Qualification of low-cost sensors for the purpose of environmental noise assessment

Gwenaël Guillaume, David Ecotiere, Judicaël Picaut, Nicolas Fortin, Jérémy Ardouin

QUALIFICATION OF LOW COST SENSORS FOR THE PURPOSE OF ENVIRONMENTAL NOISE ASSESSMENT

Gwenaël Guillaume[1] **David Écotière**[1] **Judicaël Picaut**[2]
Nicolas Fortin[2] **Jérémy Ardouin**[3]
[1] UMRAE, CEREMA, Univ Gustave Eiffel, IFSTTAR, F-67035 Strasbourg, France
[2] UMRAE, Univ Gustave Eiffel, IFSTTAR, CEREMA, F-44344 Bouguenais, France
[3] Wi6Labs, F-35510 Cesson-Sévigné, France
gwenael.guillaume@cerema.fr, judicael.picaut@univ-eiffel.fr

ABSTRACT

Within the meaning of the European Directive 2002/49/EC, noise assessment relies on the production of strategic noise maps for large cities that are entirely based on numerical simulations. The relevancy of these maps is debatable owing to unquantified uncertainties and to the consideration of a limited number of sound sources. Noise observatories could provide a more complete representation of the sound environments, especially where other kind of sound sources dominates. However, the wide variety of soundscapes from one place to the other requires to rely on a sufficiently high number of devices and consequently to low-cost sensors. The deployment of such sensors for the purpose of environmental noise monitoring is investigated within the framework of the CENSE project that aims at proposing an innovative methodology for producing upgraded noise maps from both simulations and measurements. A series of innovative noise sensors has been especially designed as part of this research project that are based on MEMS microphones and low consumption microcontrollers, with a cloud connection to central remote servers through a hybrid wireless/wired communication network and power-line communication systems offered by the public lighting network. The designed noise sensors have been qualified under various meteorological conditions in a climate chamber in order to check the potential sensor drift according to both the temperature and relative humidity with a controlled sound load. This communication presents the promising results issued from this experimental campaign and highlights the suitability of the designed sensors for the purpose of environmental noise monitoring.

1. INTRODUCTION

Noise maps could be improved and made more realistic by combining simulations together with in situ measurements. This would require long-term acoustic observations with a relatively fine spatial granularity of sensors that can not reasonably been reached with a cluster of Class 1 equipment for cost-effectiveness reasons [1]. The development of an innovative methodology for upgrading noise maps with experimental data issued from a low-cost sensor network constitutes the global objective of the CENSE project [2]. This network, deployed for several years in a French city centre, is composed of specific sensors that were designed and implemented within the framework of the project based on low-cost new technologies. The reliability, accuracy and robustness of these sensors for the purpose of long term outdoor noise monitoring is investigated in the present work which pursue a preliminary qualification study presented in [3]. The analysis focuses on the sensitivity of the developed sensors to meteorological conditions, namely temperature and relative humidity. Firstly, the measurement environment and sensors are detailed and the procedure established to qualify the reliability and robustness of the innovative acoustic sensor is presented. Then, the experimental data processing are explained and the accuracy of the measurements are analysed in comparison with reference sensor measurements.

2. EXPERIMENTAL SET-UP AND PROCEDURE

2.1 Low-cost noise sensors

Two kind of low cost sensors were designed and developed within the framework of the Cense project with the aim of building up a wireless sensor network: wireless self-powered devices (“nodes” sensors) powered by means

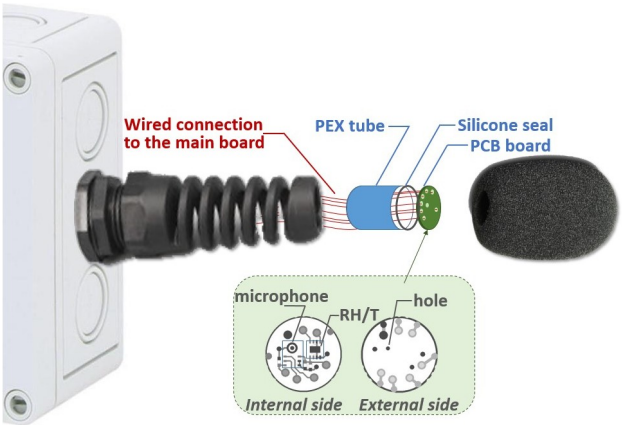


Figure 1: Layout scheme of “nodes” and “gateways” sensors with integrated microphone, temperature and hygrometry sensors.

of a solar panel and wired devices ("gateways" sensors) powered by the BYES Citybox technology [1]. Both sensors are deisgned as depicted at figure 1 and incorporate a MEMS microphone (InvenSense ICS-43432 [2]) integrated on a PCB board side by side with a humidity and temperature sensor (RH/T IC SHT30A) that is connected to a microcontroller by a PEX tube. The electronic boards are integrated into a waterproof branching box. In the present study, four prototypes (named #1 to #4) of "gateways" sensors are tested, but a similar behavior is expected for the "nodes" sensors. Note that the RH/T sensor is used to control the humidity and temperature at the microphone level, not of the ambient air, and was initially included to allow the correction of sound levels according to temperature and humidity.

2.2 Test equipment and reference sensors

The experimental set-up used to control meteorological conditions consists of an environmental chamber (Heraeus HC 2020, figure 2(a)-(b) in which are placed the acoustic and meteorological sensors. Reference temperature and relative humidity values are recorded by means of a HOBO U12 temperature and relative humidity (T/RH) data logger (figure 2(c)) placed inside the environmental chamber which is connected to an external computer and managed by means of the dedicated free software `HOBOware` [3]. These latter T/RH variables are recorded into spreadsheet files, together with the date and time of the recording, in the form of one-minute average values. A Class 1 sonometer (01dB FUSION, figure 2(d)) is used as a reference device to check the reliability of the low-cost sensors. The sound source used for the experiment is a sound calibrator (Brüel & Kjaer type 4231) that thus generates an 1 kHz sine wave at 94 dB. Two identical sound calibrators were used in the present work.

[1] `https://www.bouygues-es.com/cities-and-regions/urban-lighting`

[2] `https://invensense.tdk.com/products/digital/ics-43432/`

[3] `www.onsetcomp.com/hoboware-free-download`.

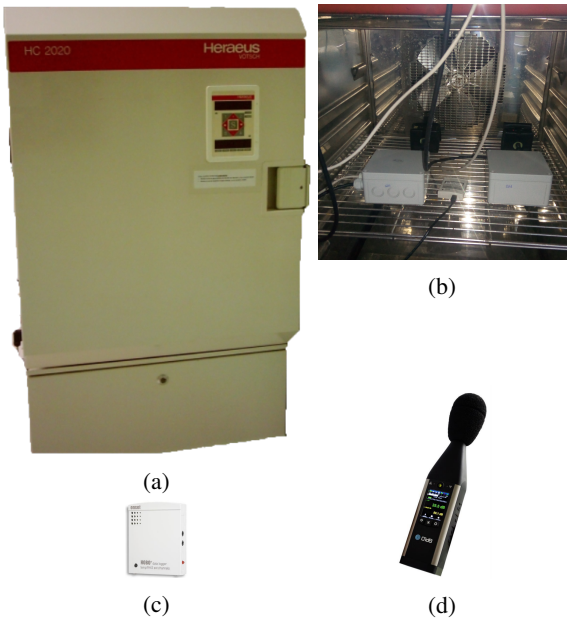


Figure 2: Test equipment: (a-b) environmental chamber, (c) temperature and relative humidity data logger and (d) sonometer.

2.3 Qualification procedure

The qualification of the low-cost acoustic sensors consists in controlling their stability under different meteorological conditions in comparison with reference measurements carried out with a sonometer. The procedure consists in submitting the acoustic sensors to temperature and humidity cycles while continuously recording the time-stamped one-second A-weighted sound pressure level $L_{\mathrm{Aeq,1s}}$ issued from the controlled sound source (*i.e.* the sound calibrator). The acoustic sensors (*i.e.* low-cost sensors and sonometer) are thus subjected to 6 successive cycles of meteorological conditions for which temperature and humidity conditions are imposed in the form of one-hour duration stages (figure 3):

- **1st cycle:** temperature cycle with stages from 34° C to -4° C by steps of -2° C and no humidity constraint;
- **2st cycle:** temperature cycle with stages from 32° C to 20° C by steps of -4° C and relative humidity set-point of 50%;
- **3st cycle:** temperature cycle with stages from 32° C to 16° C by steps of -4° C and relative humidity set-point of 60%;
- **4st cycle:** temperature cycle with stages from 32° C to 12° C by steps of -4° C and relative humidity set-point of 70%;
- **5st cycle:** temperature cycle with stages from 32° C to 12° C by steps of -4° C and relative humidity set-point of 80%;

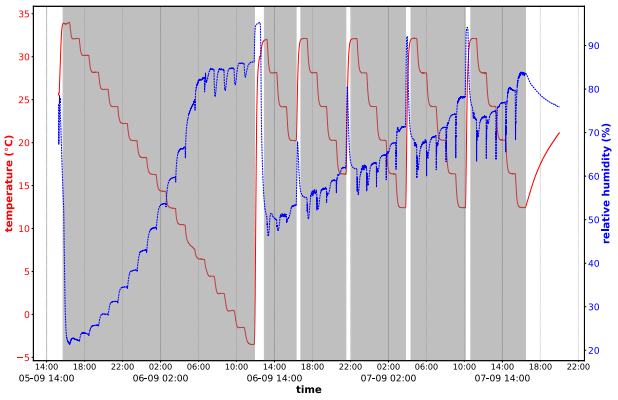


Figure 3: Cycles of meteorological conditions: climate cycles (gray areas), temperature (red continuous line) and humidity (blue dotted line) conditions.

- **6st cycle:** temperature cycle with stages from 32° C to 12° C by steps of -4° C and relative humidity set-point of 90%.

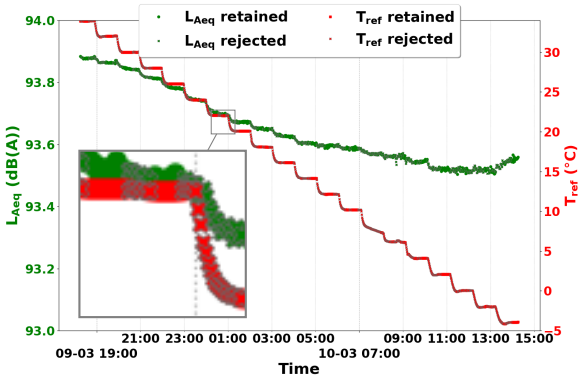
Each test that consisted in submitting the acoustic sensors to the 6 successive meteorological cycles and lasted about 2 days. Thus, the series of measurements were repeated 3 times by placing alternately the acoustic sensors in the climatic chamber: a first series was carried out with the sonometer only, a second one with the low-cost sensors #1 and #2, and a last one with the sensors #3 and #4. Prior to each series of measurements, clocks of the acoustic sensors (*i.e.* low-cost sensors or sonometer) and of the computer that manages the HOBO sensor are synchronised. In addition, each acoustic device is calibrated at ambient temperature before running each series with the sound calibrator used for the experiment according to the standard procedure (1 kHz sine wave at 94 dB). The low-cost sensors are calibrated by recording the $L_{\text{Aeq,1s}}$ with the sound calibrator during 90 s, then calculating the $L_{\text{Aeq,1min}}$ over the last minute of measurement, and finally applying the correction at the sensor level directly in the audio processing scripts. During the entire duration of each measurement series, the sound calibrator acts as a controlled sound source by emitting continuously a 1 kHz sine wave at 94 dB and the acoustic sensors record the A-weighted sound pressure level $L_{\text{Aeq,1s}}$.

3. DATA PROCESSING AND ANALYSIS

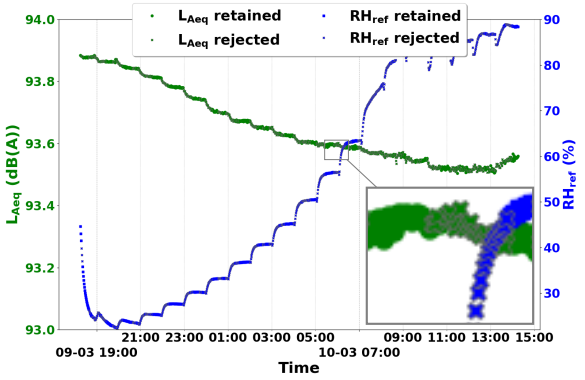
3.1 Database creation and filtering

Temperature, humidity and acoustic data issued from the low-cost sensors, sonometer and T/HR data logger are first collated to form a common experimental database. One-minute averaged values of temperature T_{sensor}, relative humidity RH_{sensor} and acoustic indicator L_{Aeq} are computed over the same time periods as reference meteorological data T_{ref} and RH_{ref} issued from the reference T/RH sensor. The built-up database is then cleaned up by removing data that correspond to the periods during which the temperature in the environmental chamber is not stabilised. This process is not performed on relative humidity since the environmental chamber does not enable to guarantee sufficiently stable hygrometric conditions. Thus the data for which the temperature gradient between two successive records is higher than 0.01° C are removed from the database as depicted at figure 4 for the L_{Aeq} values and at figure 5 for temperature and relative humidity data issued from the low-cost sensor #1, both compared with the reference acoustic and meteorological data.

Regarding the temperature and humidity values given by the low cost sensor (figure 5), despite the temperature follow the same trend as the reference one, the location of the RH/T sensor inside the PEX tube (see figure 1) strongly affects the humidity measurements. As underlined in section 2.1, these measurements are however used to control the temperature and humidity conditions at the microphone level. Concerning the acoustic measurements, the behavior



(a) L_{Aeq} (green) vs. T_{ref} (red)



(b) L_{Aeq} (green) vs. RH_{ref} (blue)

Figure 4: Illustration of the database cleaning process result for the acoustic (green markers) vs. (a) temperature (red markers) and (b) humidity (blue markers) over the 1st meteorological cycle. The left and right y-axis scales correspond to the low-cost (sensor #1) and reference data respectively. Rejected data appear as gray crosses.

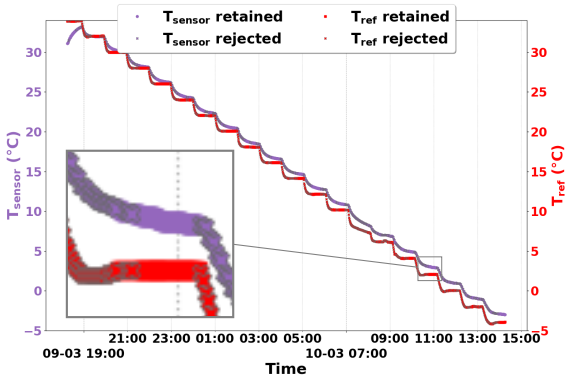
of the low cost sensor according to the ambient temperature and humidity can be oserved at figure 4. This point is further studied in the next section.

3.2 Statistical analysis

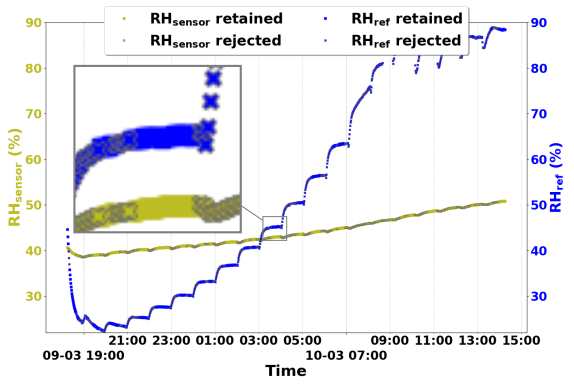
A statistical study is thus performed on the cleaned database to analyse the behavior of the low-cost sensors for all tested meteorological conditions (*i.e.* on the basis of the experimental data over the 6 meteorological cycles).

Regarding acoustic data over the whole of meteorological conditions, as presented in table 1, the mean values of the A-weighted sound levels L_{Aeq} recorded by the low-cost sensors are very close to the expected value of 94 dB(A). Besides, the standard deviation is very low and of the same order of magnitude as that of the sonometer, except for the sensor #3 for which results are lightly more dispersed than for the three other sensors.

A pairwise comparison is then performed for each acoustic sensor between the L_{Aeq} indicator and the ambient temperature or relative humidity given by the temperature and relative humidity reference HOBO sensor alternately.



(a) T_{sensor} (purple) vs. T_{ref} (red)



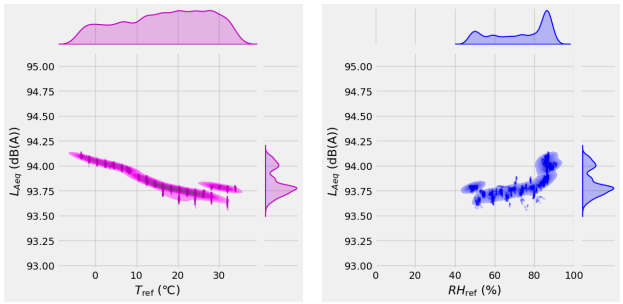
(b) RH_{sensor} (yellow) vs. RH_{ref} (blue)

Figure 5: Illustration of the database cleaning process result for the low-cost (sensor #1) and reference sensors (a) temperatures (purple and red markers resp.) and (b) relative humidities (yellow and blue markers resp.) over the 1st meteorological cycle. The left and right y-axis scales correspond to the low-cost (sensor #1) and reference data respectively. Rejected data appear as gray crosses.

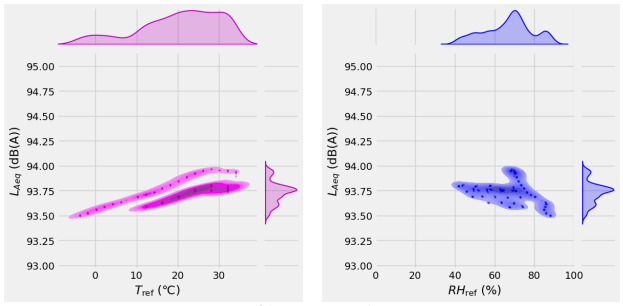
Table 1: Mean, median and standard deviation values of L_{Aeq} (dB(A)) for all meteorological conditions.

sensor	mean	std.	median
sonometer	93.83	0.13	93.79
sensor #1	93.73	0.11	93.75
sensor #2	93.37	0.15	93.41
sensor #3	93.91	0.34	93.79
sensor #4	93.67	0.10	93.65

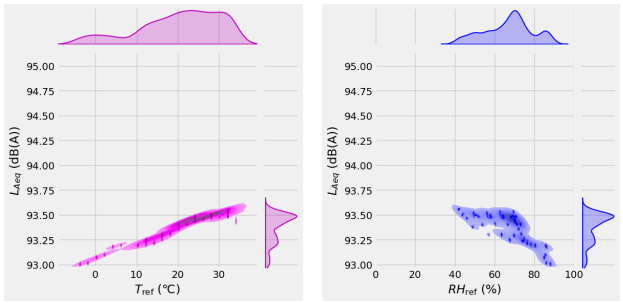
The results presented at figure 6 show that the sound levels recorded by the low-cost sensors (figures 6(b-e) tend to linearly increase as temperature increases or as humidity decreases. The effect of temperature on the microphone sensitivity (figures 6(b-e), left-side graphs) is consistent with the expected tendencies [4] and the standard deviation on L_{Aeq} values remains constant and low whatever the temperature, except for the sensor #3 that exhibits greater



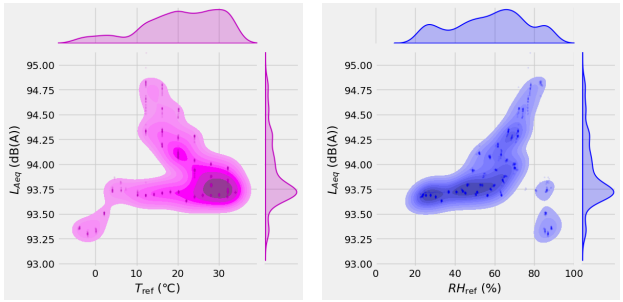
(a) Sonometer



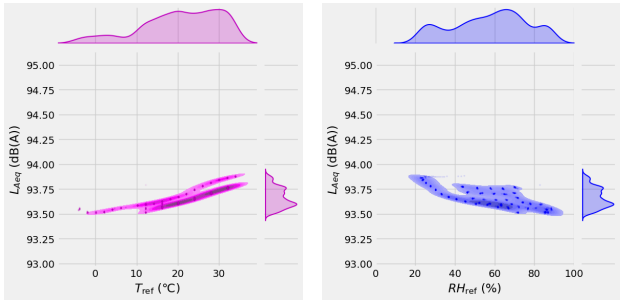
(b) sensor #1



(c) sensor #2

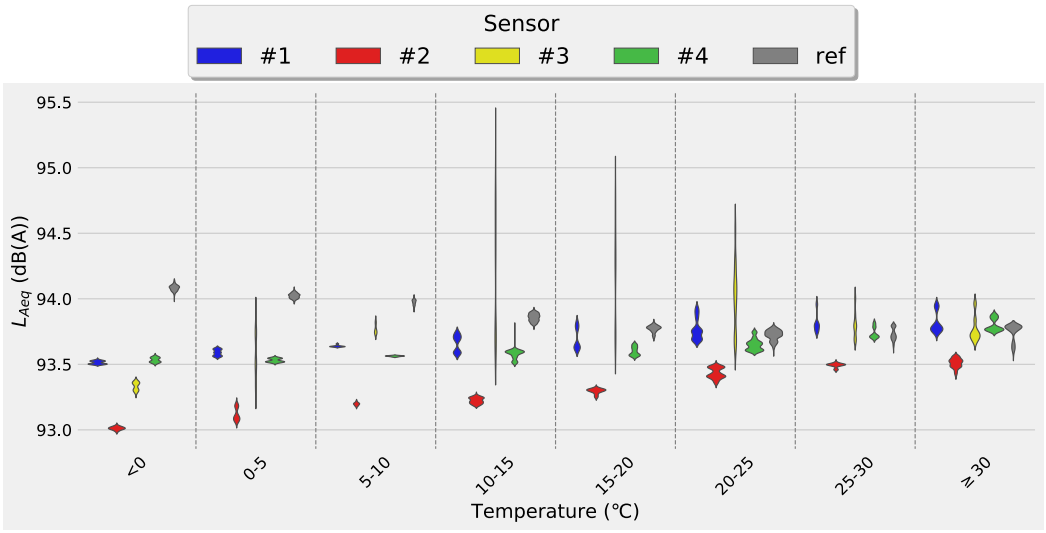


(d) sensor #3

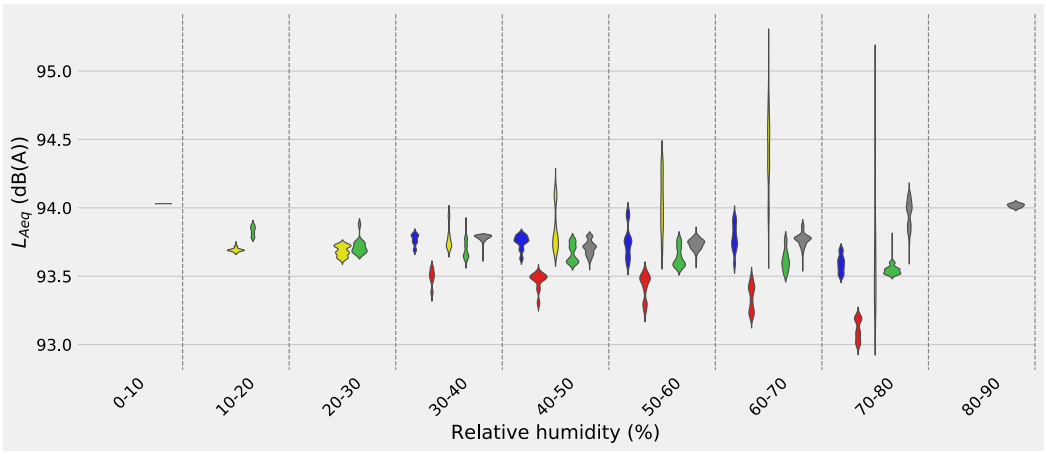


(e) sensor #4

Figure 6: Pairwise scatter plots between the L_{Aeq} indicator and (left) temperature and (right) relative humidity: (a) sonometer and (b-e) low-cost sensors.



(a) Temperature



(b) Humidity

Figure 7: Categorical plots of the L_{Aeq} values according to (a) the temperature and (b) relative humidity for the sonometer and low-cost sensors respectively.

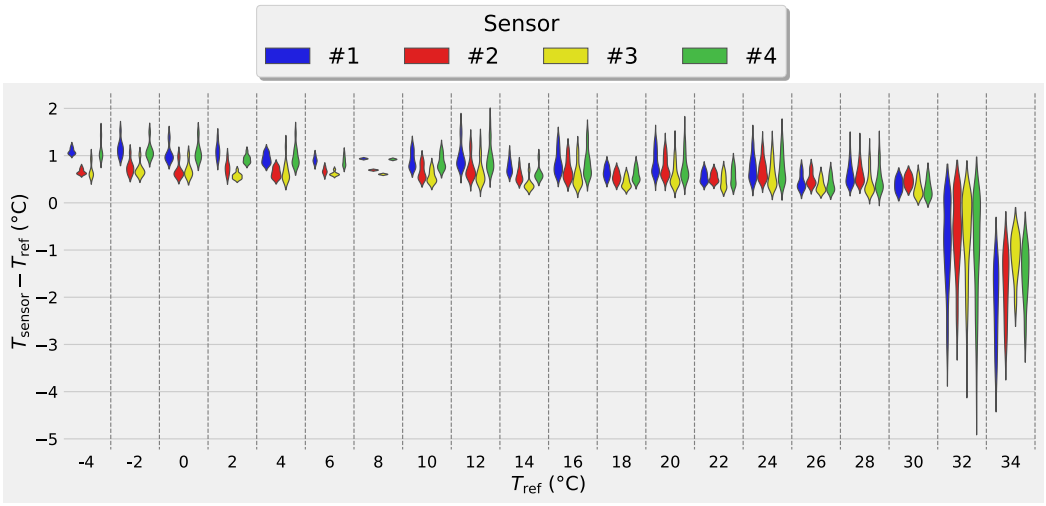
dispersion. The behavior of the sonometer according to temperature (figure 6a, left-side graph), which is characteristic of the integrated electret-type microphone, is opposite to the one of low-cost sensors. Regarding the effect of humidity on L_{Aeq} values (figures 6b-e, right-side graphs), results are more dispersed whether for the low-cost sensors or sonometer. An opposite trend is globally observed if comparing the responses of both kind of sensors according to the ambient humidity. As mentionned above, one can note that the discrepancies of the acoustic response of the sensor #3 according to both temperature and hygrometry is greater than the ones of other low-cost sensors what can be due to a tightness defect between the PEX tube and the sound calibrator. By the way, table 2 shows that the root-mean-square deviation (RMSD) of the temperature and relative humidity given by the low-cost sensors and reference sensors lightly increases for the sensor #3.

By now, the distributions of L_{Aeq} values are analysed within temperature and relative humidity categories as presented at figure 7. Temperature and relative humidity categories are defined over ranges of 5° C and 10% respectively. Results show that both temperature and humidity have a weak effect on the acoustic measurements. The standard deviation of L_{Aeq} is of the same order of magnitude for the low-cost sensors as for the sonometer, except for the sensor #3 which exhibits the largest deviations.

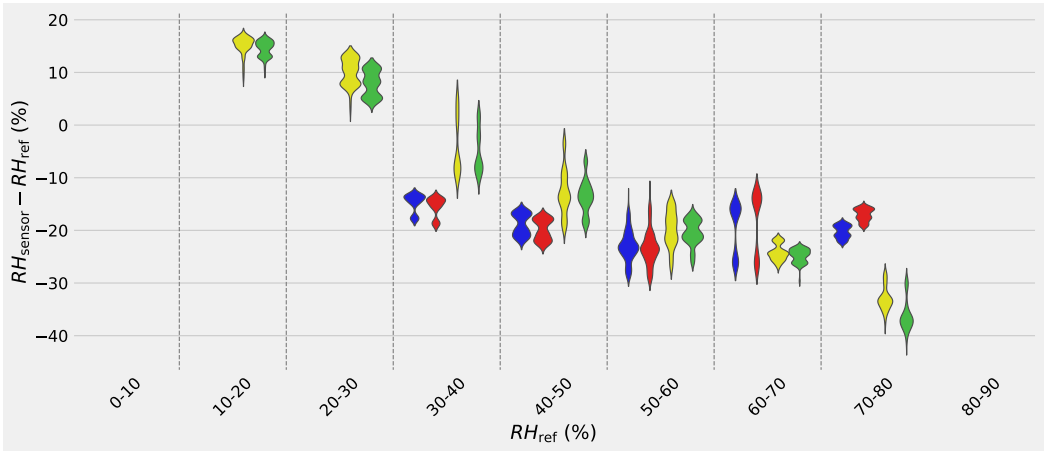
Table 2: Root-mean-square deviation (RMSD, in %) between temperature and relative humidity issued from the HOBO and low-cost sensors.

low-cost sensor		#1	#2	#3	#4
RMSD (%)	T	0.97	0.81	0.72	0.95
	RH	20.42	20.06	19.73	20.58

Regarding the temperature and humidity values provided by the low-cost sensors, the figure 8 presents the deviation in comparison to the values issued from the reference T/RH sensor. Temperature ranges are refined with categories defined over ranges of 5° C. Humidity ranges are identical as the ones in figure 7b. Although the RH/T sensor is not intended to measure the ambient meteorolog-



(a) Temperature



(b) Humidity

Figure 8: Categorical plots of the deviation of (a) temperature and (b) relative humidity measured by the low-cost sensors compared to reference T/HR sensor measurements.

ical conditions, the error on temperature values is fairly acceptable until 30° C and on the order of 1° C. On the other hand, the error on humidity values is too large to use this sensor with the aim of estimating the ambient relative humidity. Note that all acoustic sensors have not been submitted to strictly identical humidity conditions due to the difficulty to manage accurately the humidity inside the climatic chamber, what is noticeable at figures 7b and 8b.

4. CONCLUSION

Low-cost sensors could help to reach an interesting spatial granularity for the purpose of monitoring environmental noise. The critical point concerns the confidence in the measurements carried out with such devices. Innovative acoustic measurement systems dedicated to environmental noise monitoring were designed within the framework of a research project and are investigated under various meterological conditions in terms of reliability, accuracy and robustness. Series of acoustic measurements were performed with the developed low-cost sensors placed in climatic chamber by imposing temperature and relative humidity cycles. Results demonstrate the satisfying accuracy of the implemented acoustic sensors for the targeted purpose. Future investigations will concern the reliability of the low-cost sensors over a long period of time by controlling the accuracy of acoustic measurements in comparison with a reference sensor.

5. ACKNOWLEDGEMENTS

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