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PAPER

On the ability of consumer electronics microphones for environmental noise monitoring

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The massive production of microphones for consumer electronics, and the shift from dedicated processing hardware to PC-based systems, opens the way to build affordable, extensive noise measurement networks. Applications include *e.g.* noise limit and urban soundscape monitoring, and validation of calculated noise maps. Microphones are the critical components of such a network. Therefore, in a first step, some basic characteristics of 8 microphones, distributed over a wide range of price classes, were measured in a standardized way in an anechoic chamber. In a next step, a thorough evaluation was made of the ability of these microphones to be used for environmental noise monitoring. This was done during a continuous, half-year lasting outdoor experiment, characterized by a wide variety of meteorological conditions. While some microphones failed during the course of this test, it was shown that it is possible to identify cheap microphones that highly correlate to the reference microphone during the full test period. When the deviations are expressed in total A-weighted (road traffic) noise levels, values of less than 1 dBA are obtained, in excess to the deviation amongst reference microphones themselves.

Introduction

Noise annoyance is a major environmental problem in urbanized regions. Exposure to traffic noise is associated with a wide range of negative effects on human health and well-being. It was estimated that outside their homes, near 44% of the European population (in the year 2000) was exposed to road traffic noise levels above the World Health Organization's threshold for onset of negative health effects.[1] Examples of the adverse effects of exposure to traffic noise are not only annoyance,[2] but also sleep disturbance,[3,4] negative impacts on cognitive functioning (especially in children)[5] and the contribution to cardiovascular diseases.[6,7]

The European Environmental Noise Directive[8] obliges each member state to make noise maps of, amongst others, their major highways and highly populated agglomerations. A noise map is most often a calculation exercise, showing an estimation of long-term averaged noise levels with a fine spatial resolution. Based on such maps, action plans have to be proposed for problem areas.

However, producing accurate city noise maps is a hard task. The complexity of the sound propagation problem in a densely build-up environment is high.[9] Typically, geometrical acoustics approaches are applied for noise mapping calculations. However, even in a single street, a large number of multiple

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Environmental impact

Noise pollution is an increasingly growing threat for the well-being and the public health in industrialized countries. Although the large advances made in predicting tools for noise exposure assessment during the last decades, the full complexity of the sound propagation problem, together with an accurate representation of the distribution of noise sources, is most often not sufficiently captured in an urban environment. Therefore, measurements are still an important tool for assessing the public's exposure to noise. The work presented in this paper shows that the large cost for extended noise monitoring networks can be strongly reduced by using microphones appearing in consumer electronics devices. It was shown that it is possible to identify such microphones that result in only small level differences compared to reference equipment, making them useful in many environmental noise monitoring applications.

reflections between façades (bordering the street) is needed,[10] leading to very long computing times. In practice, the maximum number of reflections taken into account is most often set to a fixed number to limit computing times; this decision is usually not based on accuracy considerations. At shielded locations, predicting correct levels with a noise mapping calculation method is even more problematic.[11] Besides computational and propagation related issues, a good estimation of the relevant noise sources and their spatial and temporal distribution is needed given the fact that the acoustic environment is strongly source-driven. Most often, noise maps highly rely on the output of traffic models, inducing additional uncertainties.

Taking these problems into account, validation of such city noise maps with measurements seems necessary. Although the technology exists for noise measurement networks, their application is very limited by the high cost of logging units and sensors (microphones) found on the (commercial) market nowadays.

Two recent evolutions could lead to an affordable noise monitoring network. Nowadays, microphones appear a lot in consumer electronics (like mobile phones, laptops, portable digital music players, *etc.*) and hearing aids. Due to mass production, such devices come at a (very) low price. The microphone technology of these cheaper devices is nevertheless very similar to the technology of high-quality measurement microphones.

A second interesting evolution is that the processing and logging of the raw signal produced by the microphone capsule are shifted from dedicated hardware to PC-based systems. Of special interest are the so-called Single Board Computers (SBCs). Such devices can be seen as stripped-down integrated PCs, with all basic functionalities, but with a more limited computational performance. When equipping these with a sound card and a network card, they are well-suited as nodes in a noise measurement network. Furthermore, such SBCs use low-power processing units, making them suitable for networked low-power applications.

The price difference between cheaper approaches and dedicated measurement microphones and logging hardware is huge, and can easily exceed a factor of 100. In this paper, it is studied to what extent such cheaper noise measurement systems can be used for environmental noise monitoring. The studies presented in ref. 12 and 13 have similar interests in affordable noise monitoring networks.

In this paper, results of the detailed testing of such cheap microphones are presented. In a first step, the performance of SBCs as logging units and microphones of different price classes is checked in an anechoic chamber. The main focus in this paper is on a half-year lasting outdoor test near a busy road. The noise levels obtained by the cheaper variants were compared with simultaneous time-synchronized measurements with high-quality equipment.

In this introduction, the validation of city noise maps is presented as a useful environmental application of an extensive noise measurement network. It is clear that applications are manifold, and could range from noise monitoring near industrial facilities to prevent neighbourhood complaints in an early stage to *e.g.* community-based noise monitoring near airports.

Selecting microphones and logging unit

Eight on-shelf and off-shelf microphones, distributed over a wide range of price classes, were tested. An overview of some basic characteristics is given in Table 1. All of these, except for one (the MEMS microphone, see further), use pre-polarized condenser microphone technology (also called electret microphones).

Professional measurement microphones can be categorized into different accuracy classes, according to some preset norms.[14] Types 0, I, and II are usually distinguished. With increasing type number, accuracy goals become less strict. These goals deal *e.g.* with a change in sensitivity in function of angle of incidence on the microphone membrane, or the maximum change in observed output after 1 hour in a constant sound field. Two professional

Table 1 Product details, prices and measured noise floors of the 8 selected microphones

ID	Type	Membrane diameter	Microphone sensitivity[a] (dB re 1 V Pa^{-1})	Frequency range[a]	Power supply	Cost (including pre-amplification where needed)	Noise floor at 1 kHz (measured)
ELECTRET1	Electret	<1/8″	−45 dB	20 Hz to 20 kHz	Line powering	1 €	35 dB
ELECTRET2	Electret	<1/8″	−68 dB	20 Hz to 10 kHz	Line powering	3 €	41 dB
ELECTRET3	Electret	<1/8″	−40 dB	100 Hz to 10 kHz	Line powering	30 €	32 dB
ELECTRET4	Electret	<1/8″	−40 dB	40 Hz to 15 kHz	Line powering	50 €	36 dB
MEMS1	MEMS	<1/8″	−32 dB	100 Hz to 6 kHz	Line powering	30 €	23 dB
TYPEII	Electret	1/4″	−26 dB	20 Hz to 20 kHz	ICP preamplifier	300 €	15 dB
REF1	Electret	1/2″	−26 dB	3.5 Hz to 20 kHz	ICP preamplifier	2000 €	15 dB
REF2	Electret	1/2″	−26 dB	6.3 Hz to 20 kHz	ICP preamplifier	2000 €	13 dB

[a] Following product sheets.

high-quality (type I) measurement microphones were included in the test (further indicated by REF1 and REF2). These will serve as reference equipment producing the ground truth noise level. A professional low-noise pre-amplifier with an Integrated Circuit Piezoelectric (ICP) feeding is used to complete the measurement chain. For operation outdoors, a professional outdoor protection unit (including windscreen and rain protection) is used. Next, a type II microphone was added to the test as well (indicated further by TYPEII). The microphone capsule was delivered integrated with a pre-amplifier and an outdoor protection unit. ICP feeding was needed here as well.

Next, 5 non-dedicated measurement microphones were considered. A main advantage of these devices is that pre-amplification is not needed. To make such microphones operational, a small RC-circuit was built. In this way, the output voltage of a PC sound card could be used ("line powering"). As the sensitivity of these microphones differs, an adequate amplification factor for the sound card was set to select an operational amplitude range. Three microphones fell in the price range from 30 to 50 Euro; these are two electret microphones (ELECTRET3 and ELECTRET4) and one MEMS microphone. A MEMS (micro-electrical–mechanical system) microphone is a recent type of microphone technology.[15] Here, the pressure sensitive membrane is etched directly on the chip itself. It has a similar working mechanism as a common electret microphone. Finally, two very cheap electret microphones were selected (ELECTRET1 and ELECTRET2) of only a few Euros. For these 5 devices, self-fabricated rain-caps and windscreens were made.

It is clear that the prices shown in Table 1 are indicative, and are subject to (often rapid) market evolutions. Note that only microphone capsules and pre-amplifiers (where needed) are taken into account. For microphone TYPEII, the outdoor unit is included in the price. Furthermore, the prices given for the professional measurement microphones contain research and development costs. Without taking these aspects into account, the cost ratio between the cheapest and most expensive microphone exceeds roughly 1000.

The logging and processing of the raw microphone data were performed with a SBC. The choice of the specific SBC was a compromise between its price, robustness (*e.g.* the absence of moving hardware parts like fans and hard disk drives), energy consumption, and past experience with this type of system board. The SBC has a 500 MHz AMD Geode processor, and was equipped with 256 MB DDR DRAM. An audio-card was placed on the board with a signal-to-noise ratio exceeding 100 dB (18 bit resolution), and delivers a microphone feeding voltage measured at 1.5 V. The total energy consumption when performing noise measurements is near 5 W. The full cost of the SBC is about 100 Euro. For the processing of the raw microphone signal, the Euterpe software platform[16] running under a Microsoft Windows XP operating system was used. Since this processing is rather computational intensive, each microphone needs its own SBC.

Indoor testing

The specifications provided by the microphone product sheets cannot be easily used for inter-comparison and relevant information is often lacking, mainly for the very cheap variants. Furthermore, the full measurement chain (including pre-amplifiers where needed, ICP feeding, RC-circuit, the sound card of the SBC, weather protection, *etc.*) determines the behaviour. Therefore, in a first step, some basic characteristics are measured in a standardized way in a full anechoic chamber. In all cases, normal incident sound on the microphone membrane is considered. Of main interest are the noise floor (lowest sound pressure level that can be measured, which is limited by instrumentation noise in the circuit), saturation level (highest sound pressure level that can be measured, limited by the maximum movement of the membrane), and flatness of the frequency response and linearity (similarity of the sensitivity at different sound frequencies and sound pressure levels).

Calibration was performed in various ways. The measurement microphones could be directly calibrated by putting a 1/2″ pistonphone (Svantek SV30A, operating at 94 dB, producing a pure tone of 1 kHz) on the microphone capsule. Microphones ELECTRET4 and MEMS1 were designed in such a way that the pressure sensitive membrane is located at the end of a rigid 1/2″ cylinder, at its centre. In this way, a standard pistonphone can still be used for calibration. ELECTRET1, ELECTRET2, and ELECTRET3 had another design. For these, a free field calibration was performed in a full anechoic chamber. These microphones were placed directly beside a reference microphone, and an intense 1 kHz pure tone was produced by the loudspeaker in front of them. The exact level measured at the reference microphone (which was calibrated in advance) was then used for the microphone to be calibrated. For similarity, a level near 94 dB was used as well.

In a first step, the quality of the SBC and integrated sound card was checked. Two identical type I reference microphones (Bruel and Kjaer type 4189 microphone capsule) and pre-amplifiers were placed directly beside each other, close to a loudspeaker in the anechoic chamber. One reference microphone was connected to a dedicated noise measurement hardware system (Bruel and Kjaer PULSE software system, with front-end type 3560C), the other one to the SBC (with an additional ICP feeding). Both logging systems were put outside the anechoic chamber to prevent noise generated by instrumentation fans. Both pink noise and a 1 kHz pure tone were produced by the loudspeaker, at various intensities. The only difference that could be observed was a very small increase in the noise floor in the measurement based on the SBC (for a 1 kHz pure tone, there was an increase from 11 dB to 13 dB). Since these are extremely low levels, the quality of the SBC was considered to be very good.

For the detailed testing, each microphone under test was connected to a SBC. The amplification factor of the sound card determines the dynamic range of the measurements. In a first test, this factor was set as high as possible, without increasing the noise floor relative to lower amplification values. This resulted in fractions near 0.2 to 0.3 of the maximum possible amplification. The reference noise level in the indoor test (REF0) is in all cases provided by the reference microphone (Bruel and Kjaer type 4189 microphone capsule) connected to the dedicated noise measurement hardware system (Bruel and Kjaer PULSE software system, with front-end type 3560C).

Test results are shown in Table 1 and Fig. 1. Saturation near 100 dB was not observed for any of the microphones. As for the noise floor, significant differences between the various

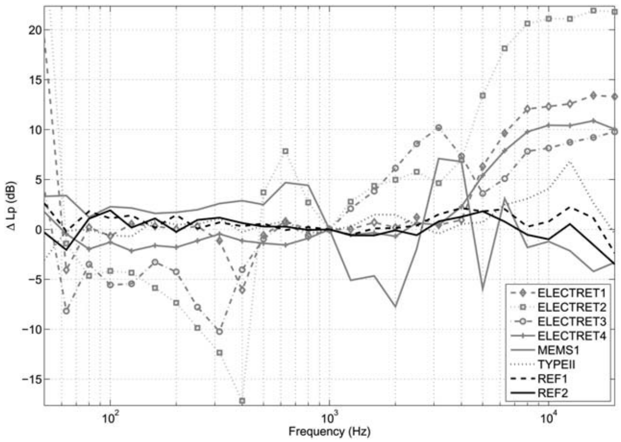

Fig. 1 Frequency response of the tested microphones as measured in an anechoic chamber for pink noise with a total sound pressure level of 70 dBA (measured at REF0), relative to REF0. The level difference at the 1 kHz 1/3 octave band between REF0 and the tested microphones is used as a constant factor to correct other 1/3 octave band values.

microphones could be measured. For a 1 kHz pure tone, the noise floors of the measurement microphones (REF1, REF2 and TYPEII) are smaller than or equal to 15 dB. The much cheaper MEMS microphone has a noise floor of only 23 dB. For the other electret microphones, noise floors are significantly higher. ELECTRET1, ELECTRET3 and ELECTRET4 have noise floors between 32 and 36 dB. ELECTRET2 has a noise floor exceeding 40 dB for the 1 kHz pure tone.

The frequency-dependent microphone sensitivity at 70 dBA (measured at REF0) is shown in Fig. 1. Pink noise was emitted by the loudspeaker over the full audible frequency range. The level difference at the 1 kHz 1/3 octave band between REF0 and the tested microphones is used as a constant factor to correct other 1/3 octave band levels. REF1 and REF2 have an almost flat response up to 10 kHz. The TYPEII microphone gives a deviation of a few dB at 10 kHz. ELECTRET1 and ELECTRET4 have a reasonably flat response up to a few kHz. At 10 kHz, a deviation above 10 dB is measured for both. The MEMS microphone, ELECTRET2 and ELECTRET3 show strong deviations from flatness over the sound frequency range considered.

Total sound pressure levels ranging from 50 dBA till 90 dBA were considered for assessing linearity in the frequency response. A linear response means that the deviations from a flat frequency response are independent of the total sound pressure level at the microphone. Highly linear behaviour is found for REF1, REF2, and TYPEII over the full audible range (not shown). For MEMS1, highly linear behaviour is observed up to 10 kHz. For ELECTRET1, ELECTRET3, and ELECTRET4, linearity of the frequency response is limited to 3–4 kHz. ELECTRET2 has a non-linear behaviour over the full frequency range.

In general, it can be concluded that both the frequency response and noise floor are related to the price of the microphone. With increasing cost, the noise floor decreases and the frequency response becomes more flat and linear. The non-flat frequency response can be corrected for to some extent in the processing software assuming that it is stable over time. Combining several microphones at the same measurement node, while applying cross-correlation techniques, is a possibility to reduce the noise floor. However, such operations complicate the signal processing in the data acquisition equipment too much for our application.

Outdoor testing

Measurement setup

Weather resistance and wearing can only be realistically tested outdoors. Therefore, a half-year lasting outdoor test was set up. A sufficiently long test period is needed to assess the microphone performance in various weather conditions, and to check cumulative weather effects. The experiment started at December, 21 in 2009 and ended at June, 30 in 2010.

All microphones were attached next to each other on a 2 m wide horizontal bar on the roof of the Zuiderpoort-building in the city of Ghent (Belgium), with direct view towards a busy viaduct (at about 150 m, at an almost equal height as the roof level and parallel to the test bar). The average microphone height was 1.7 m relative to roof level. The hourly equivalent total sound pressure levels are at most days limited to 65 dBA during daytime, and drop to 50 dBA during the calmest hours at night. A typical hourly equivalent frequency spectrum during morning rush hour is depicted in Fig. 2.

A photograph of the test setup is shown in Fig. 3. At the ends of the test bar, REF1 and REF2 microphones were placed. The other microphones were placed in between them. The use of two reference microphones will provide certainty on the correct level, and will also show the measurement difference over time that occurs even when using best available techniques to measure sound pressure levels. Since both reference microphones are located at the ends of the bar, the maximum difference in sound pressure level by the non-coinciding location is accounted for as well.

In front of the test bar, an outdoor loudspeaker (Bose Free-Space 360P series II) was placed. At fixed times (twice a day, at 10.00 h and 22.00 h) 10 s pink noise events were emitted, with sufficient energy in the 1/3 octave bands from 100 Hz to 10 kHz, relative to the environmental noise levels. This is done since the dominant traffic noise at the test location is rather limited in frequency content, with small day-by-day variability. In this way, the variation in spectral sensitivity over time could be checked over a broader frequency range. The distance between the loudspeaker and the test bar was 3.5 m.

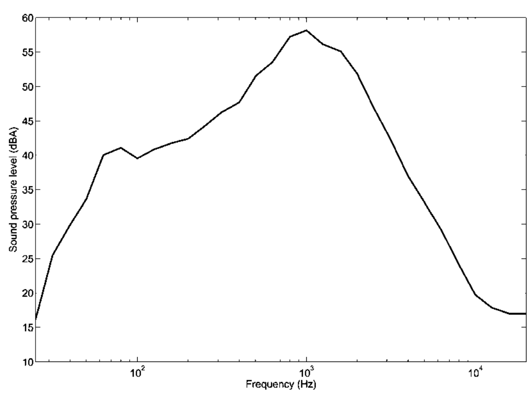

Fig. 2 Typical hourly equivalent spectrum measured at REF1 during morning rush hour.

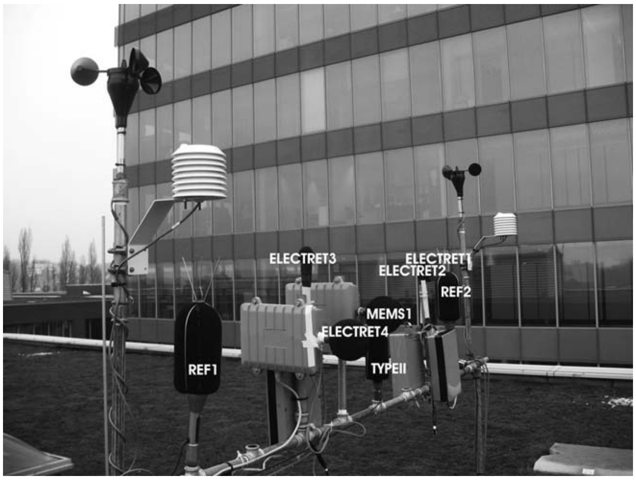

Fig. 3 Photograph of test bar showing the tested microphones and some meteorological sensors.

On-site meteorological data was measured. The local wind speed and air temperature were recorded with sensors, placed at both ends of the test bar (see Fig. 3). Other relevant meteorological parameters like relative humidity and rainfall intensity were obtained from a meteorological observation station (above roof level) at 1.3 km from the test bar. Hourly averaged meteorological data are available during the full monitoring period. The winter period was characterized by long freezing periods, and mostly high relative humidity values. The minimum air temperature recorded near the microphones was -10 °C; the maximum air temperature exceeded 30 °C. Wind speeds were mostly limited, and were at maximum 6 m s^{-1}. The cumulative rainfall intensity during the test period was 136 mm.

The basic logging consisted of 1 s equivalent sound pressure levels, expressed in 1/3 octave bands. Each microphone was connected to its own SBC. All SBCs were connected in a small computer network. The clocks of the SBCs were synchronized by a network time protocol (ntp) server.

The calibration values as obtained from the indoor test were used, since exactly the same measurement chains were applied for each microphone. It was chosen not to have (hard) calibration moments during the experiment (see further for more details on this aspect).

Results

Results of the outdoor test were analysed by means of correlation analysis and by calculating the long-term average level difference between the microphones under test and one of the reference microphones (REF1). Similar measures were used in ref. 17 for the comparison of noise dosimeters. Furthermore, the influence of meteorological parameters and the temporal frequency-dependent variability are further explored.

Correlation analysis

Linear correlation analysis between the synchronized time series of two microphones shows how well the course over time is followed. The correlation between each microphone under test and REF1 is calculated, for each hour separately during the test period. The hourly correlation coefficient (R^2) over time for total A-weighted sound pressure levels is depicted in Fig. 4 for each microphone separately. These same data are shown in a more condensed way by means of the cumulative distribution curves in Fig. 5. The results in Fig. 4 show that the R^2-values can change significantly from hour to hour. Also when comparing both reference microphones (REF1 and REF2), correlation coefficients deviate from the optimal value of 1. Fig. 4 shows *e.g.* that ELECTRET2 and ELECTRET3 failed in February. ELECTRET1 failed at the end of June. During a sufficiently long period, these microphones did not show any correlation with the reference microphone. These microphones were removed from the test at the end of month where failure was observed.

All microphones, except for ELECTRET2 and ELECTRET3, have a limited fraction of data at low correlation classes. The second reference microphone, REF2, has only 2.5% of data with a correlation coefficient R^2 lower than 0.9. At this same correlation value, ELECTRET4, TYPEII, ELECTRET1, and MEMS1 have a cumulative fraction of 9.5%, 15.8%, 16.9%, and 21.7%, respectively.

Although the large difference in cost, ELECTRET4 shows better hour-by-hour correlation with REF1 than TYPEII. ELECTRET1 has a similar steep slope in the cumulative distribution curve starting from $R^2 = 0.9$ as also observed in the case of ELECTRET4 or TYPEII; the higher fraction at very low correlation values is caused by the period with microphone failure near the end of the outdoor experiment.

Deviations in measured overall sound levels

A more practical quality measure is a long-term averaged estimation of the error in dBA when using a particular type of microphone. Although all devices were calibrated, the measured sound pressure levels in the first hours of operation outdoors were set equal to REF1. In this way, the difference in location of the microphones on the test bar, and the influence by the presence of the other microphones (*e.g.* reflection and scattering of sound waves on their housings) will be levelled out. This virtual calibration can be done in different ways. In a first approach (*approach a*), only the total A-weighted level difference is adjusted for. In the second approach (*approach b*), the different frequency responses are taken into account. A correction factor

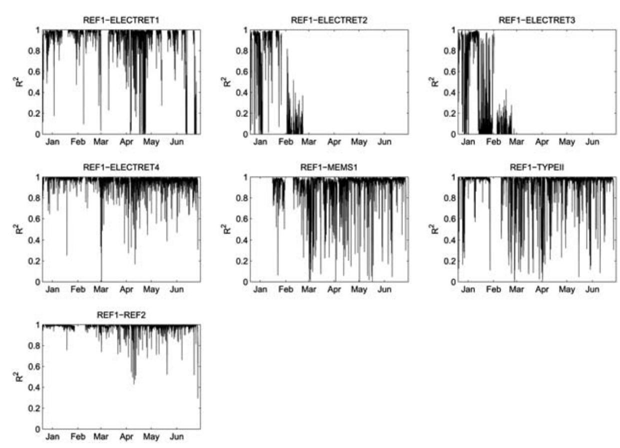

Fig. 4 Hour-by-hour correlation coefficients R^2 between each tested microphone and REF1 during the full monitoring period.

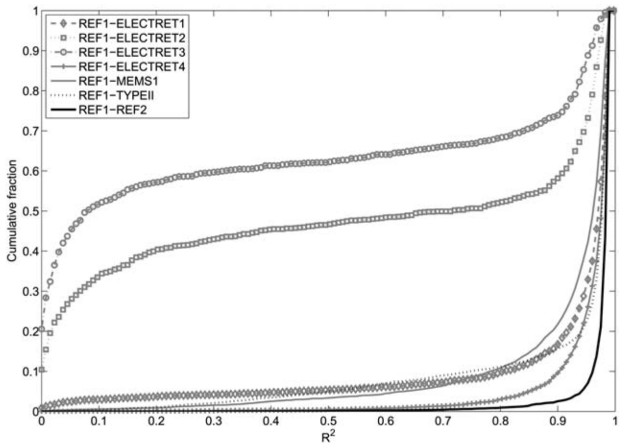

Fig. 5 Cumulative distribution curves of the correlation coefficients R^2 between each tested microphone and REF1.

is then calculated for each 1/3 octave band separately. This additional virtual calibration was not performed during the correlation analysis since a fixed offset in level between two microphones will not influence the correlation coefficients. In practice, regular calibration is common in long-term noise monitoring. Therefore, the effect of on-site (virtual) calibration at the beginning of each month on the global error is assessed as well.

Results for the globally averaged error (based on hourly equivalent total A-weighted sound pressure levels) for each tested microphone, relative to REF1, are given in Table 2. The values in between brackets are the standard deviations. The graphs in Fig. 6 show the evolution over time by means of monthly averaged errors for the single and month-by-month virtual calibrations, combined with approaches a and b.

For the one-time on-site calibration at the beginning of the experiment, the global error obtained in dBA over the full monitoring period at REF2, relative to REF1, amounts to 0.7 dBA. When applying a month-by-month calibration, this error reduces to 0.5 dBA. These will be the minimum errors that can be expected with the cheaper microphones. Even with "best available techniques", there is still a non-negligible variability in the measured noise levels. The TYPEII microphone gives a global error of 1.0 dBA. Monthly calibration leads to a slight increase in the error. ELECTRET4 and ELECTRET1 give similar errors for the one-time calibration of 1.6 dBA. For multiple calibrations, this deviation relative to the reference microphone reduces to respectively 1.3 and 1.5 dBA. Such deviations are still acceptable, certainly in light of the variation observed between reference microphones. The other microphones in the test resulted in much higher errors. MEMS1, ELECTRET2 and ELECTRET3 give 2.8 dBA, 4.3 dBA, and 6.6 dBA, respectively (single calibration, approach a). The MEMS1 microphone leads to much higher errors in the case of a month-by-month calibration. The reason for this will be explained when discussing meteorological effects on microphone performance (see next section). The behaviour of ELECTRET3 is hardly affected by month-by-month calibration, while for ELECTRET2 an improvement is observed relative to a single calibration in time. For MEMS1, ELECTRET2, and ELECTRET3, small differences between applying approach a and approach b are observed, in contrast to the other microphones in the test. For these 3 microphones, the frequency response differs much more from flatness than for the others. However, approach b does not decrease the overall error, relative to approach a. A main cause for this is the presence of a very dominant traffic noise source at our location, characterized by limited variation in frequency content over time. At locations with a variety of other noise sources, it is expected that approach b will lead to an improvement, relative to approach a.

When looking at the evolution of monthly averaged errors for REF2, there is an increasing trend. In the beginning of the test, errors were very minor (<0.3 dBA), but they exceed 1 dBA starting from June 2010. Month-by-month calibration seems to temper this increase to a limited extent only.

The error produced by the TYPEII microphone is very constant (near 1 dBA) during the monitoring period. ELECTRET4 had a very limited deviation relative to REF1 in the first 3 months of the experiment (0.5 dBA) and stayed between 1 and 2 dBA during the rest of the experiment. Month-by-month calibration seems especially interesting to limit errors in the second half of the monitoring period and could result in a decrease in the error of near 0.5 dBA relative to the one-moment calibration at the beginning of the experiment. The deviation produced by ELECTRET1 stayed constant near 1 dBA in the first few months of the experiment, but gradually increased starting from March on. In June, errors exceeded 2 dBA in all calibration approaches considered, caused by microphone failure.

ELECTRET2 and ELECTRET3 do not seem to be suited for long-term outdoor noise monitoring. While in December 2009

Table 2 Averaged, hourly equivalent total sound pressure level in dBA during the full monitoring period (from the middle of December 2009 until the end of June 2010), relative to REF1. Results are shown for a single (virtual) calibration at the beginning of the experiment, and for a monthly (virtual) calibration. Approach a corrects for total sound pressure level only, approach b takes into account the possible non-flat (location-dependent) frequency response. The values in between brackets are the standard deviations

	Single calibration in time		Month-by-month calibration	
ID	Approach a (dBA)	Approach b (dBA)	Approach a (dBA)	Approach b (dBA)
ELECTRET1	1.6 (2.0)	1.6 (2.2)	1.5 (2.0)	1.5 (2.3)
ELECTRET2	4.3 (4.1)	4.5 (4.5)	3.7 (3.6)	3.7 (4.2)
ELECTRET3	6.6 (7.1)	7.2 (7.8)	6.6 (7.1)	7.3 (8.4)
ELECTRET4	1.6 (1.5)	1.6 (1.5)	1.3 (0.9)	1.3 (0.9)
MEMS1	2.8 (3.2)	2.9 (3.4)	5.5 (7.5)	5.9 (7.7)
TYPEII	1.0 (0.9)	1.0 (0.9)	1.2 (1.0)	1.1 (1.0)
REF2	0.7 (0.6)	0.7 (0.6)	0.5 (0.5)	0.5 (0.5)

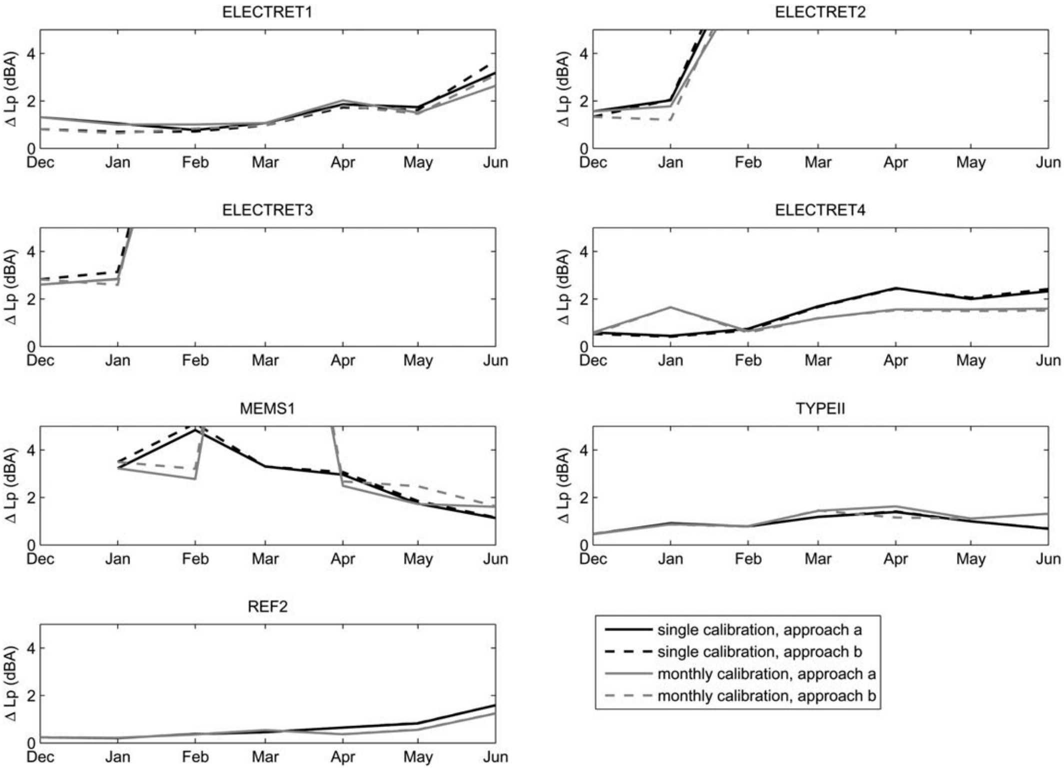

Fig. 6 Month-by-month evolution of the deviation of the tested microphones, relative to REF1, for monthly averaged, hourly equivalent total sound pressure levels. Single and monthly calibrations are considered, combined with approaches a and b.

and January 2010 a constant error was observed, it increased tremendously during February (which is, however, the month of the failures, while data of the full month are included here). Even the error in the beginning of the experiment was high, especially in the case of ELECTRET3.

The MEMS1 microphone shows a completely different course of the error over time. While in the first half of the experiment very high errors were observed, an error of only 1 dBA (relative to REF1) remained near the end of the experiment.

Influence of meteorological parameters

In Fig. 7, scatter plots between the error relative to REF1 and the measured on-site air temperature are presented for some of the tested microphones. Microphones that failed during the monitoring period are not considered here. Results for the one-moment calibration and approach b are used. In Fig. 8 and 9, the influence of relative humidity and local wind speed is shown.

The hourly equivalent level difference between the reference microphones REF1 and REF2 shows no dependence on the meteorological parameters measured. The difference between microphone TYPEII and REF1 shows only a very small dependence on temperature and relative humidity. ELECTRET4 is strongly (negatively) correlated with temperature, and positively correlated with relative humidity. Note, however, that at the test location, air temperature and relative humidity are strongly correlated as well. With increasing air temperature, relative humidity decreases. MEMS1 shows inconsistent behaviour at air temperatures below 20 °C, and similarly at high relative humidity values, while a very limited error is found at higher temperatures. This is consistent with the trend towards smaller errors starting from May 2010, as shown in Fig. 6. If periods with inconsistent behaviour occur during the moments of (monthly) calibration, high errors in the rest of the month can be expected. This seems to be the reason for the high errors observed in the case of month-by-month calibration of the MEMS1 microphone (see Table 2).

As an example, the effect of applying a simple temperature correction for ELECTRET4 on the global error is assessed. The best-fitted, linear regression curve reads $C = -0.174T + 0.113$,

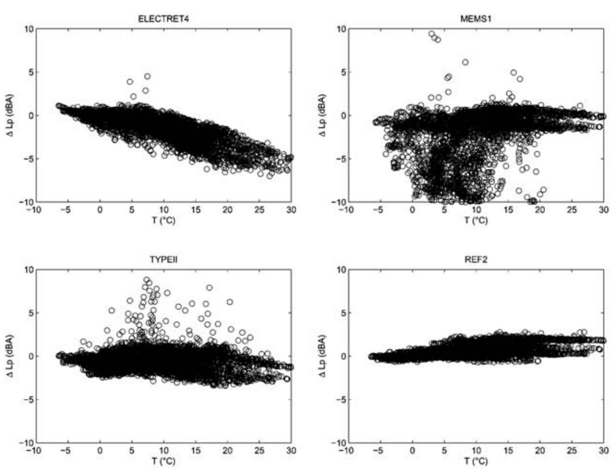

Fig. 7 Scatter plots between air temperature T and the difference between the selected microphones and REF1, for the single moment calibration using approach b. The full monitoring period is considered.

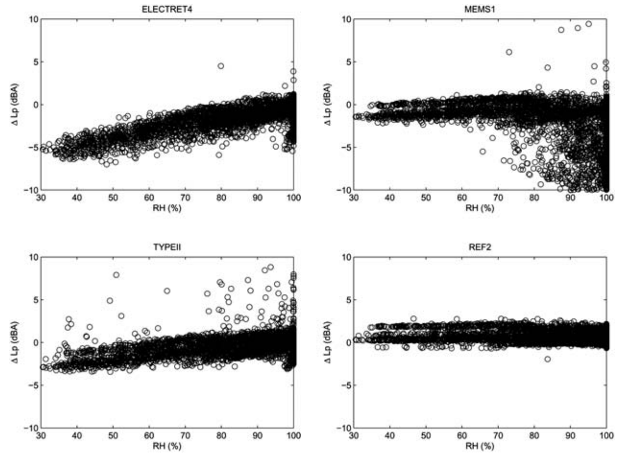

Fig. 8 See caption of Fig. 7, but now for relative humidity, indicated by RH.

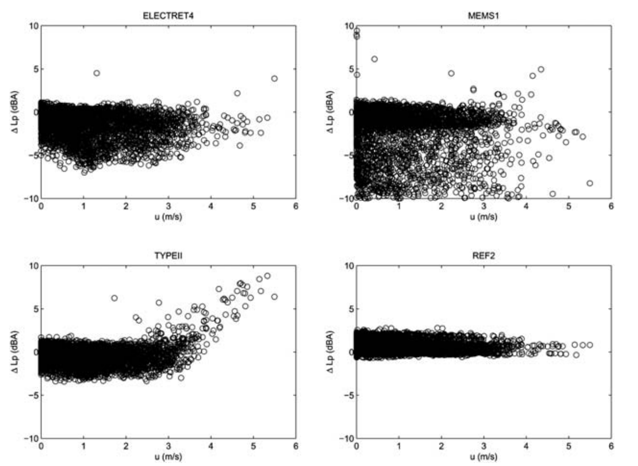

Fig. 9 See caption of Fig. 7, but now for the magnitude of the on-site wind speed, indicated by *u*.

where C is the correction factor to be subtracted from the ELECTRET4 data when considering total hourly equivalent sound pressure levels in dBA, and T is the on-site air temperature expressed in °C. The correlation coefficient R of this regression line equals −0.79. Note that the intercept depends on the meteorological conditions at the moment of calibration. Since air temperature and relative humidity are also correlated at the test site ($R = -0.73$), correcting for a single parameter was found to be sufficient. As a result, the global error (single calibration, approach b) over the full monitoring period was reduced from 1.6 dBA (with a standard deviation of 1.5 dBA, see Table 2) to 0.8 dBA (with a standard deviation of 0.8 dBA). The availability of air temperature data could lead to smaller deviations relative to reference equipment. Note that air temperature sensors are typically very cheap. In Fig. 10, the effect of applying the temperature correction on the evolution of the hourly error relative to REF1 over the full monitoring period is shown. In the uncorrected case, a clear drift in the data is observed when performing a single virtual calibration at the beginning of the experiment. By applying the air temperature correction, this long-term drift is removed.

In Fig. 11, a detail of the first ten days of May, 2010 is depicted, together with the air temperature measurements in this same period. In the uncorrected case, it can be observed that at night (lower temperatures), the error at ELECTRET4, relative to REF1, decreases. During the daytime, this error increases because of the higher air temperatures. This is consistent with the fact that the calibration was performed at a moment where the air temperature was near 0 °C. It seems that the magnitude of the correlation coefficient only allows for a global long-term drift removal. Even in the corrected case, day–night variation is still visible in the results. However, the average error has become very small.

Starting from about 3 m s^{-1}, the error obtained by the TYPEII microphone strongly increases with increasing wind speed. At 5 m s^{-1}, an error of near 10 dBA is observed. A plausible reason is the limited quality of the weather protection unit which was delivered with this microphone. For the other microphones, no trend between the on-site wind speed at microphone height and the error relative to REF1 was observed. The rather broad data spread at *e.g.* ELECTRET4 is caused by the coincidence of wind speed with more influencing meteorological parameters like temperature and relative humidity.

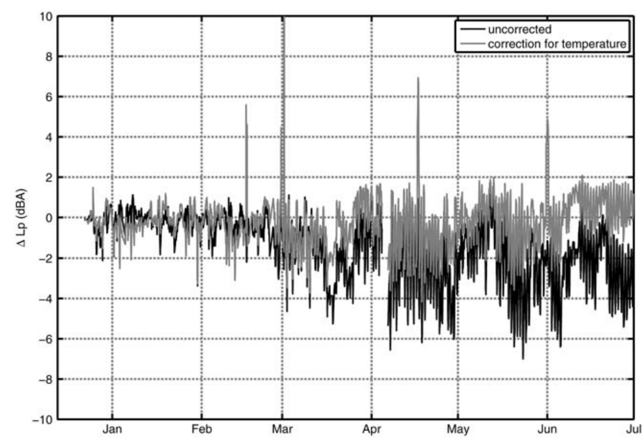

Fig. 10 Evolution over time of the hourly equivalent errors by using ELECTRET4, relative to REF1, for total noise levels during the full monitoring period. The uncorrected case and the air temperature corrected case are presented. In both cases, approach b is used.

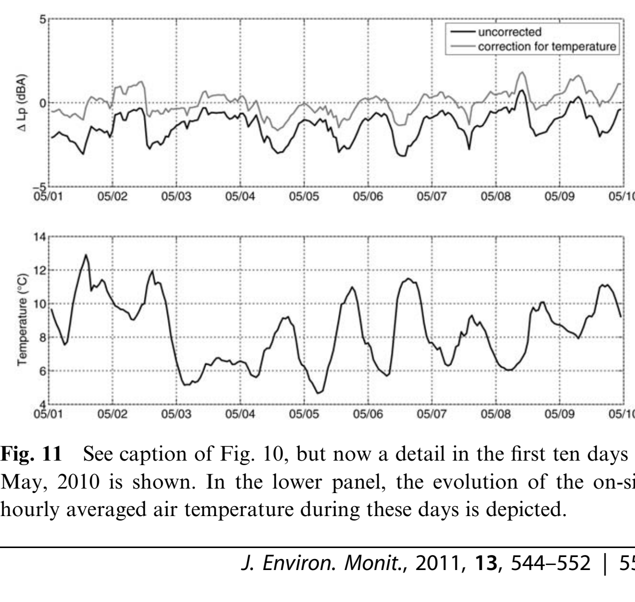

Fig. 11 See caption of Fig. 10, but now a detail in the first ten days of May, 2010 is shown. In the lower panel, the evolution of the on-site hourly averaged air temperature during these days is depicted.

Variability of spectral sensitivity over time

The temporal variability of the spectral deviation at all microphones, relative to the reference microphone (REF1), is shown in Fig. 12. This figure is assembled by considering the measurements during the pink noise events that were emitted twice a day (at 10.00 h and 22.00 h) by the outdoor loudspeaker placed in front of the test bar. The noise levels produced by the loudspeaker were typically 10 dB higher than the environmental noise levels in the 1/3 octave bands ranging from 100 Hz to 10 kHz. Measurements are referred to REF1 to account for possible changes in the sound produced by the loudspeaker during the experiment.

ELECTRET4 shows a very constant performance over the frequency range considered. The standard deviations are limited and rather frequency-independent. The magnitude of the standard deviation is somewhat higher than the one observed at the TYPEII microphone. For the latter, however, the frequency response is more flat at higher frequencies, as can be seen in Fig. 1. At most 1/3 octave bands, the TYPEII microphone shows a slightly increased variation over time compared to REF2. ELECTRET1 shows constant but much higher standard deviations when compared *e.g.* to ELECTRET4. The MEMS1 microphone is characterized by a strong variability, which seems to be most pronounced below 1 kHz. Note that for microphones with a low variability in the frequency response, a non-flat spectral response can be more accurately calibrated out.

Conclusions and discussion

In this study, it is assessed to what extent cheap microphones, appearing in consumer electronics, can be used for environmental noise monitoring. The long-term outdoor test showed that it is possible to identify microphones that only resulted in a small additional averaged error (limited to 1 dBA), relative to the differences occurring between reference microphones themselves (measured at 0.5–0.7 dBA). This additional (but limited) error must further be seen in the viewpoint of the very large increase in cost of reference equipment relative to the cheaper variants.

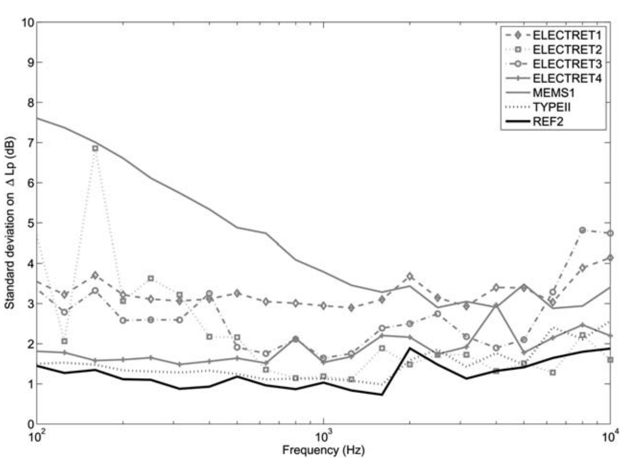

Fig. 12 Outdoor level variability at all microphones, relative to REF1, for individual 1/3 octave bands ranging from 100 Hz to 10 kHz, over the full monitoring period. The pink noise events emitted twice a day by the outdoor loudspeaker are used to assemble this figure.

In this study, it was shown as an example that air temperature correction could further reduce the difference in measured sound pressure levels relative to the reference microphone. Air temperature sensors are very cheap so the cost of the measurement node will only increase to a very limited extent.

Replacing microphones that failed after a given period (*e.g.* after a few months) is another viable option. The latter is still much more economic given the huge difference in prices compared to dedicated measurement microphones. Even for the latter, human intervention is needed (for calibration checking) and replacing the cheap sensors could become a part of normal operation. A quick and reliable identification of deviant sensor behaviour is then of course important in an extended microphone network. Algorithms will be developed to perform this non-trivial task.

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References

1 L. den Boer and A. Schroten, Traffic Noise Reduction in Europe: Health Effects, Social Costs and Technical and Policy Options to Reduce Road and Rail Traffic Noise, *Report of CE Delft*, Commissioned by the European Federation for Transport and Environment (T&E), Brussels, 2007.
2 D. Ouis, *Journal of Environmental Psychology*, 2001, **21**, 101–120.
3 B. Griefahn, A. Marks and S. Robens, *J. Sound Vib.*, 2006, **295**, 129–140.
4 B. Griefahn, P. Bröde, A. Marks and M. Basner, *Sleep*, 2008, **31**, 569–577.
5 C. Clark, R. Martinez, E. van Kempen, A. Tamuno, J. Head, W. Hugh, M. Davies, M. Haines, I. Lopez Barrio, M. Matheson and S. Stansfeld, *Am. J. Epidemiol.*, 2005, **163**, 27–37.
6 W. Babisch, *Noise and Health*, 2008, **10**, 27–33.
7 L. Barregard, E. Bonde and E. Öhrström, *Occup. Environ. Med.*, 2009, **66**, 410–415.
8 Directive 2002/49/EC of the European Parliament and Council of 25 June 2002 relating to the assessment and management of environmental noise.
9 T. Van Renterghem, E. Salomons and D. Botteldooren, *Appl. Acoust.*, 2006, **67**, 487–510.
10 E. Salomons, H. Polinder, W. Lohman, H. Zhou, H. Borst and H. Miedema, *J. Acoust. Soc. Am.*, 2010, **126**, 2340–2349.
11 T. Kihlman, M. Ögren and W. Kropp, *Proceedings of the 31st International Congress and Exhibition on Noise Control Engineering*, Dearborn, 2002.
12 R. Barhama, M. Goldsmith, M. Chan, D. Simmons, L. Trowsdale and S. Bull, *Proceedings of 8th European Conference on Noise Control*, Edinburgh, 2009.
13 M. Bell and F. Galatioto, *Proceedings of 8th European Conference on Noise Control*, Edinburgh, 2009.
14 Standard of the International Electrotechnical Commission IEC 61672, 2002: Electroacoustics—sound level meters, part 1: Specifications.
15 P. Scheeper, B. Nordstrand, J. Gullov, B. Liu, T. Clausen, L. Midjord and T. Storgaard-Larsen, *J. Microelectromech. Syst.*, 2003, **12**, 880–891.
16 A. Touhafi, B. Coudron, G. Braeckman, M. Raadschelders and J. Wambacq, *Proceedings of 17th International Congress on Acoustics*, Rome, 2001.
17 F. Huang, T. Shih, J. Lee, T. Wang and P. Wang, *J. Environ. Monit.*, 2010, **12**, 748–758.

