Meteorological influence on sound propagation between adjacent city canyons: A real-life experiment

Timothy Van Renterghem[a] and Dick Botteldooren
Department of Information Technology, Ghent University, Sint-Pietersnieuwstraat 41, B-9000 Gent, Belgium

(Received 7 January 2010; revised 7 April 2010; accepted 11 April 2010)

Sound propagation between a courtyard and an adjacent street canyon, as influenced by a wide range of meteorological conditions, was investigated by means of a real-life experiment in a dense urban setting. During several months, test signals were emitted on a regular base by an outdoor loudspeaker in the courtyard and recorded by wall-mounted microphones in the courtyard and the street canyon. Detailed meteorological observations were made at nearby buildings with sensors at roof level. A thorough quality check of the recorded signals was performed, given the large amount of shielding and the presence of background noise. With increasing wind speed and sound frequency, a strong increase in coherence loss was observed. The wide variety of measured vertical temperature lapses was shown to have no effect given the short propagation distance. With increasing downwind wind speed, refraction into the shielded canyon was observed to a limited degree only. The rather small effect of building-induced refraction of sound by wind could be qualitatively explained by the geometry of the city canyons under study.
 [DOI: 10.1121/1.3425731]

PACS number(s): 43.28.Fp, 43.28.Gq, 43.50.Rq [VEO] Pages: 3335–3346

I. INTRODUCTION

The meteorological influences on outdoor sound propagation are well known. Various experiments and numerical simulations showed the importance of refraction of sound and turbulence in the atmosphere for sound propagation between sources and receivers close to the surface of the earth.[1,2] For sound propagation over unobstructed terrain, refraction by vertical gradients in the horizontal wind speed component and air temperature gradients becomes more and more important with increasing propagated distances. At short distance from the source (roughly less than 100 m), the variation in sound level by meteorological effects for broadband noise are most often limited.[3] Turbulent scattering, on the other hand, may have a significant effect at destructive ground interferences even at short distances.[4,5]

In some situations, strong meteorological effects can be observed at very short propagation distances as well. An important case is the effect of wind on noise barrier performance. The shielding by a noise barrier is often largely reduced in case of downwind sound propagation, even at short distances behind it.[6–11] This is caused by the screen-induced refraction of sound by wind. The typical wind field near a barrier leads to large gradients in the horizontal component of the wind speed, just above the barrier top, leading to downward refraction. At larger distances behind the barrier, open-field refraction becomes dominant again. Meteorological effects on noise barrier performance have been thoroughly studied.[6–11] Turbulent scattering[12,13] is another important factor, limiting barrier performance in a realistic outdoor environment.

When considering sound propagation in an urban environment, some clear analogies with noise barriers can be identified. A common geometry in historically grown (European) cities is the street canyon, which can be defined as a rather narrow street enclosed by tall buildings. The buildings constituting a typical street canyon can be seen as thick noise barriers on either side of road traffic noise sources. Furthermore, at the shielded, non-directly exposed side of buildings in a dense city, only diffracted waves are found. It was shown in Refs. 10 and 11 that for situations with noise barriers on either side of the sound source, negative wind effects become more pronounced compared to the case of a single noise barrier. Important gradients in the horizontal wind speed component are also present near roof level. Therefore, it can be reasonably expected that meteorological effects could be important as well in an urban environment.

Studies on the meteorological influences on sound propagation in a city are however scarce. Numerical calculations in idealized geometries indicate that wind effects and turbulent scattering into shielded city canyons lead to significant variations in sound levels.[14–16] In Ref. 14, calculations showed that turbulent scattering into a city canyon is negligible at low frequencies, but increases the level with 2 to 5 dB at the 1.6 kHz 1/3 octave band, compared to a non-turbulent atmosphere. In Ref. 15, two-dimensional numerical calculations of sound propagation between adjacent, identical, 10-m wide city canyons showed the important influence of downward refraction and turbulent scattering. In Ref. 15 and 16, wind effects were shown to be dependent on roof shape.

However, experimental verification of such findings is lacking. In this paper, a well-controlled experiment in a densely built-up part of a city is described. The propagation of test signals between adjacent city canyons is studied as influenced by meteorological parameters, measured on-site above roof level. In Sec. II, the experimental setup is described. In Sec. III, the signal processing methodology to achieve quality measurements of the propagated test signals

[a]Author to whom correspondence should be addressed. Electronic mail: timothy.van.renterghem@intec.ugent.be

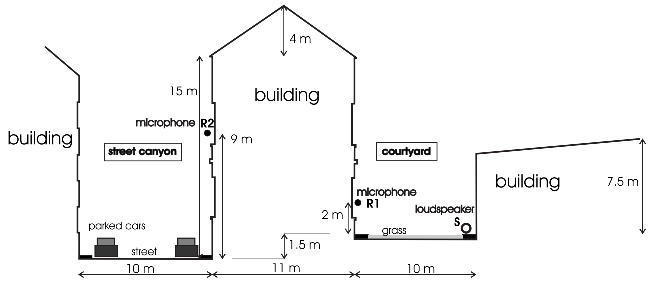

FIG. 1. Cross-section of the adjacent city canyons under study, with indication of the dimensions and the location of the loudspeaker (s), the directly exposed microphone (R1) and the shielded microphone (R2).

is dealt with. In Sec. IV, an overview of the meteorological parameters measured during the experiment and results on the influence of meteorological parameters on sound propagation are presented and discussed. Finally, conclusions are drawn in Sec. V.

II. EXPERIMENTAL SETUP

A. Site description

The measurements were performed near the building complex of the Faculty of Engineering of the Ghent University (Belgium). This building is located in a densely built-up part of the city. A cross-section of the two adjacent city canyons under study is presented in Fig. 1. An ortho photo of the neighborhood is shown in Fig. 2. An outdoor loudspeaker was used to emit predefined test signals on a regular base. For practical reasons, the loudspeaker (indicated by S in Figs. 1 and 2) was placed in a courtyard inside the building complex, and the signals propagated to a street canyon at the other side of this part of the building. The courtyard is fully enclosed by tall buildings. A large 7.5-m high building is present inside this courtyard. As can be seen from Fig. 2, this inner building closes almost completely part of the courtyard. The façade of this inner building can therefore be considered as one of the façades forming the source canyon. In the courtyard, grassland is present. Near the edges of the courtyard, there is a 1-m wide pavement.

FIG. 2. Ortho photo of the neighborhood of the adjacent city canyons under study. S indicates the location of the loudspeaker, R1 and R2 are the microphones attached to the façades of the building. M0, M1, and M2 are the locations where meteorological parameters were measured above roof level.

Simultaneous recordings were made at two microphones. Microphone 1 (indicated with R1 in Figs. 1 and 2) was attached to the façade of the courtyard (at a height of 2 m relative to the courtyard floor), at the other side of the loudspeaker. Microphone 2 (indicated with R2 in Figs. 1 and 2) was attached to a façade in the street canyon (at a height of 9 m relative to the street surface). The street canyon has a small width-height ratio: the width of the street is 10 m, while the building top height is close to 19 m. The street canyon has a length of more than 100 m. At both sides of this street, parked cars are present, changing configurations over time. Microphone 2 was located near the middle of the street canyon, at sufficient distance from intersections with nearby roads.

The façades of the buildings contain a large number of ornaments and recessions and protrusions, and reflect part of the sound energy in a diffuse way. The street canyon has an almost perfect north-south orientation. The building over which the emitted signals propagated, has a 4-m high ridge roof, measured from the gutter height, which is at 15 m from street level. The building has a constant cross-section in the part under study.

B. Acoustical instrumentation

A 4-channel monitoring system (Swing, from Sinus Messtechnik GmbH, Germany) was used for the acoustical measurements. Since this is multiple channel equipment, time synchronization between the measurements at both microphones is ensured. The Sinus Measurement Toolbox (SMT) for MATLAB was used to program measurement cycles. Recordings were made at a sample frequency of 51.2 kHz, with 1/2 in. condenser measurement microphones (MK250, Microtech Gefell, Germany). Pre-amplifiers (MV 210, Microtech Gefell, Germany) and dehumidifiers (TA202, Microtech Gefell, Germany) completed the measurement chain. A weather proof outdoor unit (WME 950, Microtech Gefell, Germany) with birdspikes was used. At the startup of the experiment, a calibration was performed with a Bruel and Kjaer 124.06 dB pistonphone emitting a single sound frequency at 251.2 Hz. Every 2 weeks, the calibration was checked. No corrections were needed during the measurement period since deviations were each time smaller than 0.2 dB. A Bose freespace 360P series II outdoor loudspeaker was used to emit test signals. This cylinder-like loudspeaker has a diameter of 37 cm and a height of 38 cm. It has a 360° horizontal radiation pattern; in vertical direction, the −6 dB point is limited to 50° at 1 kHz.

C. Meteorological observations

The measurements were performed during winter time, in the period between November 2008 and March 2009.

Given the important influence of the built environment on meteorological parameters, and their strong spatial variation in a city, on-site measurements were needed at close distance from the city canyons under study. Therefore, at various locations in the neighborhood, meteorological observations were made. An overview of these locations can be found in Fig. 2. At M1, there is a professional weather station from the Observatory of the Ghent University. Relative humidity, air temperature, air pressure, and rainfall intensity are measured above a small piece of grassland, at about an equal height of the roof top of the building over which the test signals propagated (20 m relative to street level). At this same location M1, wind speed and wind direction are measured with sensors attached to a 5-m high mast (25 m relative to street level). This data was available as 1-h averages.

Additional air temperature sensors were placed near the city canyons under study to have an idea of the vertical temperature lapse in the area under study. At location M2, the sensor was placed at a shaded side of a small 5 m^2-building at a corner of the building, extending 3 m above the roof. This height corresponds to the height of the air temperature measurements at M1. A second additional air temperature sensor was placed at location M0, which is a tall library tower. The temperature sensors were attached at the parapet of a balcony at a height of about 60 m.

III. SIGNAL PROCESSING

This experiment was performed in a real-life situation, and this induced some difficulties. First, there was background noise at microphone 2 (R2) from sound sources in the surroundings. Furthermore, the building over which the test signals propagated provided a large amount of shielding. On the other hand, emitting very intense levels at the loudspeaker (S) was not an option, given the presence of possibly annoyed dwellers in the street canyon. This restraint was strengthened since the test signals were mainly emitted during the evening and night hours, when people are at home or asleep. During office hours, no test signals were produced given the presence of lecture rooms and offices looking at the courtyard where the loudspeaker was present. Emitting signals at evening and night hours has, however, the advantage that it relaxed to some degree problems with background noise in the street canyon. Only on Sundays, test signals were emitted during daytime as well.

High-level linear frequency sweeps were emitted by the loudspeaker on a regular base (once an hour). 90 days of valid measurements in the period between November 4, 2008 and March 18, 2009 were gathered. At the moments where no test signals were emitted, background noise levels were recorded at both microphones.

At the start of the experiment, the source level was fine-tuned to find a compromise between the signal-to-noise ratio at R2, and possible annoyance by dwellers. During the full monitoring period, the source level was kept constant. The signal-to-noise ratio was improved by:

- Cross-correlating the recorded signals with the source signal before calculating levels.
- Limiting the frequency range of the emitted test signals (from 75 to 1075 Hz). The building in between both microphones resulted in a high degree of shielding. Including higher frequencies would have demanded even higher source power levels, given the strong increase in shielding with sound frequency. Furthermore, higher frequencies are more annoying and are less masked by background noise.
- The use of sufficiently long frequency sweeps. The sweeps were originally 30 s long, but it was found that splitting the signal in five 6 s intervals (corresponding to a frequency span of 200 Hz) lead to an important increase in the number of good quality samples. In case of background noise dominant only in a particular frequency range, valid measurements are still possible in other frequency ranges.
- Signal repetition at each hour with an interval of a few seconds (10 times), and averaging out valid impulse responses. Only when the dominant noise energy was present in a given time window based on travel time considerations, a repetition was kept for the averaging. This time window starts at the inherent delay of the measurement equipment (which was 0.65 s), and ends at the arrival of the shortest propagation path between the source and receiver, augmented by 1 s. This additional 1 s allows for reverberation in the canyons. This implies however that very late reverberations will be neglected. It would be hard for these anyway to be sufficient above the background noise level. This 1 s reverberation time was further set as fixed for consistency throughout the measurement campaign. The acoustical energy in this selected interval had to be at least 3 times higher than the energy in the remaining part of the cross-correlated time signal in order to consider for averaging.
- At least 3 valid repetitions were demanded to come to a valid measurement at a particular hour. Averaging out cross-correlated time signals further reduced accidental correlations with background noise. If this condition was not fulfilled, no data is present at the given hour and frequency interval.

Finally, the Fourier transform was calculated based on the averaged cross-correlated time signals, and sound levels were expressed as 1/3 octave bands, with center frequencies ranging from 100 to 800 Hz. An additional Hann window around the time interval of interest was applied to the averaged cross-correlated signal, before transforming to the frequency domain. This procedure resulted in a different number of good quality data points per 1/3 octave band, ranging from 448 to 639 when considering the full measurement campaign. The above described signal processing methodology is illustrated by the scheme in Fig. 3.

Since the background level at R1 was very low, signal processing was less critical there. The same signal treatment was however performed. The difference between the levels at R1 and R2 is further called "attenuation" by the intermediate building. R1 was mainly used to catch possible variations in the actually emitted source power level by the outdoor loudspeaker during the course of the experiment.

Two examples of cross-correlated signals are shown in Figs. 4 and 5, in the courtyard (R1, directly exposed canyon) and the street canyon (R2, shielded canyon), respectively. The recorded signal and the source signal were both filtered to retain only sound frequencies in the 875–1075 Hz interval before cross-correlating. No averaging has been performed. At R1, the first peak is the largest one, and corresponds to the direct sound arrival, in combination with the ground reflection. Afterwards, a rapid decay of the sound energy is ob-

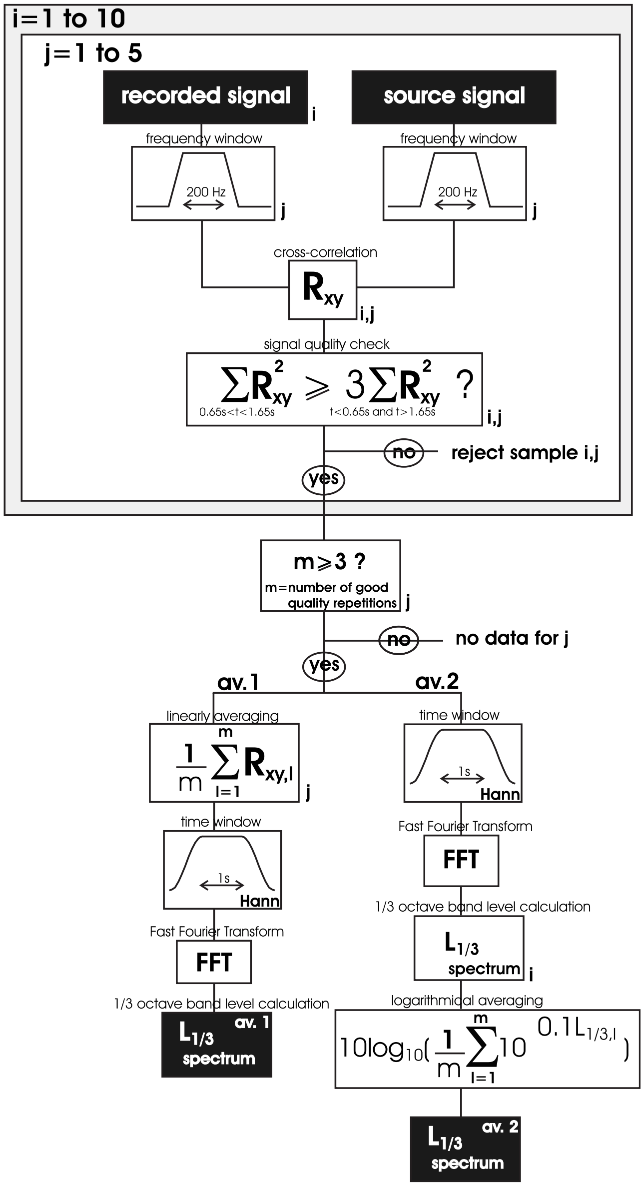

FIG. 3. Signal processing methodology scheme, including the two averaging procedures (av.1 and av.2) followed in this study. R_{xy} indicates a cross-correlation calculation between the recorded pressure and the transmitted signal to the loudspeaker. L1/3 represents the 1/3 octave band sound pressure level. Variable *i* runs over the successive signal repetitions, while j is a running variable over the 5 frequency interval split-ups of the original 30 s signals. Variable *l* runs over the repetitions with a sufficient signal-to-noise ratio.

served. The initial delay of 0.65 s (interval a in Fig. 5) corresponds to the delay of the measurement equipment. Background noise levels at the courtyard are very low, and a very good signal-to-noise ratio is obtained. At R2, a much slower decay of the energy over time is observed (interval c in Fig. 5). In a first phase (interval b in Fig. 5), there is an increase in energy with time. The most intense peaks do not arrive first in time, in contrast to what is observed in the source canyon. The first peaks correspond to pure diffraction paths involving multiple, successively diffracted waves over the roof. The later peaks did undergo reflections at the façades in the canyons under study. This typical behavior in a non-directly exposed canyon was found as well based on the detailed scale modeling of adjacent city canyons described in Ref. 17. Time-domain simulations in Ref. 18 lead to this same conclusion. It can be further observed that the background levels were much higher at R2 (interval d in Fig. 5).

In Fig. 6, the signal selection procedure is illustrated. All cross-correlated time signals are shown at a given hour during the measurement campaign. Rows 1–10 indicate the consecutive signal repetitions, while the 5 columns show the filtered cross-correlated time signals. From left to right, the frequency intervals are 75–275, 275–475, 475–675, 675–875, and 875–1075 Hz. The signals that have survived the quality check are indicated in black, the other ones in gray. In the last row, the linearly averaged time signals are shown for the frequency intervals where at least 3 measurements with a sufficient signal-to-noise ratio are present. Since it can be assumed that correlation between the emitted signals and the background noise is random, this linear averaging of the cross-correlated signals further increases the signal-to-noise ratio. This averaging procedure (further indicated as av.1) has however some consequences for the correlation between sound shielding and meteorological parameters, as will be discussed further in this paper. Therefore, a second averaging procedure (further indicated as av.2) is defined. Instead of averaging the cross-correlated signals before expressing as 1/3 octave bands, the good quality repetitions are directly expressed as 1/3 octave bands, and logarithmical averaging is performed afterwards. The signal flows for these two averaging procedures are depicted in the scheme in Fig. 3.

IV. EXPERIMENTAL RESULTS

A. Meteorological observations

Since the attenuation measurements were mainly made during winter time and during evening and night hours, the values for the relative humidity are high; more than 80% of the data points have a relative humidity above 90%. The air temperatures ranged from −10 to 15 °C during the experiment. Most temperature measurements are in the range between 0 and 5 °C. In Fig. 7(a), a scatter plot of air temperature versus relative humidity at observation point M1 is shown. Note that in Fig. 7 all meteorological data is depicted at the moments signals were emitted by the loudspeaker. Only data points corresponding to moments with a sufficient signal-to-noise ratio (see Sec. III) will be considered in further analysis.

In Fig. 7(b), a scatter plot is shown of the wind direction versus the wind speed at meteorological observation point M1. The measured wind speeds ranged from 1 m/s till 13 m/s during the campaign. The wind direction has a bimodal distribution, where the wind directions orthogonal to the length axis of the street canyon have the largest probabilities. The 90° wind direction (wind blowing from east to west) corresponds to upwind sound propagation. The 270° wind direction (wind blowing from west to east) corresponds to downwind sound propagation, and is characterized by higher wind speeds than in the upwind case.

In Fig. 7(c), a scatter plot of the wind speed versus the air temperature difference between meteo observation point M0 and M2 is given. Air temperature at M0 (library tower) is

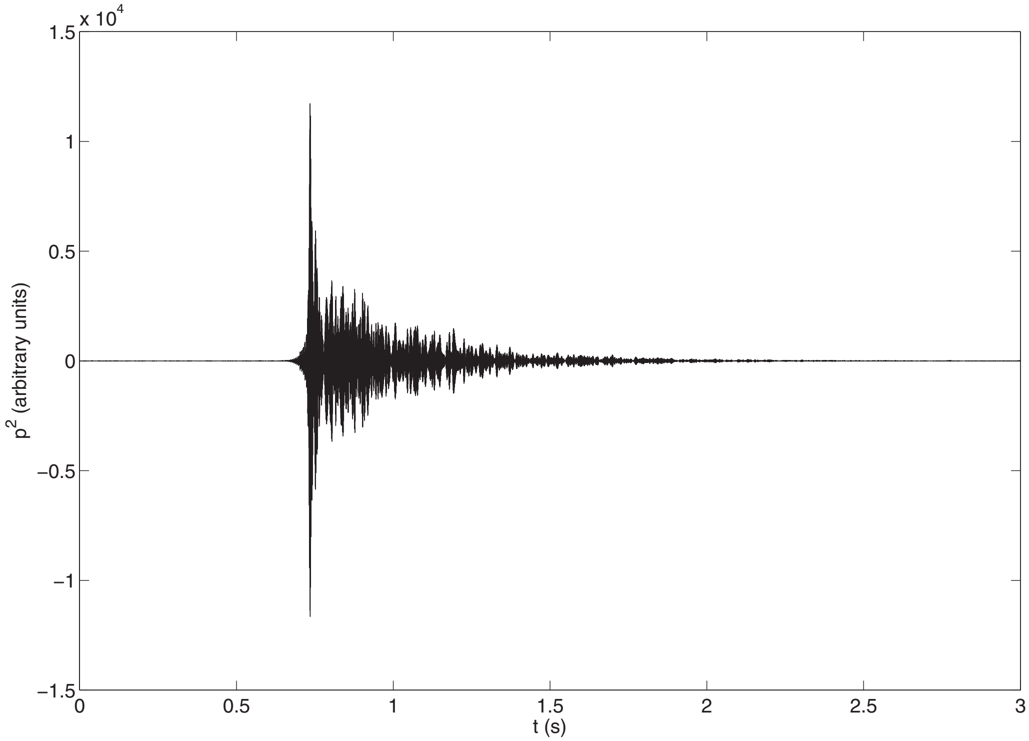

FIG. 4. Cross-correlated time signal at R1, in the directly exposed canyon (courtyard). The frequency content is in the range 875–1075 Hz. In the *y*-axis, an arbitrary pressure scale is used.

measured at a height of 60 m, relative to the street level of the receiving canyon. The air temperature sensor at M2 is placed at a height near 20 m. Positive values indicate a temperature inversion situation above the roofs of the street canyon. Since measurements are mainly obtained during evening and night hours in winter, periods with often strong temperature inversions were found.

This way of measuring the vertical temperature lapse

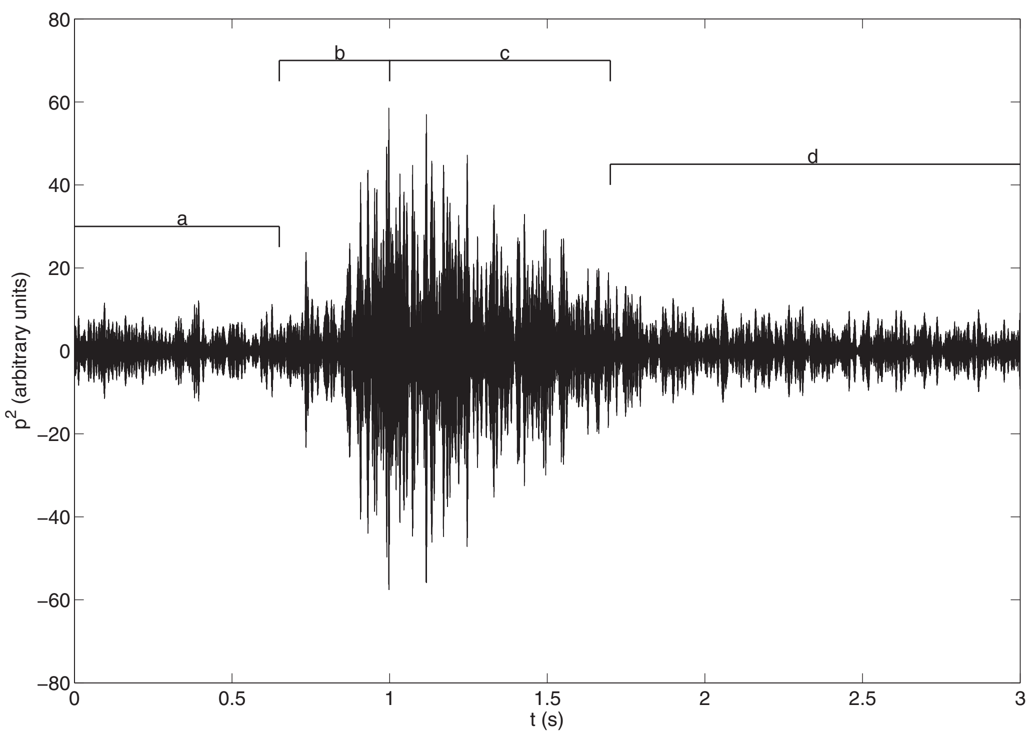

FIG. 5. Cross-correlated time signal at R2, in the non-directly exposed canyon (street canyon). The frequency content is in the range 875–1075 Hz. In the *y*-axis, an arbitrary pressure scale is used. This signal is recorded at the same time as the signal depicted in Fig. 4. Different intervals can be identified. Interval a represents the initial delay of the measurement equipment; interval b is the time period with a build-up of acoustical energy in the receiving canyon; in interval c the acoustical energy is decaying; in interval d the interaction between the frequency sweep and background noise becomes visible.

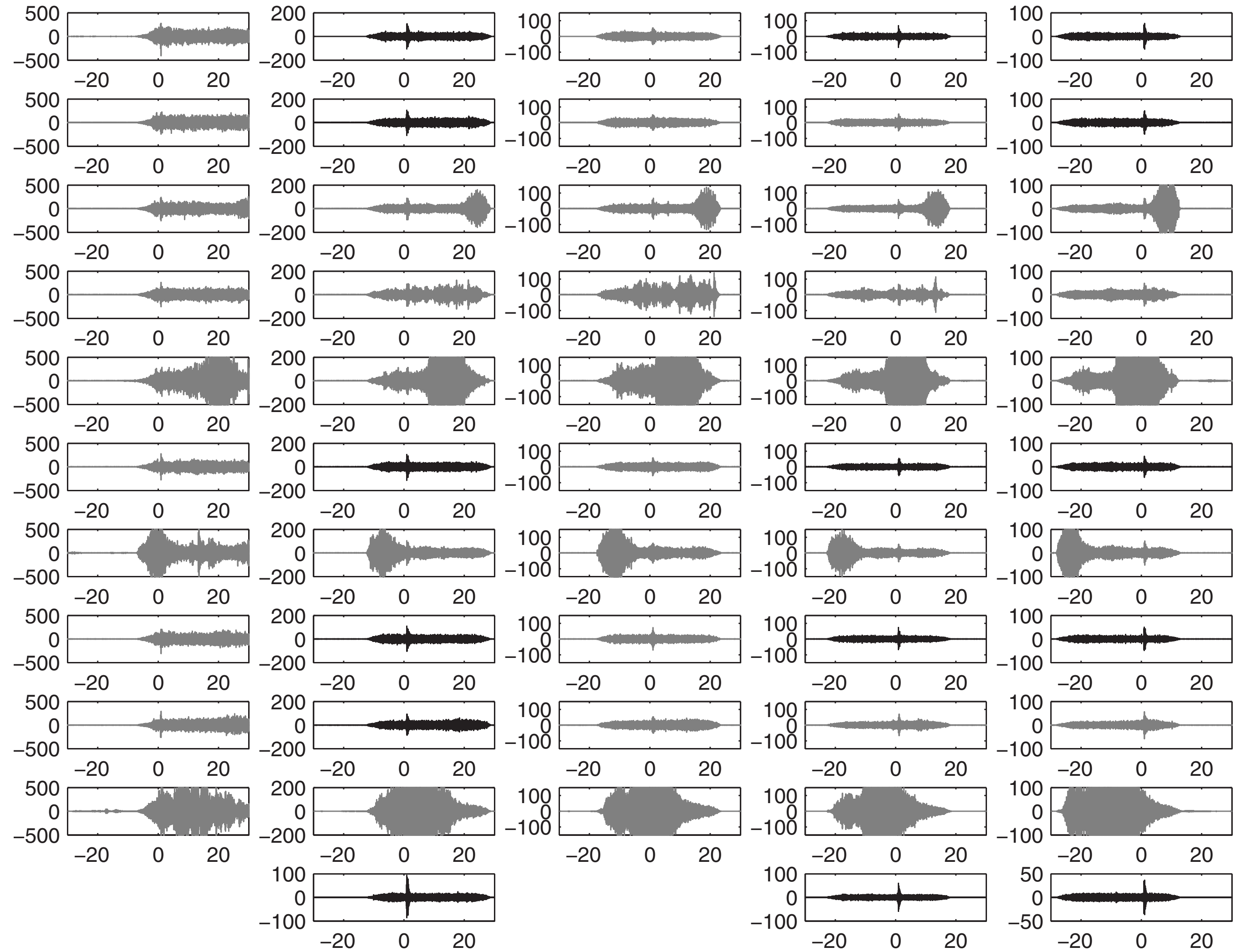

FIG. 6. Overview of the cross-correlated time signals at a given hour, at microphone R2 in the street canyon. Rows 1–10 are the consecutive repetitions of the test signal; the plots in columns 1–5 show the filtered time signals, with increasing frequency (intervals of 200 Hz, from 75 to 1075 Hz, going from left to right). The good quality cross-correlated signals are indicated in black: The acoustical energy in the interval 0.65–1.65 s is in that case at least 3 times higher than the energy in the remaining part of the cross-correlated time signal. If this condition is not fulfilled, the plots are shown in gray. The last row shows the linearly averaged time signal, in case at least 3 good quality repetitions are found for a given frequency range (av.1). In the *x*-axis, time is shown in s. The *y*-axis is an arbitrary pressure scale.

could be subject to discussion, and the influence of the building and roof materials near the sensors cannot be neglected. On the other hand, no alternatives were available to gather such data on the rather fine temporal resolution of one hour in a dense urban environment. The vertical temperature lapse data should therefore be considered with care. Nevertheless, the relation between wind speed and the vertical temperature lapse as shown in Fig. 7(c) makes sense. Periods with high wind speeds induce a high degree of mixing in the atmosphere, leading to the adiabatic air temperature profile: This means that there is a small decrease of air temperature with height. At periods with very low wind speeds, large positive values for the vertical temperature lapse also appear. In this situation, the mixing in the atmosphere is much more limited, and the built-up of a temperature inversion situation is likely, certainly since mainly night and evening hours are present in the data set.

In Fig. 7(d), the correlation between the air temperature difference between M0 and M1, and the air temperature difference between M0 and M2 is shown. The heights of the air temperature sensors at M1 and M2 are the same. This data is linearly correlated to an important degree. There is a shift of the temperature difference of about 0.5 °C toward higher values when using the sensor at location M1. This difference is most likely caused by the presence of a small piece of grassland under the sensor at M1, while the most influencing surface is a brick wall close to M2. At M0, the sensor is located close to a concrete floor and concrete parapet. The grassland will influence in a complex way the temperature measurements at M1, depending on the soil moisture content. For further evaluations, the sensor at M2 is chosen since it is not influenced by rain fall intensity. Furthermore, a similar surface as at observation point M0 is present.

B. Independence of attenuation on background noise level

In Fig. 8, scatter plots of the attenuation of the test signals (i.e., the level difference between R1 and R2) versus the

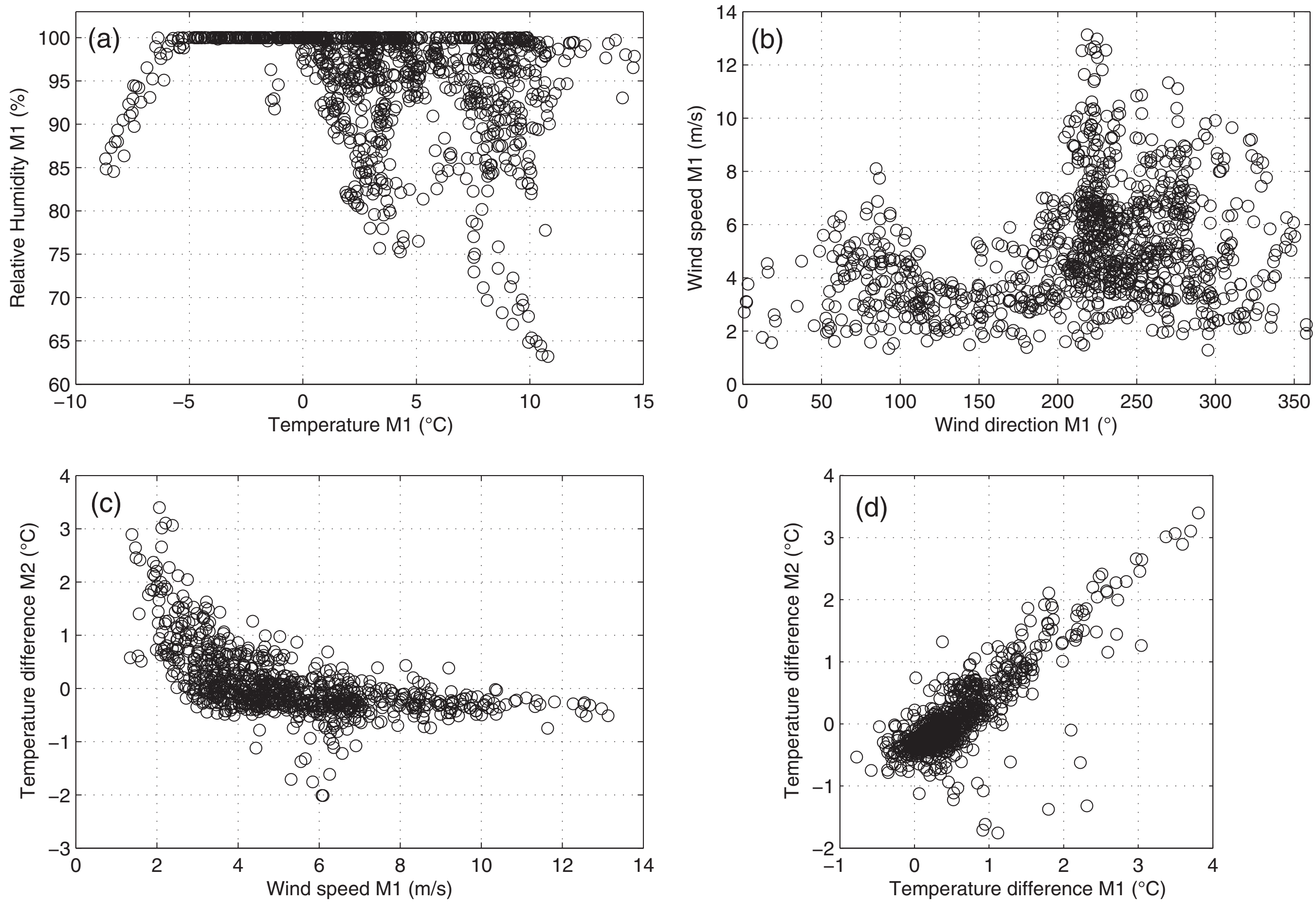

FIG. 7. Scatter plots of measured meteorological parameters during the campaign: (a) Air temperature versus relative humidity, measured at observation point M1 (at a height of 20 m); (b) wind direction versus wind speed, measured at the 5-m mast at M1 (at a height of 25 m); (c) wind speed at M1 versus the air temperature difference between observation point M0 (at a height of 60 m) and M2 (at a height of 20 m). Positive values indicate a temperature inversion situation; (d) air temperature difference between observation points M0 and M1 versus the air temperature difference between observation points M0 and M2.

background noise levels measured at R2 are shown. The test signals were emitted and recorded during the first 300 s of an hour. The equivalent background noise levels L_{bg} presented in Fig. 8 were measured during the remaining 3300 s in this same hour. Both the attenuation of the test signals and the equivalent background noise levels are expressed in 1/3 octave bands. These figures clearly show that the attenuation is independent of the ambient level at R2: The spread in attenuation level is much lower than the variation in background level. Moreover, small attenuation values do not have a larger occurrence in periods with high background noise, while high attenuations do not a have a larger probability in periods with a limited amount of background noise. This holds for all 1/3 octave bands considered in this experiment. The signal processing methodology as described in Sec. III can therefore be considered as adequate. The correlation with the background noise at R1 is not considered here, since the ambient levels in the courtyard were very low, while the test signals can directly reach microphone R1, without propagating over the building.

C. Influence of meteorological parameters on attenuation

This section studies the correlation between the attenuation of the test signals when propagated over the roof and the driving meteorological parameters for refraction of sound in the atmosphere. These are the vertical temperature lapse and the wind speed combined with wind direction.

Box plots allow presenting data in a compact and concise way, while still giving sufficient information on their distribution. In a boxplot, the (middle) horizontal line in the box indicates the median of the data. The box is closed by the first and third quartile. The whiskers extend to 1.5 times the interquartile distance above the maximum value inside the box, and to 1.5 times the interquartile distance below the minimum value inside the box. Data points that fall outside these limits are indicated with the plus-signs. The notches give the confidence interval on the median of the data; two medians are significantly different at the 5% level if their intervals do not overlap.

The independent data, which is the meteorological parameter under study, is classified. Although measurements were performed during 90 days, some classes are only sparsely populated. This holds mainly for the more extreme conditions. Furthermore, the vertical air temperature lapse and the wind speed are clearly correlated, as is shown and discussed in Sec. IV A. To purely look at the influence of a particular parameter, minimum and maximum values for the other parameters need to be set. These limits are set in such a way that as many as possible classes have a reasonable

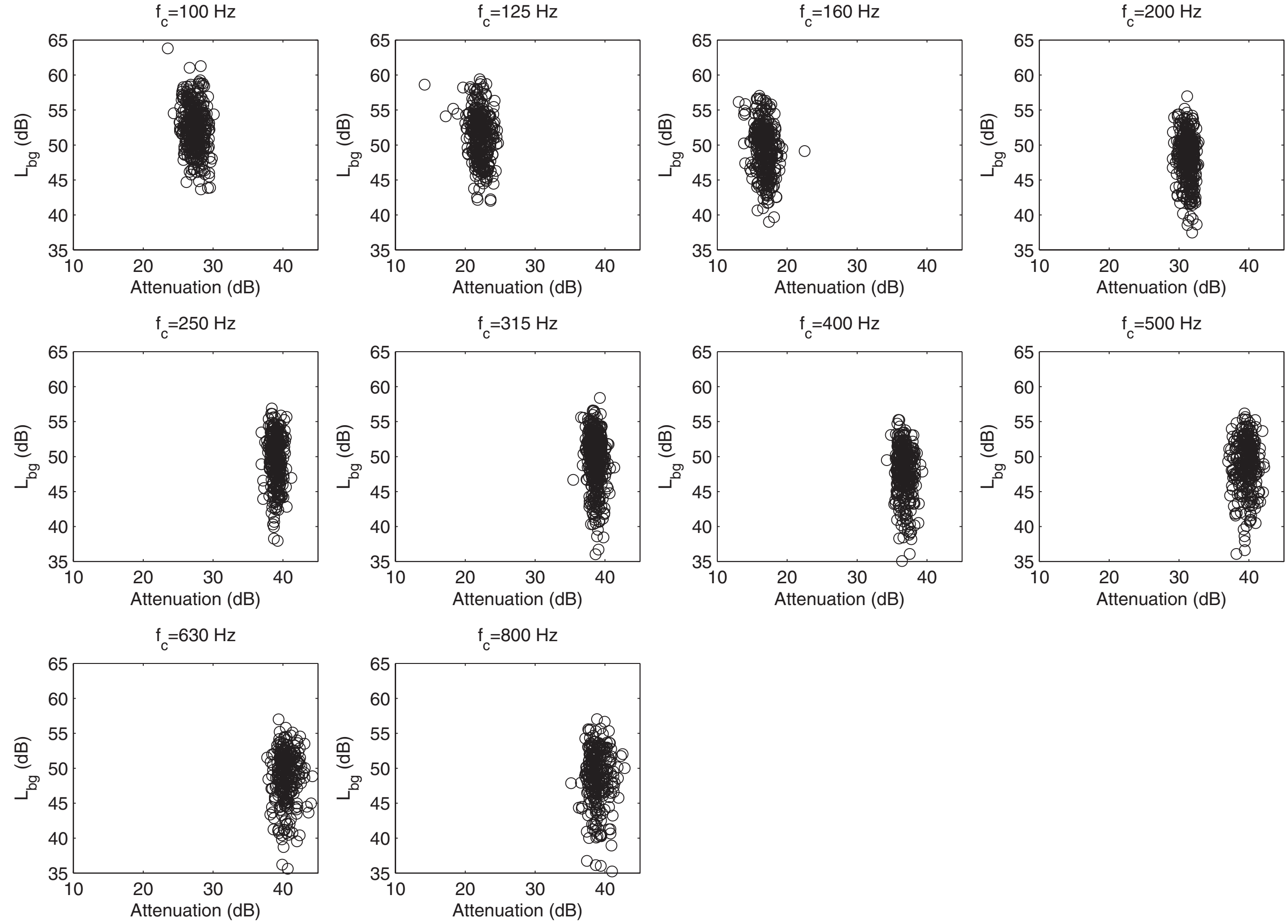

FIG. 8. Scatter plots between the attenuation of the test signals after propagation over the building and the equivalent background noise level at R2 (shielded canyon) during the remaining time of the hour L_{bg}. 1/3 octave bands levels with center frequencies ranging from 100 Hz till 800 Hz are shown.

number of data points. Constant class widths of the independent variable are used for all 1/3 octave bands considered. All data is shown, even when only a single data point is present in a given class. The numbers of data points per class are explicitly shown next to each boxplot.

In Fig. 9, the effect of the air temperature difference between M0 and M2 on the attenuation is shown. Classes of 0.4 °C are defined. The maximum wind speed allowed is 5 m/s. Periods with rainfall are not considered. The effect of the temperature lapse is very limited: For most 1/3 octave bands, the medians stay well within 1 dB for the rather large spread in the experimental data between −1.2 to 2.4 °C. Almost no significantly different attenuation medians can be found when considering temperature difference classes with sufficient number of data points. The effect of the two averaging procedures to deal with repetitions of the test signal in a given hour was very small when looking at the vertical temperature lapse.

When looking at the effect of wind speed, the averaging procedure now becomes important. In Fig. 10, the effect of wind speed on the attenuation is shown, for the averaging procedure involving a linear averaging of good quality cross-correlated time signals before expressing results in frequency bands (av.1). All wind directions are included. This means that there is a mixture of upwind, downwind, and cross-wind sound propagation conditions, and that the attenuation should be rather independent of wind speed. This holds for the 1/3 octave bands with center frequencies up to 500 Hz. At 630 and 800 Hz, an important increase in attenuation with increasing wind speed is observed. At 800 Hz, a significant difference in the attenuation median of about 4 dB is observed between the wind speed class of 2 and 12 m/s. This effect at higher 1/3 octave bands is caused by turbulence in the atmosphere above the city canyons, leading to coherence loss. The reflections arrived at the microphone R2 with slightly different travel times during the different repetitions of the emitted signal, depending on the momentary state of the atmosphere. Averaging cross-correlated time signals is useful to improve the signal-to-noise ratio, but also lead to virtual lower levels at R2 caused by these small peak shifts, and consequently higher attenuations. At microphone R1, the direct sound path was dominant, and no dependence on wind speed is observed at all 1/3 octave bands considered. The medians stay within 0.5 dB for the full range of wind speeds measured during the campaign.

This influence of the averaging technique (see Sec. III) is convincingly illustrated in Fig. 11 by applying the two ways of averaging to a selection of the same data, with increasing frequency and wind speed. The attenuations obtained by av.1 are subtracted from those calculated with av.2.

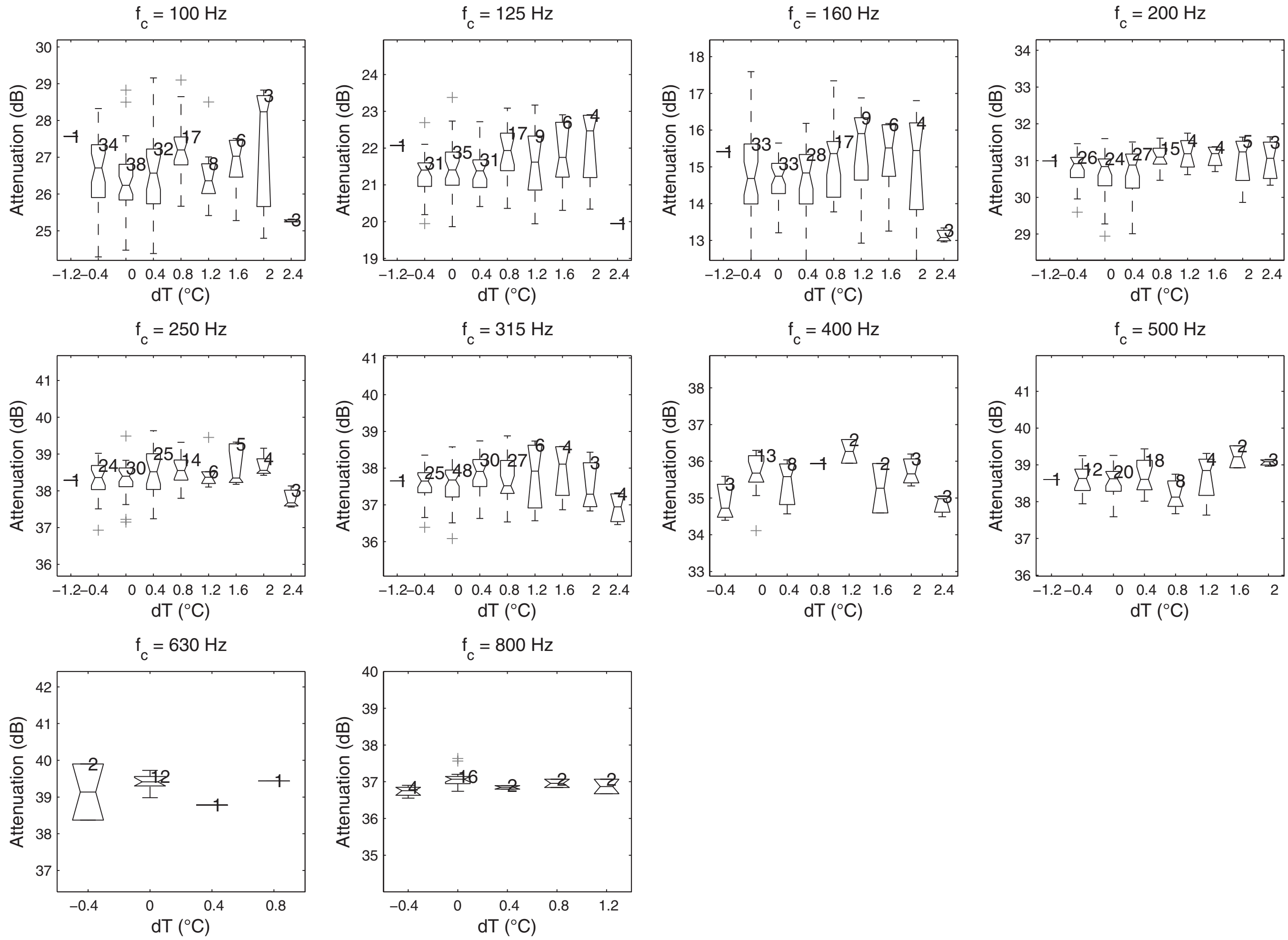

FIG. 9. Effect of the air temperature difference between M0 and M2 on the attenuation of the test signals between the courtyard (R1) and the street canyon (R2). The temperature difference is shown in 0.4 °C classes. 1/3 octave bands ranging from 100 to 800 Hz are shown. The maximum wind speed considered is 5 m/s at M1. Periods with rainfall were omitted. Good quality cross-correlated time signals are linearly averaged (av.1). The number of data points per air temperature difference class is explicitly shown next to each boxplot.

At low frequencies, the effect of the averaging technique is limited and wind speed has no influence. With increasing frequencies and wind speed, turbulence in the atmosphere becomes more pronounced, and the level difference between the averaging techniques becomes larger. At wind speeds above 12 m/s, these differences may exceed 6 dB. A significant effect of wind speed is also observed near 160 Hz, where a minimum in the attenuation spectrum is observed. This is caused by a destructive interference at R1, a constructive interference at R2, or a combination of both. Such minima are sensitive to turbulence, which is also typically observed when looking at ground effects.[4,5]

In Fig. 12, the effect of downwind wind speed on attenuation is shown by using the averaging technique which is less sensitive to travel time shifts of the different sound paths: the good quality repetitions are first expressed in frequency bands, and logarithmically averaged afterwards (av.2). The downwind wind speed is defined as the wind vector projected on the west-to-east direction. Large positive values indicate downwind sound propagation conditions; large negative values indicate upwind sound propagation. Values close to zero could be either low wind speeds (independent of wind direction), or large winds blowing along the length axis of the street canyon (cross-wind). Given the distribution of wind direction as shown in Fig. 7(b), the latter option is less likely. At the 100–160 Hz 1/3 octave bands, no effects of wind speed are seen. For the 200–315 Hz bands, a decrease in attenuation is observed with increasing downwind wind speed, indicating downward refraction into the non-directly exposed canyon. The differences in the medians are a few dB. At the 400 and 500 Hz octave bands, this effect is less clear. For 630 and 800 Hz, good quality samples in upwind sound propagation conditions are not present anymore in the data set. Only a small range in wind speed is seen, and a rather constant attenuation is observed. However, the absence of data points in the upwind situation is a qualitative indication that the attenuation is higher there, leading to low levels at R2, with a signal-to-noise ratio which was considered to be inadequate to retain in the data set.

V. CONCLUSIONS AND DISCUSSION

In this paper, the meteorological influence on sound transmission between a source canyon and a shielded canyon in a densely built-up part of a city is studied. During 90 days in the period from November 2008 to March 2009, linear

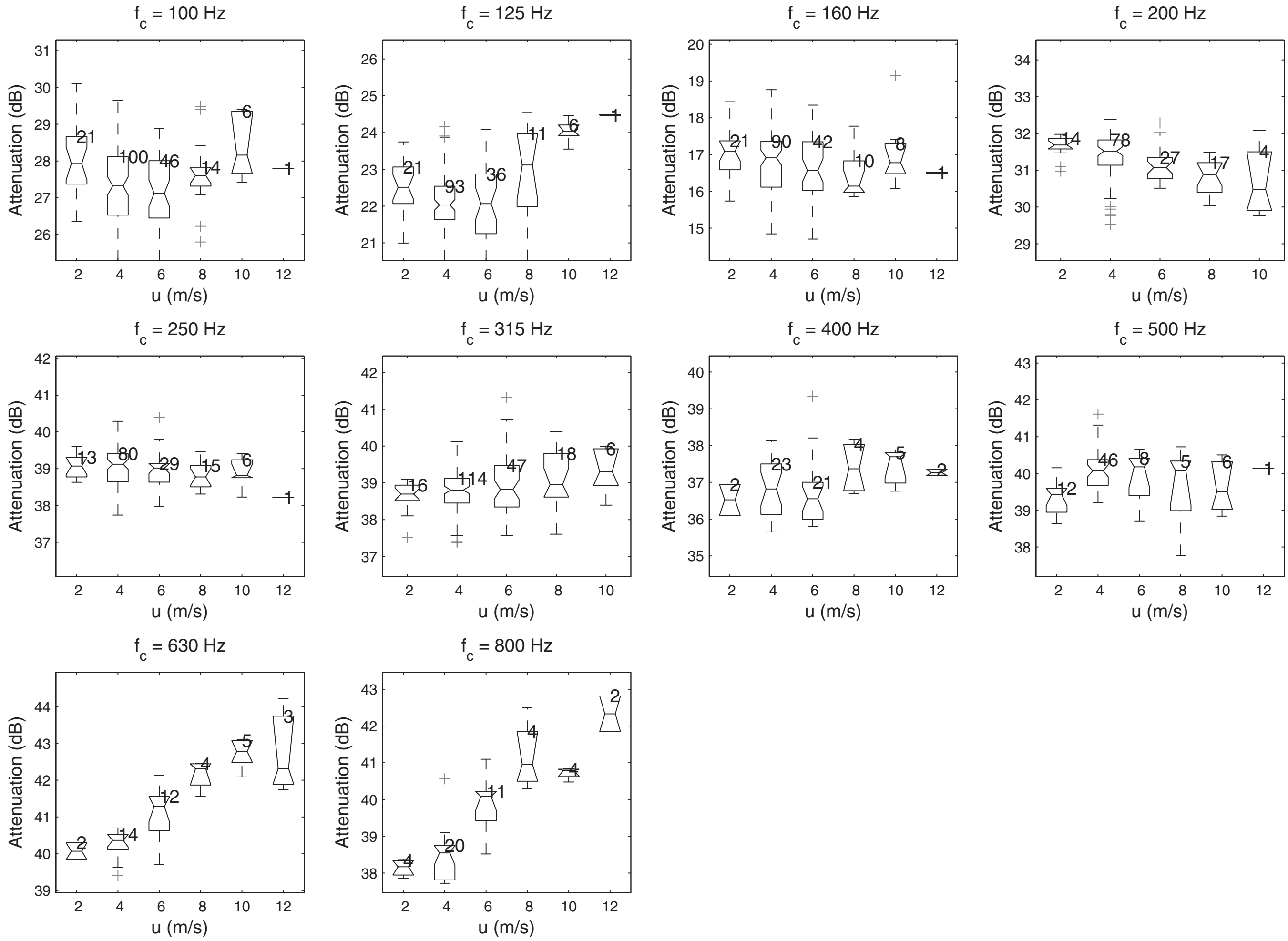

FIG. 10. Effect of wind speed u at M1 on the attenuation of the test signals between the courtyard (R1) and the street canyon (R2). Wind speed classes with a width of 2 m/s are used. 1/3 octave bands ranging from 100 Hz to 800 Hz are shown. The absolute value of the temperature difference between M0 and M2 is limited to 1 °C. Periods with rainfall were omitted. Good quality cross-correlated time signals are linearly averaged (av.1). The number of data points per wind speed class is explicitly shown next to each boxplot.

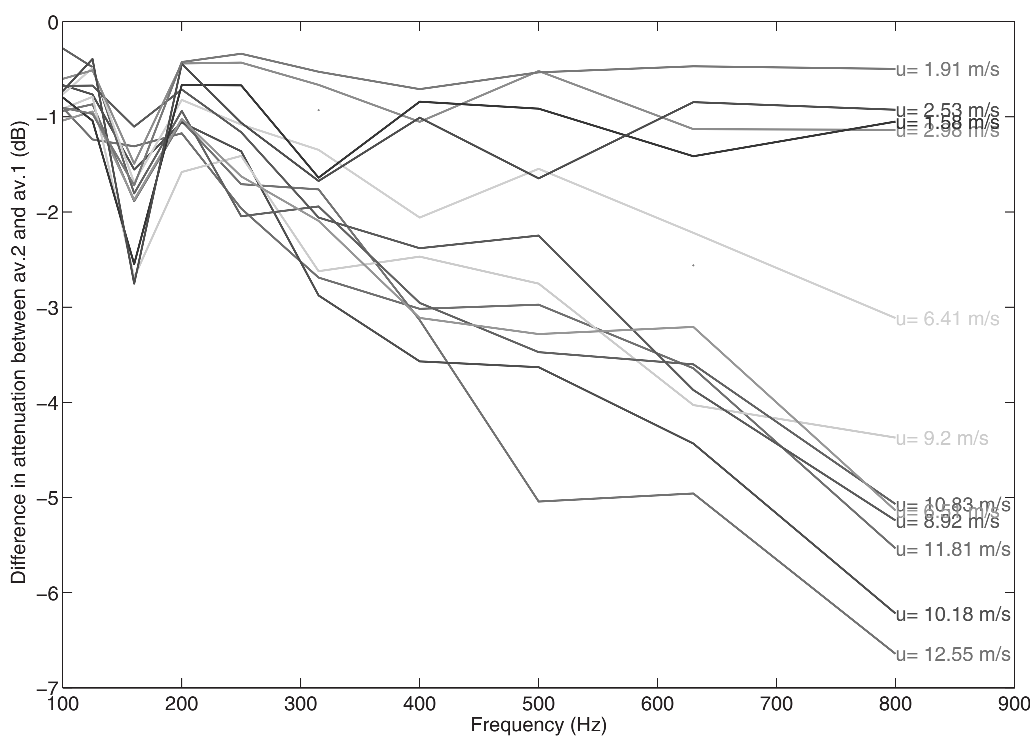

FIG. 11. Difference in attenuation between averaging procedure av.2 and av.1 as described in Sec. III, with increasing 1/3 octave band center frequency and wind speed u (wind direction is not considered here).

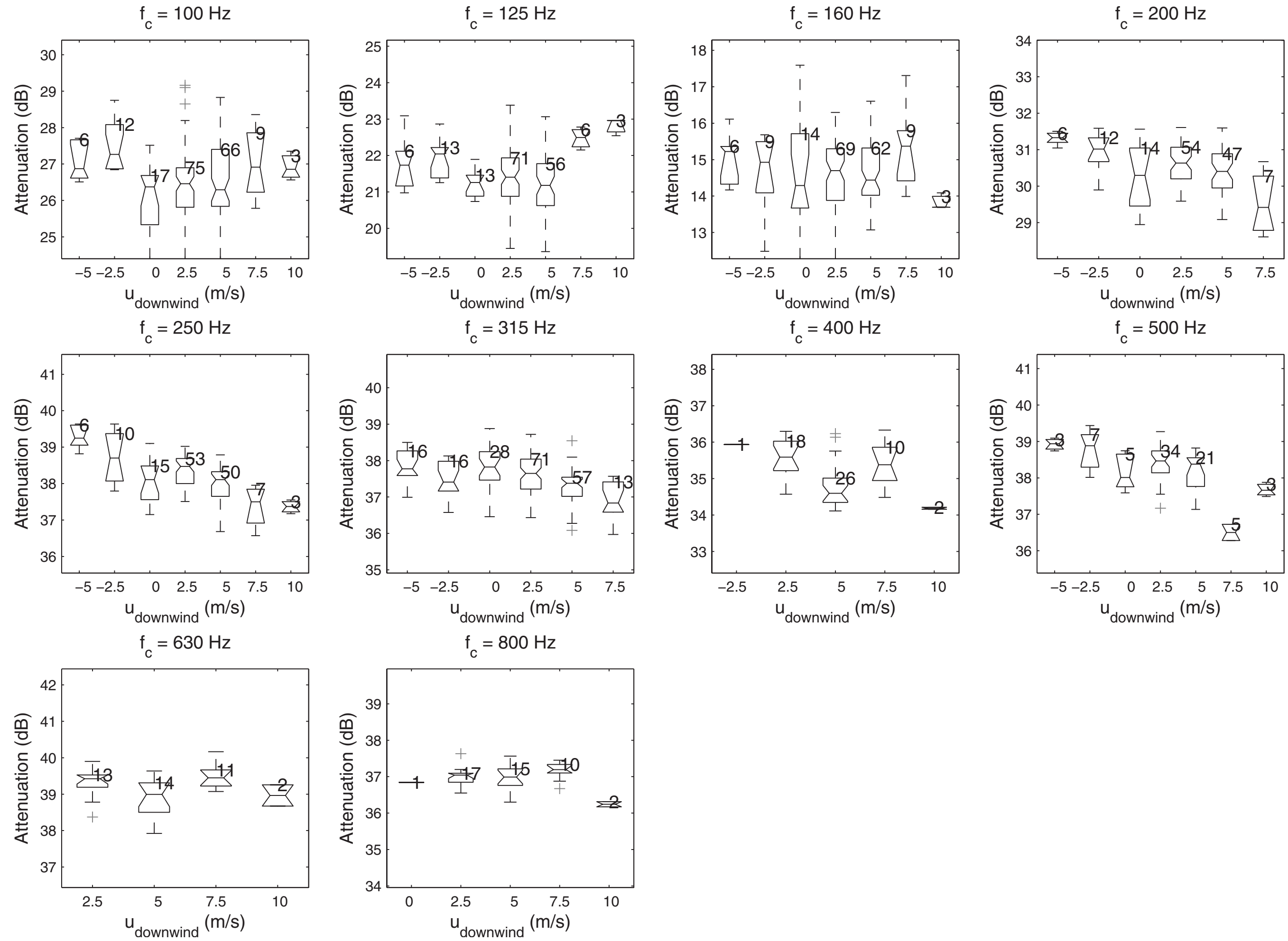

FIG. 12. Effect of downwind wind speed u_{downwind} at M1 on the attenuation of the test signals between the courtyard (R1) and the street canyon (R2). Wind speed classes with a width of 2.5 m/s are used. 1/3 octave bands ranging from 100 Hz to 800 Hz are shown. The absolute value of the temperature difference between M0 and M2 is limited to 1 °C. Periods with rainfall were omitted. Good quality 1/3 octave band levels are logarithmically averaged (av.2). The number of data points per downwind wind speed class is explicitly shown next to each boxplot.

frequency sweeps were emitted in the source canyon, mainly during the evening and night hours. At the same time, detailed meteorological observations were made in the direct neighborhood of the canyons under study. The signal processing methodology is an important aspect of this study. At one hand, there was a high degree of shielding by the building separating the canyons and an important amount of city background noise in the receiving canyon. Increasing the loudspeaker intensity was not an option since noise annoyance for dwellers in the receiving canyon had to be avoided. Therefore, a thorough quality check was needed on the recorded signals after cross-correlating with the original source signal. It was shown that the attenuation of all 1/3 octave bands considered (from 100 to 800 Hz) are independent of the background noise levels.

The vertical temperature lapse was measured by air temperature sensors placed at the roofs of buildings with different heights. Although this way of determining the stability of the atmosphere in the first tens of meters above the roofs could be questioned, some proof is provided in this paper that these measurements are qualitatively sound. There is no effect of the strong temperature inversion situations that were measured on the attenuation of the test signals. This is not surprising, since a rather strong increase in air temperature of few degrees in the first ten of meters above the roofs leads to gradients in the speed of sound that are too small to see effects at such short propagation distances. Downward refraction by increasing air temperature with height could therefore only be expected at longer propagation distances. Temperature lapse effects in the direct vicinity of noise barriers have not been reported either.

A strong and significant effect is observed by turbulence in the atmosphere. This became clear when comparing two averaging techniques, of which one (av.1) is sensitive to small changes in the arrival times of individual reflections. With increasing wind speed and sound frequency, coherence loss was shown to become important.

The effect of refraction by wind is small. For the 1/3 octave bands with center frequencies between 200 and 500 Hz, a decrease in attenuation of maximum 2 dB has been observed with increasing downwind wind speed. For the 630 and 800 Hz 1/3 octave bands, upwind sound propagation conditions were not present in the data set gathered during the experiment. For these, it can be expected that in such situations the levels were too low to have a sufficient signal-to-noise ratio. A decrease in attenuation with increasing downwind wind speed is likely for these frequency bands as well.

This limited effect of refraction by wind can be explained by looking at the geometry of the adjacent canyons under study. The numerical calculations described in Ref. 15 predicted important effects, up to an increase in level of 10 dB for the octave band of 1000 Hz when comparing downwind propagation to a windless atmosphere. There, fully symmetric adjacent canyons were modeled. All façades forming the canyons had a flat roof and an equal height of 10 m. The geometry in the real-life experiment described in this paper differs from this idealized numerical study mainly by the much higher intermediate building of 19 m, and since one of the façades forming the source canyon is only 7.5 m high. The width of the source canyon, shielded canyon, and the building in between is very similar in the numerical and the real-life setup. Of main importance to observe effects of refraction by wind speed gradients is the presence of sound rays that leave the canyon almost horizontally after a number of reflections. If such rays are bent downward only a little, they are captured in the receiving canyon and might reach a shielded microphone. In our experiment, such rays do not contribute sufficiently to the receiver R2. Furthermore, the width-height ratio of the receiving canyon is very small. A higher width-height ratio makes it easier to capture such rays before reaching the farthest façade. Another reason for these limited effects is the presence of a 4 m high ridge roof, relative to the gutter height. Computational fluid dynamics simulations performed in Ref. 19 show that gradients in the horizontal component of the wind speed are smaller compared to flat roofs, and are present at larger heights above the canyons. Therefore, refraction of sound by wind is less pronounced.

ACKNOWLEDGMENTS

The research equipment used in this study was granted (Grant No. BOF 05B04206) by the Special Research Fund of the Ghent University. We further acknowledge the Public Observatory "Armand Pien" of the Ghent University for providing meteorological data during the monitoring period (at location M1, see Fig. 2).

[1]E. Salomons, *Computational Atmospheric Acoustics* (Kluwer Academic, Dordrecht, 2001).
[2]K. Attenborough, K. Li, and K. Horoshenkov, *Predicting Outdoor Sound* (Taylor and Francis, Oxon, 2007).
[3]V. Zouboff, Y. Brunet, M. Berengier, and E. Sechet, "A qualitative approach of atmospherical effects on long range sound propagation," in *Proceedings of the 6th International Symposium on Long Range Sound Propagation*, edited by D. Havelock and M. Stinson (NRCC, Ottawa, 1994), pp. 251–269.
[4]G. Daigle, J. Piercy, and T. Embleton, "Effects of atmospheric turbulence on the interference of sound waves near a hard boundary," J. Acoust. Soc. Am. **64**, 622–630 (1978).
[5]P. Chevret, P. Blanc-Benon, and D. Juve, "A numerical model for sound propagation through a turbulent atmosphere near the ground," J. Acoust. Soc. Am. **100**, 3587–3599 (1996).
[6]R. DeJong and E. Stusnick, "Scale model studies of the effect of wind on acoustic barrier performance," Noise Control Eng. **6**, 101–109 (1976).
[7]K. Rasmussen and M. Arranz, "The insertion loss of screens under the influence of wind," J. Acoust. Soc. Am. **104**, 2692–2698 (1998).
[8]E. Salomons, "Reduction of the performance of a noise screen due to screen-induced wind-speed gradients. Numerical computations and wind tunnel experiments," J. Acoust. Soc. Am. **105**, 2287–2293 (1999).
[9]N. Barriere and Y. Gabillet, "Sound propagation over a barrier with realistic wind gradients. Comparison of wind tunnel experiments with GFPE computations," Acust. Acta Acust. **85**, 325–334 (1999).
[10]T. Van Renterghem, D. Botteldooren, W. Cornelis, and D. Gabriels, "Reducing screen-induced refraction of noise barriers in wind by vegetative screens," Acust. Acta Acust. **88**, 231–238 (2002).
[11]T. Van Renterghem and D. Botteldooren, "Numerical simulation of the effect of trees on downwind noise barrier performance," Acust. Acta Acust. **89**, 764–778 (2003).
[12]G. Daigle, "Diffraction of sound by a noise barrier in the presence of atmospheric turbulence," J. Acoust. Soc. Am. **71**, 847–854 (1982).
[13]J. Forssén and M. Ogren, "Thick barrier noise-reduction in the presence of atmospheric turbulence: Measurements and numerical modeling," Appl. Acoust. **63**, 173–187 (2002).
[14]M. Ögren and J. Forssen, "Modelling of a city canyon problem in a turbulent atmosphere using an equivalent sources approach," Appl. Acoust. **65**, 629–642 (2004).
[15]T. Van Renterghem, E. Salomons, and D. Botteldooren, "Parameter study of sound propagation between city canyons with coupled FDTD-PE model," Appl. Acoust. **67**, 487–510 (2006).
[16]D. Heimann, "Three-dimensional linearised Euler model simulations of sound propagation in idealised urban situations with wind effects," Appl. Acoust. **68**, 217–237 (2007).
[17]M. Hornikx and J. Forssen, "A scale model study of parallel urban canyons," Acust. Acta Acust. **94**, 265–281 (2008).
[18]T. Van Renterghem and D. Botteldooren, "The importance of roof shape for road traffic noise shielding in the urban environment," J. Sound Vib. **329**, 1422–1434 (2010).
[19]T. Van Renterghem, "The finite-difference time-domain method for simulation of sound propagation in a moving medium," Ph.D. thesis, University Ghent, Ghent, Belgium (2003).