediction are found in e.g. [1, 47] and [43].

The Monin-Obukhov sound speed profiles can be approximated by the log-lin profile

$$c(z) = c_0 + c_1 z/z_l + c_2 \log(z/z_0 + 1), \quad z_l = 1\text{m}. \tag{4.1}$$

The parameter z_0 is called the roughness length, and is regarded as a property of the terrain. A typical value for grassland is 0.1 m. For woodland 1-10 m is reasonable. A systematic study of the log-lin approximation is found in [8], where a year-long series of measurements from a 50 m tall weather tower (on a flat meadow) was fitted with a log-lin profiles. The authors found good agreement even under conditions that were more stable than the Monin-Obukhov theory allows. Construction of vertical profiles based on single height measurements was considered in [9], with cloud cover and time of day as additional input data. As a simple alternative, piecewise linear profiles representing worst case scenarios are suggested in [1]. Railway noise measurements at 200 m range are presented in [11] along with tethersonde measurements fitted with Monin-Obukhov similarity theory profiles.

The Haslemoen part of the Norwegian trials were performed in flatter and more homogeneous terrain than at Finnskogen. Hence it would be the most likely to conform to similarity theory or log-lin type profiles. Profiles resulting from averaging of the measurements are plotted in [15]. Several are clearly not well captured by log-lin profiles. It should be kept in mind that surface layer theory is not valid at the heights considered.

4.3 Turbulence and short-term fluctuations

Turbulence can be modelled as a stochastic fluctuation μ added to the refractive index c_0/c. Such a model and its numerical implementation is detailed in [34]. It represents homogeneous and isotropic turbulence. A Von Karman correlation function for the fluctuation μ is reported to work well. Temperature and wind fluctuations can be parametrised separately. The resulting 2D stochastic process is approximated by a finite sum of independent Fourier modes. Mean sound levels are calculated with Monte Carlo simulations. The important fluctuation modes are stated to be those on the scale of about one acoustic wavelength. Hence, this model should work well when the wave length is within the inertial range of the flow.

Turbulence has two major effects: Scattering acoustic energy into shadow regions, and perturbing interference patterns. This renders interference minima generally unpredictable, and shadow region sound levels easily underestimated. Often a minimum relative sound level is set at e.g. -20 dB, but no general rule exists for determining such a floor value. In order to avoid underestimation of the noise level in interference minima, averaging over a frequency band can help. In [5] shadow regions are studied numerically and some qualitative conclusions are made about sensitivities. Comparisons are made with parametrised approaches used in e.g. Harmonoise ([33]).

Monte Carlo sampling is computationally costly because convergence is slow: The error is inverse proportional to the square root of the number of samples. Some alternatives have been investigated as described in Section 2. In the case of turbulence, no significant improvements to Monte Carlo have been reported, though.

Generalisations to the homogeneous and anisotropic model have been presented in [50, 28]. It was found that the primary vertical length scale influencing propagation is height above ground, whereas horizontally it is the thickness of the boundary layer. Approximate formulas for the second order moment $\mathrm{E}[p(r,z)\overline{p}(r,z')]$ has been derived for simple geometries. In [30] temporal covariation in sound level was computed.

4.4 Meso- and microscale meteorological models

An alternative to analytical profiles and ground measurements is provided by meso- and microscale meteorological simulations. These simulations are three-dimensional, hence computationally intensive, but very general scenarios can be addressed.

Short-range (up to 100 m) propagation was studied in [23]. Topography and experimentally determined (strongly) range-dependent impedance was included in the simulations. Sound speed profiles used in the acoustic simulations were range-independent and only changed with perpendicular distance to the ground (a natural approximation due to a rotated Cartesian coordinate system). Logarithmic shapes were imposed on the lowest 5 meters. The authors noted that including the vertical component of velocity improved accuracy of acoustics simulation of interference patterns at higher frequencies (above 500 Hz, and increasingly important with range and wind speed). Excellent agreement with experiments was demonstrated at 25 and 75 m for 'moderately strong' downwind conditions. The simulated wind fields compared very favourably to local weather tower measurements. The authors further suggested combining local measurements with mesoscale simulations in order to characterize locally representative propagation conditions. They provided an example of this which is difficult to interpret. A similar experimental set-up was used in [2] to validate both a mesoscale model and an acoustic model (a 'transmission line matrix method').

A mesoscale simulation of an artificial valley was coupled with an acoustic simulation in [10]. Emphasis was on diurnal variation. A coastal area in the Netherlands has been studied with a meteorological-acoustical model in [39]. Annual noise level averages were calculated. The model and microphone measurements were compared in [40]. Five minute averages were used for measured sound levels, while simulated noise profiles were based on weather conditions 'representative for one hour'. There was fair agreement in the cases shown: Crosswind and headwind. Noise complaints were also seen to correlate with predicted high sound levels, which serves to validate the model.

In [14] the Haslemoen winter trial data were compared with FFP calculations using input from a mesoscale simulation. A day with strong wind conditions was considered, with geostrophic wind of strength 25 m/s. Simulated wind profiles were found to agree well with the tethersonde data up to 250 m, above which the wind was too strong to use the tethersonde. The measured weather profiles appeared smoother than the simulated profiles, otherwise good to fair agreement seems to have resulted. A morning inversion from the September Finnskogen trials was studied with mesoscale simulation in [13]. Fairly good agreement was found with measurements, except that the simulated inversion broke up too fast. Possible reasons and model improvements are discussed. Weather profiles calculated with the mesoscale method was used as input to FFP calculations, and the result is compared with sound levels based on tethersonde data. There were no associated acoustic measurements available.

4.5 Predictive skill of weather representation

In [44, 45] the predictive skills of various weather models were assessed. In order to have a detailed and realistic reference atmosphere, high resolution LES turbulence simulations were chosen. Various simplified range-independent weather profiles deduced from the LES data were used as input in an acoustic model. The resulting sound levels were compared to those resulting from using the full LES data set. The goal was to see whether sound levels could be predicted more accurately than with a neutral, windless atmosphere. Two major limitations of the study are a short range of 1 km, and a flat, homogeneous ground structure.

The authors concluded that weather information improved prediction of mean sound levels, and, to some extent, prediction of instantaneous sound levels. Vertical weather profiles based on both temporal and horizontal averaging performed better than local, instantaneous profile samples (with flat, homogeneous ground the horizontal averaging of sound speed has a similar effect to, and perhaps serves to improve accuracy of, temporal averaging). For predicting instantaneous sound levels, the average weather profiles gave more accurate predictions than local, instantaneous profiles. Some improvement from using global average profiles came from averaging only horizontally only along the propagation path, and not in time. Notably, this gave improved results in the shadow region. Monin-Obukhov similarity theory worked about equally well as the global average profiles, but that may be limited to the relatively short range of 1 km, which keeps propagation within the surface layer. The experiment demonstrated that local, instantaneous vertical profiles have limited value, since they did not improve on the neutral atmosphere simulations.

Several other main conclusions are worth summarising here. Interference patterns were not ’predictable in detail’, but averaging over a frequency band helped. The mean weather profiles underestimated sound level in shadow regions. Adding stochastic fluctuations to the refractive index was found to improve modelling of shadow regions and interference minima, but at great computational cost. A von Karman turbulence model was used, and the result perhaps serves as a validation of this model. It is interesting to note that overestimation in shadow regions was observed with instantaneous profiles. Evidently, the horizontal variability reduces scattering effect.

4.6 Describing weather variability

For long term noise mapping, it is essential to characterise weather variability. The term ’weather classification’ is often used. It is used broadly and could either mean weather types that represent the weather in general, or that represent different sound propagation conditions. Ideally, one wishes to have a probabilistic description of weather variability, so that statistics of sound levels can be calculated.

Pasquill categories have been employed for classifying acoustic propagation conditions as described in [1]. They are based on cloud cover and time of day/season. Signed wind strength should be used as a second parameter. This classification does not imply anything about the likelihood of any type of weather. It however captures a lot of sound level variability according to [25], with up to 20 dB variation in mean sound level between categories at (a flat) 3 km distance.

The measurements of [38] have been used to to study weather classification schemes in [32]. The Pasquill categories were found to not be useful in the temperate ’hilly’ terrain, but in the flat desert terrain there was a clear difference between stable and unstable categories. An alternative classification based on Monin-Obukhov similarity theory was also tested, and found to be useful in both climates. This classification scheme is based on the the effective sound speed gradient, and hence depends on propagation direction. The two approaches were also combined for a richer classification. Regarding the use of similarity theory, it does require somewhat sophisticated measurements and parametrisation, and the authors describe how it was done. It is also noteworthy that similarity theory is used with some success in hilly terrain, for which the theory possibly does not apply.

A stochastic model for local weather was derived from the weather tower measurements in [8] (described above). A log-lin model was used, resulting in two stochastic parameters. Cartesian sampling grids were proposed and it was found that a 5 by 5 grid was sufficient for calculating long-term mean sound levels. Most likely some form of piecewise constant interpolation was used between sample points.

In [19] the relationship between large scale atmospheric circulation and local gradients in sound and wind speed was studied. Pairs of automatic weather stations at different heights were positioned near a set of Norwegian shooting ranges. One station was placed near each range, and one on a nearby elevation, allowing a gradient to be calculated. The large scale weather was classified with circulation index (CI) according to the geostrophic wind direction and the sign of its curvature. It was found that temperature gradient could be reconstructed from time of day, season and CI. The exact relationship and its strength varied with location. Wind direction was connected to CI to varying extent with strong influence of topographic features etc. Wind speed could not be predicted from CI. Nevertheless, it was found that including CI improved prediction of effective sound speed gradients.

Temperature inversions are important to predict, due to the resulting downward increased noise levels. At the Rena practice range a warning system is in use ([20]). The predictions are based on statistical analysis of historical data from four weather stations located at various elevations in the area. Probability distributions for the gradients between each station pair was developed. A clear positive correlation was found between the different station pair gradients, hence inversion warnings are only given for the whole area as one.

5 Summary

Recent acoustics research articles on long-range sound propagation have been reviewed. The articles demonstrate that outdoor noise prediction is highly challenging due to random weather variability, with variations up to tens of dB reported. We highlight the following facts:

1. Propagation of instantaneous noise events such as explosions are not possible to predict accurately due to random weather variations.
2. Mean noise levels can be calculated with significantly improved accuracy given the right atmospheric data.
3. It is highly important how the weather is represented. Instantaneous, local profiles lead to overestimation of noise. Ensemble means should be sought.
4. Interference patterns due to ground effects are generally not possible to predict accurately.
5. Low-frequency narrow-band sound fields show a lot of structure just above soft ground, in particular a ’quiet height’. The predictability of the ’quiet height’ is an open question.
6. Shadow region sound levels can be calculated with stochastic turbulence models. However, no efficient computational techniques exist.

7. Pasquill category is an important parameter for flat ground propagation. In the non-flat case there is evidence of the contrary.
8. Local inversion conditions can in many cases be predicted from synoptic scale weather patterns.

Obtaining good weather data in the presence of terrain is particularly challenging, but the following conclusions can be made:

1. Meso-scale meteorological simulations can improve noise prediction in the presence of terrain.
2. Over non-flat terrain, there is little evidence in favour of analytical sound speed profiles such as Monin-Obukhov similarity theory and log-lin forms.
3. Measurements at Finnskogen indicate that the atmosphere is strongly horizontally homogeneous over at least ranges of 12 km. This provides support to the method of horizontal extrapolation from weather stations.
4. Long-range blast noise experimental campaigns in non-flat terrain and with atmospheric data have been performed in Norway and in the United States.

Computational algorithms for uncertainty quantification and sensitivity analysis are important tools due to atmospheric variability. Ground modelling also introduces uncertainty. Algorithms found in the literature include Monte Carlo sampling, latin hypercube sampling, simple grid-based sampling, cluster weighted modelling, Doehlert designs, neural networks and moment methods. Which algorithms are appropriate and efficient is problem-specific.

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