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# UNCERTAINTY OF INDUSTRIAL NOISE MEASUREMENT AT DISTANT LOCATIONS FROM THE SOURCE

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Methodologies for industry noise measurement usually include the range of weather conditions in which the measurements must be taken. The effects of meteorological conditions on sound propagation are small for short distances, and larger for longer distances at greater receiver and source heights.

One can find some algorithms in ISO 9613-1,2 for calculation of weather conditions impact on community noise, so called Cmet, but especially wind correction, is rather poor, limited to only two cases; moderate downwind and a variety of meteorological conditions as they exist over months or years. The problem begins in calculating long-term average A-weighted level using short-term data with unknown detail weather conditions on the path of sound propagation.

The paper deals with some real word data of partial uncertainties of noise prediction and measurement from large industry and impulse sound sources, taken in different meteorological conditions. It has been shown that in some cases maximum spread of the data exceeds 20 dB with the same state of industry running and completely similar weather conditions. In case of the impulse sources it has been shown uncertainty analysis for the impulse sound power and sound exposure level at reference distance of 1 km.

**Keywords:** uncertainty, industrial noise measurements, impulse noise, air absorption.

## 1. Introduction

The measurement procedures for environmental noise generated by industrial installations are specified in the so-called reference methodologies [6, 7]. In the methodology concerning the noise measurement some details are specified, like locations of measurement points, weather conditions in which the measurement should take place and the maximal extended uncertainty, which should not exceed 2.7 dB at 95% confidence level. On the other hand in the uncertainty budget for measurement and prediction of results in a given environment, according to Ishikawa diagram, one should take into account the environmental effects on both the measuring systems and the measured quantity. For the noise assessment case the measurement result will be affected by varying sound propagation conditions between the source and the measurement location, as well as variation of the source itself (e.g. the noise generated by the ventilation and air-conditions systems, coolers, or corona noise from the UHV power lines).

Among specifications of weather conditions in which the measurement should take place, considerable variation range of allowed temperatures, air humidity, atmospheric pressure and in particular wind speed (up to 5 m/s) may result in considerable spread of measurement results at long distances from the source, even if similar noise levels are recorded at the source location. However some of the weather conditions parameters are easily measured and exhibit rather stable behavior (during the measurement periods) while some other are difficult to measure (temperature gradient) and in addition may vary both in time and space (speed and direction of the wind) [1]. Considerable amount of space has been recently devoted to this problem in the HARMONOISE [3] and later IMAGINE [6] projects, in which the main attention has been focused on the measurement quality and modeling of air-traffic and industrial noise, and in particular on the effects of environmental conditions.

While the PN ISO 9613-1[4] contains the unified methods for calculation of sound attenuation effects during propagation in open space, together with algorithms used for determination of its atmospheric absorption in specific weather conditions, the applications of methods elaborated for pure tones for calculation of attenuation in frequency bands (octave or tertiary) by default introduces uncertainty of at least ±0.5 dB. Slightly better results are obtained from a method based on the spectrum integration. However in both cases detailed knowledge of the atmospheric conditions along the sound propagation path is required. In practice the most serious problem is posed by the absence of data concerning the actual direction and speed of the wind on the whole sound propagation path and temperature distribution as a function of altitude above the ground, which considerably affect the sound velocity component along the path to the receiver.

In uncertainty calculation for the LDWN noise factor in distant observation location, based on short time measurements, in addition to the work time characteristics of the source a considerable contribution is related to the detailed knowledge of weather conditions, in which the measurement has been carried out and the all-year probability distribution of occurrence of specific weather conditions, in particular the distribution of values of the wind speed component along the source-observation point direction.

The measurement results described in the present work, collected near one of the big industrial plants in Poland, show that even for similar weather conditions and working status of the plant, the spread of measurement results at 1 km distance exceeds 20 dB. The main reason of this divergence was variation of the wind direction, even for rather low wind speed values (up to 3 m/s).

In the paper partial uncertainty analysis has been presented for both measured and predicted values, obtained for steady noise near a big industrial plant and the impulse noise generated by high energy pulses, with particular attention focused on the effect of weather conditions and the spectral structure of the examined signal. For the case of pulse generated noise the uncertainty of its acoustic power and the reference level at 1 km distance have been determined.

## 2. Effects of weather conditions on the sound propagation in the open space

There are several meteorological effects that play roles in sound propagation. The most significant of these are atmospheric absorption, refraction, and scattering by atmospheric turbulence. Atmospheric absorption, due to the classical absorption and the molecular relaxation, causes a loss of energy, which depends mainly on frequency, temperature and humidity. The refraction of sound waves occurs in presence of sound speed gradient. This results in sound propagation along curved paths, what leads to ray focusing or defocusing as well as creation of shadow zones near the ground.

Several factors are important when sound waves propagate more-or-less horizontally near the ground. The basic problem can be envisaged as a sound radiating source located near the ground, a receiver that is usually located ca. 1.5 m above the ground, and a separation between the source and receiver that is relatively large compared with their altitudes above the ground.

The simplest effect of the ground on the sound field is that of interference between the direct and reflected sound fields. The processes of reflection and interference of sound waves near the ground surface depend not only on the geometrical arrangement but also on the vertical gradients of temperature and wind speed, particularly in several meters thick layer above the ground. The above mentioned gradients lead to corresponding gradients of the sound speed relative to the stationary ground.

At night the ground usually cools down by radiation emission faster than the atmosphere. The cooling spreads upwards with time. The sound speed is then grater at higher altitudes. In such a temperature inversion or for downwind propagation, a sound field curves downwards during propagation. If the vertical gradient of speed is constant, the paths of the sound are circular arcs. There can be an infinite number of such paths [2].

In the day time the ground is usually heated up by solar radiation and air nearest to the ground is heated by conduction, therefore it becomes progressively cooler with increasing height. Under these conditions sound speed decreases with height, the sound field bends upward during propagation and potentially creates a shadow region. Similar effects occur when sound propagates upwind.

While the effect of the above mentioned factors is well known and a proper quantitative correction is possible, in practice it is impossible to collect full information about the wind and temperature gradients, as well as the intensity of turbulence, which is always present in the near-to-ground layer, even in the zero-wind conditions and low values of vertical temperature gradient [2].

Taking the above into account one can reckon that incomplete knowledge of the actual distributions of temperature and wind speed is the dominant factor affecting the uncertainty of the acoustic pressure level measurement at long distance from the source, for both short- and long-term levels, including LDWN.

Average attenuation of acoustic pressure levels (simple tone of frequency $f$) caused by the atmospheric absorption is given by the formula (1) [8]

$$\delta L_i(f) = 10\log\left(\frac{p_i}{p_t}\right)^2 = \alpha s, \tag{1}$$

where $s$ – length of the sound propagation path, m; $\alpha$ – atmospheric attenuation coefficient for simple tones, dB/m. The value of this coefficient depends on relaxation frequencies of oxygen and nitrogen, which themselves are dependent on humidity, temperature and pressure of the air.

The value of the $\alpha$ coefficient can be determined for simple tones (mid-band frequencies e.g. for 1/3 octave bands) or by the spectrum integration method. The calculated values of this coefficient for simple tones, obtained from empirical formulas, can be found e.g. in Table 1, [8].

As can be found from that data e.g. for 500 Hz in the positive temperature range (5 to 30°C), the attenuation is rather insensitive to air humidity; it takes higher values at very low air humidity (for 10% the value is 4.25 dB/km), the values for average and higher humidity levels are similar and about 2.6–2.8 dB/km. Above and below that temperature range the attenuation noticeably decreases with increasing humidity. On the other hand for 50% humidity the lowest attenuation value is observed at 0°C temperature – 1.8 dB/km, higher values are observed in higher temperatures (e.g. 3.36 dB/km at +30°C) and in the negative temperature range (5.61 dB/km at $-15$°C).

Taking into account that the ambient temperature changes not only in one-year or 24 h cycles, but also as a function of altitude, in addition with varying gradient, it is incredibly difficult to evaluate its effect on the measurement result at longer distances from the source (several hundred meters).

Another method for determination of sound's atmospheric attenuation as a function of frequency, which is believed to be more accurate, is the spectrum integration method in application to broad-band sound attenuation calculations in 1/1 octave or narrower bands. Three cases are usually distinguished:

(1) known noise level at the source and attenuation along the path to the receiver required,
(2) known value at the reception point and evaluation of the sound level at source location required,
(3) known the measured level at the reception point in specific conditions, and the "reduction" to other weather condition is required.

From the meteorological point of view the case (3) seems to be the most useful, but in fact in all the cases the problem can be reduced to determination of the actual sound attenuation by the atmosphere in a given frequency band.

The total sound attenuation along the noise propagation path from a point source to the reception point, according to the PN ISO 9613-2 standard [5], is given by formula:

$$A = A_{\text{div}} + A_{\text{atm}} + A_{\text{gr}} + A_{\text{bar}} + A_{\text{misc}}\,, \tag{2}$$

where $A_{\mathrm{div}}$ – is the attenuation due to geometrical divergence, $A_{\mathrm{atm}}$ – attenuation due to atmospheric absorption, $A_{\mathrm{gr}}$ – attenuation due to ground effect, $A_{\mathrm{bar}}$ – attenuation due to a barrier, $A_{\mathrm{misc}}$ – attenuation due to miscellaneous other effects.

The standard mentioned above additionally introduces the so-called meteorological correction $(C_{\mathrm{met}})$ to calculation of the long-term levels $L_{\mathrm{AT(LT)}}$ for the case of downwind propagation. However the described algorithms are rather crude and do not refer to the wind speed, but only to the altitudes of the sound source and reception point in relation to their (horizontal) distance. The presented exemplary calculations of accuracy for the correction determination are contained in the $\pm 3$ dB range, whereas the value of the correction itself rarely exceeds 5 dB.

In the light of rules contained in the standard [5] one could conclude that the effect of weather conditions is not so important, however on the other hand when analyzing the experimental data shown in the present work, as well as the results contained in paper [11] quite different conclusions can be drawn.

The situation is even more complicated for the case of high-energy impulse noise emissions, characterized by low-frequency spectral structure (weakly attenuated by the atmosphere) and high sound levels with adversity range reaching even up to 30 km. The above mentioned conditional effects are the reason that in practice it is the weather conditions and not the original excitation level that determine the impact range of the impulse noise emissions in the environment [12].

## 3. Experimental research

### 3.1. *Measurement methodology*

The paper contains the results of a steady-state noise study, carried out near a great industrial plant in Poland and a study of impulse noise emissions caused by high-energy pulses – blasts of explosive materials [12].

For the steady-state noise the measurement points have been situated at the outer border of the plant area (reference points) and in the environment, in the noise evaluation locations. The measurements have been carried out simultaneously with time recording of acoustic events inside the plant area. The $L_{Aeq}$, $L_{A\,\mathrm{max}}$, $L_{A\,\mathrm{min}}$ levels have been measured at 5 min. intervals in the reference points and the reception points in the environment, with exact registration of the measurement time. In an independent measurement the acoustic data have been registered in buffers with time resolution of 1 s. Together with the acoustic data the basic parameters related to weather conditions have been measured: ambient temperature, air humidity and pressure, as well as the direction and speed of the wind.

The above mentioned methodology enabled the determination of sound attenuation along the path between the reference point and the reception point in given weather conditions.

For the case of the impulse noise the measurements have been carried simultaneously in two or three points. One of these points was always a reference point situated at 1 km distance from the source while the other points were evaluation points situated at 6 to 18 km from the source. The multispectra have been measured in 1/3 octave bands in the range from 8 Hz to 20 kHz, with the time resolution of 200 ms [12]. It allowed a more accurate (in relation to a direct method) determination of the exposition levels (SEL) from individual acoustic events. (individual explosions) after rejection of the recording sections which were not directly related to the examined event, however with band reduction in the low frequency range.

### *3.2. Results*

*Steady-state noise*. Figure 1 below contains exemplary time dependencies (taken from 5 different measurement sessions) of acoustic pressure level variation in reference point REF1, both in daytime and night-time. The values of averaged levels and standard deviations in all reference points (REF1, 2, 3) are shown in Table 1.

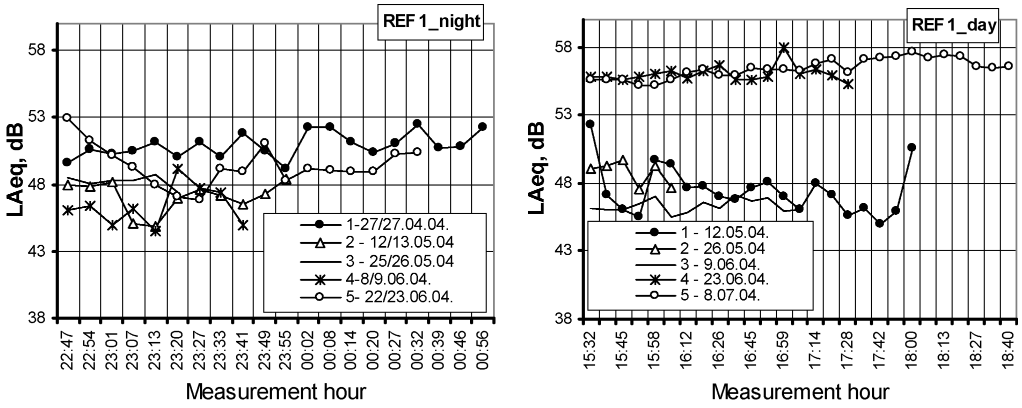


Fig. 1. Variation of noise equivalent levels in reference point REF1 in night-time and daytime, taken from 5 measurement sessions.

As can be noticed, especially in daytime, two clearly separable states of the plant activity (in that particular area) can be distinguished, with level difference of about 10 dB. In the night-time the spread of the results is greater and no distinguishable data aggregation can be noticed.

Similar tendencies in the distribution of the results (in various sessions) are also observed in the other reference points, and the differences in reference levels vary between a few dB and more than ten dB.

The results described above show, that during studies of the environment transmittance between plant area border (reference point) and evaluation point in the surrounding environment, it is necessary to measure simultaneously (preferably in time synchronization) both in the reference and evaluation point. This suggestion is additionally supported by the results shown in Table 2, where the results are gathered from 19 measurement sessions carried out over long time period. In column 22 the differences between the maximal and minimal sound equivalent level values are shown from all the

19 sessions in a given reference point. As it can be seen in some reference points the differences even exceed the 20 dB value and in fact it cannot be determined what is the actual reason of such effects. Is it the varying state of the plant activity (rather improbable because of high number of sound sources – about 1000), or is it the variation of the weather conditions.

**Table 1.** Noise measurement results in reference points.

| Noise measurement results in reference points | | | | | | | |
|---|---|---|---|---|---|---|---|
| LP | serie/time of the day | REF1 | | REF2 | | REF3 | |
| | | $L_{Aeq,ave(i)}$ | $\delta_{REF1}$ | $L_{Aeqave(i)}$ | $\delta_{REF2}$ | $L_{Aeq,śr(i)}$ | $\delta_{REF3}$ |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| 1 | **daytime** | | | | | | |
| 2 | **1** | 47.9 | 1.68 | 59.1 | 4.73 | 48.7 | 0.57 |
| 3 | **2** | 48.8 | 0.93 | 54.9 | 2.09 | 46.8 | 0.52 |
| 4 | **3** | 46.3 | 0.49 | 52.8 | 0.99 | 48.7 | 0.57 |
| 5 | **4** | 56.1 | 0.61 | 54.2 | 4.31 | 53.4 | 0.36 |
| 6 | **5** | 56.5 | 0.53 | 50 | 0.38 | 55 | 0.26 |
| 7 | $L_{Aeq,ave}$ | **53.2** | | **55.3** | | **51.7** | |
| 8 | $\delta_{Lśr}$ | **4.8** | | **3.3** | | **3.5** | |
| 9 | **nighttime** | | | | | | |
| 10 | **1** | 51 | 0.96 | 52.2 | 1.65 | 56.2 | 1.69 |
| 11 | **2** | 47.2 | 1.17 | 61.2 | 0.13 | 54.9 | 0.45 |
| 12 | **3** | 48.2 | 0.45 | 60.2 | 0.25 | 45.9 | 0.42 |
| 13 | **4** | 46.6 | 1.51 | 48.7 | 0.63 | 51.8 | 0.06 |
| 14 | **5** | 49.7 | 1.52 | 55.9 | 1.81 | 56.1 | 0.68 |
| 15 | $L_{Aeq,ave}$ | **48.8** | | **57.8** | | **54.2** | |
| 16 | $\delta_{Lśr}$ | **1.8** | | **5.3** | | **4.3** | |

$\delta_{Laver}$ - standard deviation of the results in particular reference point

The answer to this question (partial at least) can be obtained by measuring simultaneously the noise in at least two points (including one reference point) and monitoring the activity of the loudest noise sources within the plant area.

**Table 2.** Results of measurements collected in near vicinity of an industrial plant over a longer (two year) period of time.

| Measurement results gathered in vicinity of an industrial plant during night time | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Point No | No of measurement sessions | | | | | | | | | | | | | | | | | | LAeq,ave | $\delta_{LAeq}$ | ΔL |
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | | | |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 21 | 22 |
| **1** | 42.4 | 45.8 | 40.8 | 38.7 | 45.9 | 46 | 48 | 36.8 | 47.4 | 50.8 | 46.1 | 48.5 | 50 | 47.3 | 43.4 | 41.9 | 43.6 | 45.3 | 44.8 | **46.2** | **3.6** | **14.0** |
| **2** | 45.7 | 44.9 | 41.8 | 35.4 | 47.5 | 50.8 | 49.2 | 35.6 | 49.4 | 51.1 | 39.8 | 49.6 | 50.2 | 48.1 | 44.0 | 43.2 | 46.7 | 41.5 | 43.4 | **47.1** | **4.7** | **15.7** |
| **3** | 45.8 | 39.7 | 40.9 | 39.8 | 44.3 | 49.5 | 48.5 | 46.4 | 48.2 | | 38.9 | 47 | | 42.1 | 45.8 | 38.2 | 47.1 | 36.0 | 42.4 | **45.2** | **4.0** | **13.5** |
| **4** | 47.4 | 39.6 | 44.8 | 38.8 | 46.3 | | 45.9 | 33.7 | 47 | 48.2 | 41 | 44.5 | | 36.2 | 48.8 | 39.4 | 48.1 | 33.3 | 46.2 | **45.0** | **5.1** | **15.6** |
| **5** | 41.7 | 39.2 | 37.6 | 40.8 | 41.6 | | 45.1 | 35.4 | 48.5 | 49.8 | 48.4 | 46.7 | | 41.9 | 43.9 | 38.2 | 45.7 | | 41.3 | **44.7** | **4.1** | **14.4** |
| **6** | 43.6 | 37.8 | 43.8 | 38.4 | 39 | 47.7 | 46.8 | 31 | 49.6 | | 45.8 | 45.3 | | 38.6 | 46.1 | 42.2 | | | 42.9 | **44.5** | **4.7** | **18.6** |
| **7** | 41.6 | 37.5 | 33 | 45.2 | 40.5 | 46.8 | 44.9 | 42.2 | 48.8 | 44.9 | 41.7 | 42.8 | | | 42.5 | 45.9 | | | 42.6 | **44.0** | **3.7** | **15.8** |
| **8** | 38.9 | 27.4 | 30.2 | 37.8 | 40.5 | 44.8 | 38.9 | 30.2 | 45.8 | 43.3 | 40 | 37.2 | | | 44.2 | 47.1 | | | 42.7 | **42.0** | **5.8** | **19.7** |
| **9** | 40.2 | 29 | 33.9 | 46.8 | 45.1 | 50.4 | 44.1 | 36.6 | 48.9 | 48.1 | 47.3 | 39.3 | 48.9 | | 46.5 | | 44.3 | | 45.4 | **45.9** | **5.9** | **21.4** |
| **10** | 41.2 | 33.1 | 49.2 | 48.4 | 38.5 | 53 | 43.6 | 44.7 | 51.7 | 53.6 | 51 | 39.9 | 49.2 | | 50.4 | | 43.6 | 46.2 | 53.9 | **49.3** | **5.8** | **20.8** |

$\delta_{LAeq}$ - standard deviation, dB

ΔL - the diffrenece between the maximum and the mininum of the measured LEQ values, $L_{Aeq}$

In continuation the results contained in Tables 3 and 4 are the differences between the reference level and the level measured at the environment location in a given instance of time, in daytime and night-time respectively.

**Table 3.** The level differences between the reference points and points in environment locations. Daytime.

**The level differences between the reference levels in points REF1 to REF3 and points 1 to 10 in environmental locations.**

**Daytime**

| Lp | Points | | The level differences **ΔL**, in the following measurement sessions, dB | | | | | **ΔL,ave** | $\delta_{\Delta Lave}$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | **1** | **2** | **3** | **4** | **5** | | |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | **1** | **REF1** | 7.2 | 2.1 | 2.9 | 9.8 | 12.6 | **8.7** | 4.5 |
| 2 | **2** | | 4.2 | 3.1 | 3.2 | 12.0 | 16.1 | **11.0** | 6.0 |
| 3 | **3** | | 8.6 | 3.9 | 6.7 | 9.8 | 13.3 | **9.6** | 3.5 |
| 4 | **4** | | 9.6 | 3.8 | 6.2 | 12.0 | 12.7 | **10.0** | 3.8 |
| 5 | **5** | | 13.9 | 7.4 | 14.5 | 10.0 | 14.5 | **12.9** | 3.2 |
| 6 | **6** | **REF2** | 17.3 | 5.2 | 11.9 | 10.4 | 11.2 | **12.9** | 4.3 |
| 7 | **7** | | 21.9 | 14.0 | 9.3 | 13.6 | 6.4 | **16.3** | 5.8 |
| 8 | **8** | | 28.6 | 16.3 | 10.1 | 9.7 | 7.2 | **22.0** | 8.6 |
| 9 | **9** | | 29.9 | 15.7 | 6.9 | 10.2 | 4.0 | **23.2** | 10.2 |
| 10 | **10** | **REf3** | 8.8 | 5.7 | 5.9 | 3.5 | 2.8 | **5.9** | 2.4 |
| 11 | **wind/temp.** | measurement point | 0,5-2,8, NNE-NW | 0,5-3,SW-NW | 0,5-2,3,N-NW W | 1-3,S-NW | 1-3,E-SE | | |
| 12 | | | | | | | | | |
| 13 | | | 15-20 °C | 13-17 °C | 17-23 °C | 21-27 °C | 21-28 °C | | |
| 14 | | weather station | 0,5-2,3,NW | 1,6-4,5,W | 0,5-1,8,NW-NE | 2-3,S | 2,5-4,8,E-SE | | |
| 15 | | | | | | | | | |

ΔL - the average difference between LEQ in the reference level and in the environmental location , $\Delta L=L_{AREF}-L_{Ax}$

$\delta_{\Delta Lave}$ - standard deviation

**Table 4.** The level differences between the reference points and points in environment locations. Night-time.

**The level differences between the reference levels in points REF1 to REF3 and points 1 to 10 in environmental locations.**

**Night time**

| No | Point | | The level differences **ΔL**, in the following measurement sessions, dB | | | | | **ΔL,ave** | $\delta_{\Delta Lave}$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | **1** | **2** | **3** | **4** | **5** | | |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 1 | **1** | **REF1** | 7.6 | 5.4 | 4.6 | 1.3 | 4.8 | **5.2** | 2.3 |
| 2 | **2** | | 7.0 | 4.0 | 1.5 | 5.1 | 6.3 | **5.2** | 2.2 |
| 3 | **3** | | 5.2 | 9.0 | 1.1 | 10.6 | 7.3 | **7.7** | 3.7 |
| 4 | **4** | | 2.2 | 7.8 | 0.2 | 13.4 | 3.5 | **8.1** | 5.3 |
| 5 | **5** | | 7.1 | 9.0 | 2.5 | | 8.4 | **7.3** | 2.9 |
| 6 | **6** | **REF2** | 4.9 | 5.0 | 8.0 | | 6.7 | **6.4** | 1.5 |
| 7 | **7** | | 9.6 | 15.3 | | | 13.3 | **12.1** | 2.9 |
| 8 | **8** | | 7.9 | 14.1 | | | 13.2 | **11.3** | 3.3 |
| 9 | **9** | | 5.7 | | | | 10.5 | **6.3** | 3.4 |
| 10 | **10** | **REf3** | 5.8 | | 4.7 | 5.6 | 2.3 | **2.3** | 1.6 |
| 11 | **wind/temp.** | measurement point | 0,5-2,3 NE | 0-2,4 NE-NNE | 0,5-2,9 W-SW | 1,3-2 NNW | 0-0,5 NE-NW | | |
| 12 | | | | | | | | | |
| 13 | | | 7-10 °C | 12-14 °C | 7-10 °C | 10-14 °C | 12-18 °C | | |
| 14 | | weather station | 1,1-2,5 NE-SE | 0,6-2 SW-S-E | 0,5-1,3 W-SW | 1-2,6 NNW | 0,5-1,E-SE | | |
| 15 | | | | | | | | | |

ΔL - the average difference between LEQ in the reference level and in the environmental location , $\Delta L=L_{AREF}-L_{Ax}$

$\delta_{\Delta Lave}$ - standard deviation

The tables also contain the results of direction and speed of the wind at the time of the measurement, both in the measurement point and the weather station located near the plant area.

As can be noticed, taking into account the locations of the measurement points in relation to the direction of blowing wind, a considerable differences are observed in the attenuation along the path between a given reference point and the environment measurement location for situations with wind direction favorable and adverse for the sound propagation, even for low wind speed values

In daytime the greatest difference in the medium attenuation has been observed for the case of adverse winds (NW–SE) for points 7, 8, 9 and 2 (sessions no. 1 and 5) and its value spanned from 12 dB in point 2 up to 25 dB in point 9.

The above mentioned results indicate that exactly the speed and direction of the wind determine the noise distribution in the vicinity of the examined plant, while the other factors, like temperature, are practically negligible, mainly because of relatively low distances from the source – 1 to 1.5 km at most, and rather low spreading of temperature values.

*Impulse noise.* The environmental impact ranges, and as a consequence, the distances of the measurement points from the source are much bigger than for the steady-state noise. Very often the adversity ranges exceed the 10 km distance. Therefore the propagation of the impact noise to the environment to such long distances depends in practice merely on the weather conditions, including both the wind and temperature factors. Exemplary measurement results for impulse noise emissions are listed in Table 5.

**Table 5.** Results of impulse sound measurements.

| **Results of impulse sound measuremets** | | | | | | |
|---|---|---|---|---|---|---|
| Blasting No | **Sound exposure levels (SEL) A i C, dB** | | | | Reference mass (of TNT), kg | WIND |
| | REF1 (0,855 km) | | Receiver 1 (9,02 km), SSE | | | |
| | A | C | A | C | | |
| 1 | 87.2 | 114.2 | 59.1 | 80.0 | 300 | 1.3 WSW |
| 2 | 87.6 | 113.7 | 57.2 | 80.1 | 150 | 3.7 SSW |
| 3 | 89.1 | 115.0 | 58.8 | 85.2 | 150 | 2.5 S |
| 4 | 90.1 | 115.3 | 61.1 | 88.0 | 450 | 4 SSW |
| Average | **88.6** | **114.6** | **59.3** | **84.6** | | |
| Std.dev. | 1.3 | 0.7 | 1.6 | 3.9 | | |
| Level due to geometric divergence | | | **68.2** | **94.1** | | |
| Atmospheric and excess attenuation, dB/km | | | 1.09 | 1.16 | | |
| | REF2 (4,63 km) | | Receiver 2 (18,1 km), NNW | | | |
| 5 | 76.5 | 103.2 | 55.2 | 81.3 | 300.0 | 0 S |
| 6 | 75.9 | 102.5 | 58.6 | 80.4 | 300.0 | 0.8 W |
| 7 | 74.7 | 98.0 | 59.1 | 87.2 | 300.0 | 1 SW |
| 8 | 81.6 | 106.1 | 53.3 | 83.1 | 300.0 | 0.6 ESE |
| Average | **78.1** | **103.3** | **57.2** | **83.9** | | |
| Std.dev. | 3.1 | 3.3 | 2.8 | 3.0 | | |
| Level due to geometric divergence | | | **66.3** | **91.5** | | |
| Atmospheric and excess attenuation, dB/km | | | 0.68 | 0.56 | | |

The results listed in Table 5 indicate a strong relation between the speed of the wind and the total attenuation (excluding the attenuation resulting from the geometrical divergence) related to 1 km distance.

## 4. Analysis of measurement uncertainty

If the measured or predicted noise level depends on many input values then the final results is a function of many arguments [13]:

$$L_{wy} = f(X_{we1} + X_{we2} + ... + X_{wem}) \tag{3}$$

everyone of which carries some standard uncertainty $U(_{Xwei})$.

Combined standard uncertainty $U_{c(Lwe)}$, under assumption that individual arguments in formula (4) are independent, can be calculated using the formula (4):

$$u_c(L_{wy}) = \sqrt{\sum_{i=1}^{m} \left(\frac{\partial f}{\partial X_{wei}}\right)^2 u^2(X_{wei})}\,. \tag{4}$$

The uncertainty provided together with the measurement result is a multiplicity of the combined standard uncertainty and is usually called an extended uncertainty. The final result of a completed measurement is usually written in the following form:

$$L_k = L_{wy} \pm U(L_{wy}), \tag{5}$$

where $U_{(Lwy)} = kU_{c(Lwy)}$.

The value of the extension coefficient $k$ is taken in accordance with the confidence level attributed to the assumed uncertainty range.

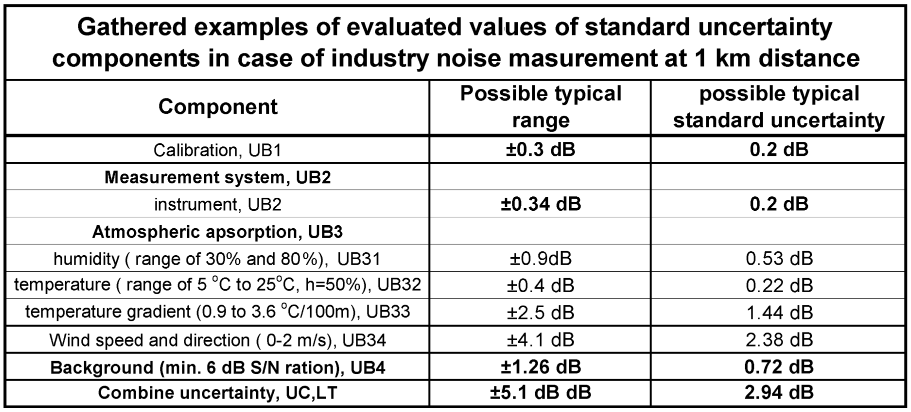
For calculation of the combined standard uncertainty it is necessary to determine the uncertainties of the partial components, related to all the input quantities, which affect the measured or predicted result, with a given form of the statistical distribution.

A more accurate analysis of uncertainty of the measurement system can be found in paper [13], but in the present work the attention has been focused on the uncertainty related to the variability of weather conditions, still all factors have been included in the uncertainty budget.

For short-term noise measurements it can be assumed that the weather conditions – temperature, air humidity and atmospheric pressure are similar, and only the direction and speed of the wind may vary, and its influence on the measurement result in each measurement point (around the plant area) is different, depending on the instantaneous value of the wind's direction and speed. In practice the vertical temperature gradient is also unknown, however it can be assumed that at the measurement time it can be approximated as constant along the whole path of the sound wave propagation, therefore the uncertainty related to the temperature gradient will be similar in all points. Assuming homogeneity of the medium, in which the sound propagates, its anisotropy will be related only to the direction and speed of the wind. Estimation of the partial uncertainty related to the wind effect is difficult, mainly because of its variability along the sound wave propagation path, but it is possible in cases when the values are measured simultaneously in all directions, with additional assumptions as specified above.

Taking into account the spatial layout of the measurement points and the obtained results it has been determined that the maximum error (wind effect correction) of the sound propagation (with wind varying between 0 and 2 m/s) is 4.1 dB/km. The standard uncertainty has been obtained as $U = 2.36$ dB/km. Exemplary listing of the uncertainty budget is shown in Table 6.

**Table 6.** Results of impulse sound measurements.



**Gathered examples of evaluated values of standard uncertainty components in case of industry noise masurement at 1 km distance**

| **Component** | **Possible typical range** | **possible typical standard uncertainty** |
|---|---|---|
| Calibration, UB1 | **±0.3 dB** | **0.2 dB** |
| **Measurement system, UB2** | | |
| instrument, UB2 | **±0.34 dB** | **0.2 dB** |
| **Atmospheric apsorption, UB3** | | |
| humidity ( range of 30% and 80%), UB31 | ±0.9dB | 0.53 dB |
| temperature ( range of 5 °C to 25°C, h=50%), UB32 | ±0.4 dB | 0.22 dB |
| temperature gradient (0.9 to 3.6 °C/100m), UB33 | ±2.5 dB | 1.44 dB |
| Wind speed and direction ( 0-2 m/s), UB34 | ±4.1 dB | 2.38 dB |
| **Background (min. 6 dB S/N ration), UB4** | **±1.26 dB** | **0.72 dB** |
| **Combine uncertainty, UC,LT** | **±5.1 dB dB** | **2.94 dB** |

From the uncertainty budget shown in Table 6 it can be noticed that definitely the dominant role is played by the wind effect, even for low wind intensities, and the temperature gradient. To much less extent the measurement result is affected by the air temperature and humidity, which additionally can be measured with sufficient precision.

Taking the above into account it can be easily noticed that at distances above 1 km the spreading of the results, even for small changes in the wind speed and direction and temperature gradient, can be as big as 5 dB. In extreme cases, as shown in paper [4], it can even reach 42 dB.

## 5. Conclusions

The measurement results included in this work indicate a strong relation between the wind direction and air temperature gradient, and the noise measurement result at long distances from the plant – 1 km or higher. Whereas the above-mentioned relations have been studied for years and is well described in the literature [2, 3], in real measurement conditions many problems are encountered in determination of the wind speed and direction along the whole sound propagation path, especially when the wind speed is rather small. In practice it is also difficult to measure properly the vertical temperature gradient, and these two factors are the dominant ones affecting the long-distance sound wave propagation.

In spite of the fact that the log-lin wind and temperature profile given by MONIN and OBUKHOV [14] exists, which quite well approximates the distribution of these quantities in the near-to-ground layer, it is much better to carry out direct measurements of these quantities in various, preferably all, classes of weather conditions, if one wants to plan and execute measurements of long-term noise levels at long distances from the source.

Taking into account the obtained results it should be concluded that the simultaneous measurement in reference points and environment reception points, limiting the effects of the noise source variability, is very important, however such approach looses some of its effectiveness in the cases when wide-spread noise sources are examined.

For the case of impulse sources the measurement should be carried out simultaneously in all the points – the reference and reception points, as well as specified sections, with accompanying wind monitoring in all the measurement points.

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