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A low-cost noise measurement device for noise mapping based on mobile sampling

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Abstract

For the production of representative noise maps, a large amount of information is necessary, which includes, among others, on-site measurements of environmental noise. Thus, mobile sampling emerges as a possible solution for the enhancement of data acquisition. The present paper proposes a low-cost noise monitoring device, in order to take georeferenced mobile measurements at each 1/3 octave band (63 Hz - 10 kHz). The implementation and accuracy tests of the equipment are presented. It is found, under laboratory and field tests, that the device measurement values are around ± 0.5 dB of those obtained with a Class 1 sound level meter for L_{Aeq} and around ± 1 dB for 1/3 octave band. Furthermore, a set of mobile measurements taken suggest that it is actually possible to perform the mobile sampling, which would improve the spatiotemporal granularity of noise measurements without compromising the accuracy, although certain requirements should be fulfilled to ensure representativeness.

Keywords: Mobile monitoring, Georeferenced sampling, Low-cost sensor,

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1 **1. Introduction**

2 To create a noise map based on measurements, the levels shown in the
3 noise map must be representative, which requires having a large amount of
4 data in both the duration of the measurements [1–4] and in sampling sites
5 [5, 6]. The measurement equipment should fulfill minimum requirements
6 regarding its accuracy which makes more expensive the sampling process.
7 As a consequence, the production of a noise map becomes a complex task
8 that demands many resources.

9 Advances in technology have allowed the development of sensor nodes pro-
10 vided with communication modules at a reduced cost but that have enough
11 processing power to perform different sensing and data transfer tasks [7].
12 In recent years, several studies regarding the design and implementation of
13 environmental monitoring stations have been carried out [8–11]. Their main
14 objective is to propose measuring tools at lower costs but that also guarantee
15 the precision of the acquired samples. Having several nodes interconnected
16 and working collaboratively to perform a global task, makes possible the idea
17 of a sensor network [12, 13], which could be applied over a wide range of tasks
18 such as environmental monitoring, medical applications, traffic counting, se-
19 curity and more [14–16]. However, the measurement points when assessing
20 street traffic noise are representative of a very specific environment, basically
21 the section of street on which they are located, unlike other environmental
22 agents with more homogeneous distribution.

23 Other sampling method that, in general, nowadays is being more common

is the participatory sensing or citizen oriented model [17]. Participatory sensing encourages the use of mobile devices, specially smartphones, to collect, analyze and share the sampled data which would increase the granularity in both spatial and temporal aspects [18]. However, participatory sensing for the specific case of environmental noise assessment has many drawbacks that are already under study. One of them is the data trustworthiness, since the sampling is left entirely in the hands of the citizen, the data integrity and representativeness is not fully assured. In [17, 18], information related to challenges and requirements to correctly address noise mapping through participatory sensing is presented. Moreover, since different devices have different sensors, their individual calibration for the wide variety of apps would reduce the advantages of participatory sensing [19, 20].

Another approach to increase spatial and temporal resolution in a more controlled environment is mobile monitoring, which enables the noise sensor to change its position while acquiring noise information. To properly represent the noise levels for map creation, the sampled data should be synchronized with its positioning information [21, 22]. Then, as the data is acquired over a large range of points across a predefined route, the spatial resolution is increased considerably, and if the route is repeated several times, the temporal resolution will also be considerably increased [23]. Thus, an important task to perform the mobile sampling is selecting the proper vehicle to mount the noise sensor. It has been shown that measurements taken walking may be convenient [24]. For the case of samples taken by car or bicycle, it is suggested that more tests should be performed since other variables such as the microphone position, the GPS accuracy and the noise contribution of

the vehicle itself should be taken into account [22]. Furthermore, mounting the measuring device in a bus for real-time noise mapping has been proposed and the requirements that should be addressed have been analyzed [25].

In order to perform mobile sampling, the first part of the present research proposes the design, implementation, calibration and accuracy tests of a low-cost Georeferenced Noise Sensor (GNS) designed to measure the noise spectrum at each 1/3 octave bands ($1/3\text{OB}$) in the frequency range from 63 Hz to 10 kHz. The aim is to take georeferenced mobile measurements with an equivalent accuracy of a Type 2 sound level meter. The device consists in a Microcontroller, a digital MEMS microphone, a Micro SD card and a GPS module. For the second part of the research, the monitoring device is mounted in a bicycle and several mobile measurements are taken simultaneously to static ones to validate the proper operation of the equipment, and to compare the mobile sampling versus the static one for three different conditions: center of the road, free field and façade.

2. Methodology

2.1. Georeferenced Noise Sensor (GNS)

2.1.1. Hardware considerations

Two goals should be addressed by the proposed mobile measurement device, one is the low price of the whole set of components, and the other one regarding the accuracy, that should be equivalent to a Type 2 sound level meter for L_{Aeq} [26].

Additionally, since the spectrum data could be very useful for the post-processing of measurements to perform more complex tasks such as vehicle

73 classification [27], soundscapes differentiation [28] or differentiating traffic
74 from leisure noise [29], the device is designed to obtain noise levels for each
75 $1/3$ OB in the mentioned frequency range. The core components of the proto-
76 type are as follows:

77 • **Processing unit:** The main processing unit should be able to per-
78 form digital signal processing tasks as well as communicating with the
79 different modules to acquire and store the noise data and location in-
80 formation. Thus, the selected microcontroller is the STM32F411RE
81 from STMicroelectronics. Its main characteristics are:

82	• 100 MHz clock speed	84	• 512kB Flash
83	• 128kB RAM	85	• 13 communication interfaces

86 • **Digital MEMS microphone:** MEMS microphones have been re-
87 placing the condenser ones in most of the consumer electronics [30].
88 Furthermore, it has been shown that the MEMS technology is able
89 to fulfill the requirements for noise measurements [26, 31]. Moreover,
90 the digital versions of the MEMS microphones are replacing the analog
91 ones, as they offer some advantages such as the reduction in possible
92 noise sources, since most of the components are integrated in the same
93 chip. Therefore, the digital MEMS microphone SPH0645LM4H-B from
94 Knowles Corporation is proposed as the noise sensor. Its frequency re-
95 sponse is shown in Figure 1 and its main characteristics are summarized
96 as follows:

- 97 • SNR of 65 dBA 99 • I2S Output
- 98 • Typ. current 600 μ A 100 • Omnidirectional

- 101 • **GPS:** For the positioning information, the module RXM-GPS-RM-
102 B from Linx Technologies was selected. Its main characteristics are:
103 low current consumption, high precision, serial communication and low
104 price. The module was complemented with an external passive antenna
105 that matches the GPS frequency range (1.575 to 1.602 GHz) and the
106 required impedance (50 Ohms).
- 107 • **Micro-SD:** Although the microcontroller is able to integrate wireless
108 modules for data sharing, the GNS is designed to work off-line and to
109 store the gathered data in a Micro-SD card attached to the processing
110 unit.
- 111 • **Other components:** A 3V cell battery is connected to the processing
112 unit to keep the Real Time Clock (RTC) synchronized. It is also used
113 to power the Static Random Access Memory (SRAM) and RTC of
114 the GPS module to have a faster Time To First Fix (TTFF). A 3.3V
115 voltage regulator is connected at the input to regulate the voltage of
116 the whole set of components. The GNS is designed to work with three
117 AA batteries but also could be powered by an external source such as
118 a mobile phone charger (up to 12 V). Table 1 shows a list of the whole
119 set of electronic components required for the measurement equipment
120 and its price. The total cost of one unit is also shown.

121 A printed circuit board (PCB), which includes all the components, was
122 designed to be attached to the microcontroller evaluation board. Figure 2

Figure 1: Frequency response of the SPH0645LM4H-B MEMS microphone according to the specification sheet of the microphone [32].

Table 1: List of materials and total price for a prototype unit.

<i>Name</i>	Description	Price (€)
<i>STM32F411RE</i>	Microcontroller with evaluation board	11.09
<i>SPH0645LM4H-B</i>	Digital MEMS microphone with evaluation board	5.70
<i>RXM-GPS-RM-B</i>	GPS Module (single chip)	16.44
<i>Passive antenna</i>	GPS antenna with micro coaxial connector	2.45
<i>MIC5504-3.3YM5-TR</i>	LDO voltage regulator	0.12
<i>Micro SD</i>	16GB Micro SD memory	11.91
<i>Connectors and case</i>	Coin cell, AA battery holder, plastic case, microphone connectors, Micro SD connector, leds, push button, cables, resistors and capacitors	17.68
Total cost:		65.39

Figure 2: Prototype of the georeferenced noise sensor (a) and PCB with components location to be mounted on the microcontroller evaluation board (b).

123 shows the final design of the GNS and its PCB.

124 2.1.2. Software considerations

125 Since multiple task should be performed almost at the same time, the
 126 core of the software implementation is programmed based on the Real Time
 127 Operative System (RTOS) of the Mbed platform developed by ARM com-
 128 pany and its partners [33]. The data must be sampled continuously to avoid
 129 losing information, and the signal processing, georeferencing and data stor-
 130 age tasks must not influence the sampling process. Then, proper timing and
 131 task synchronization should be carried on. The scheme presented in Figure
 132 3, shows the 3 main tasks of the software implementation:

- 133 (a) **Data sampling:** This task performs the sound acquisition from the
- 134 digital MEMS microphone. To ensure that no data is lost, since the
- 135 samples must be taken continuously, it is configured with the highest

136 priority. The sampled data is temporarily stored in an array of 4000 el-
 137 ements, according to capacity of RAM, which for a sampling frequency
 138 of $F_s = 32$ kHz, the vector is filled every 125 ms. Thus, once a full
 139 vector of data is obtained, it is copied to another 4000 vector array to
 140 process the data. Then, the signal processing task is triggered.

141 (b) **Signal processing:** Since the frequency response of the microphone
 142 is not totally flat for the whole range of frequencies, previous to all
 143 calculations, a filter designed to compensate the frequency response is
 144 applied to the sampled data. Then, the 125 ms A-weighted equivalent
 145 level ($SPL_{A,125ms}$) is computed. The following step is to compute the
 146 SPL for the $1/3$ OB ($SPL_{f_c,125ms}$). The $1/3$ OB filters are designed in
 147 accordance to [34, 35] for an equivalent Class 1. Moreover, in order
 148 to reduce the processing load and to improve the filter response, for
 149 frequency bands under 2.5 kHz, a decimation filter with a factor of 2
 150 is applied (groups of 4 bands). Then, the signal is filtered for each
 151 $1/3$ OB ($f_c = 63$ Hz - 10 kHz) and the $SPL_{f_c,125ms}$ for each frequency is
 152 computed. The signal processing task is repeated 8 times to achieve a
 153 sampling time of 1 s. Then, the storage task is triggered.

154 (c) **Georeferencing and data storage:** Although it is possible to store
 155 the 125 ms data, since the GPS provides positioning information each
 156 1 s, the each second equivalent level of the $1/3$ OB ($Leq_{f_c,1s}$) and the
 157 A-weighted one ($Leq_{A,1s}$) are computed based on the eight $SPL_{f_c,125ms}$
 158 and $SPL_{A,125ms}$. Then, the data is appended with the time-stamp and
 159 the geographical information. Finally the data is stored in the Micro-
 160 SD card and the cycle is repeated until the measurement is stopped.

Figure 3: Flow chart of the (a) data acquisition, (b) signal processing and (c) data storage tasks of the RTOS implementation.

2.1.3. Laboratory tests

The laboratory tests were performed inside a semi-anechoic chamber using 5 GNSs and one Type 1 sound level meter (SC-310 CESVA) as a reference. A studio quality speaker with a frequency range from 50 Hz to 12 kHz was employed to produce the testing noise. The 5 MEMS microphones of the GNSs were put as close as possible surrounding the sound level meter microphone in a circular shape. The height of the microphones array was 1 m and its distance to the speaker was 45 cm. The testing setup can be observed in Figure 4.

The first part of the laboratory tests consists in performing a calibration of the GNSs. Thus, the calibration procedure is as follows:

Figure 4: Microphone arrangement for laboratory tests.

- 172 1. **Frequency response:** For the range of frequencies from 50 Hz to 12
 173 kHz, a sine-swept signal is applied to the array of GNSs to compute
 174 the frequency response [36].
- 175 2. **Compensation filter:** A filter is designed and implemented based on
 176 the inverse of the frequency response of the microphone. The filter is
 177 normalized to zero gain on the 1 kHz frequency.
- 178 3. **Global calibration:** Once the frequency response of the microphone
 179 is flattened, a global calibration value is computed to reference the
 180 GNSs to the sound level meter at 94 dB@1 kHz. Thus, a signal of 1
 181 kHz is applied to the array of GNSs for 3 minutes. The mean difference
 182 of the L_{Aeq} for the GNSs and the sound level meter is computed and
 183 used as the global calibration value.

184 **4. Validation:** The calibration is validated applying pink and white noise
 185 at 70 and 80 dBA (bandwidth of the speaker, from 50 Hz to 12000
 186 kHz) to the GNSs and computing the Leq , L_{Aeq} and Leq_{fc} for the total
 187 measurement time (5 minutes).

188 Once the calibration is done, the accuracy tests as stated in [37] are
 189 performed as suggested in [26], to verify whether the GNS has an equivalent
 190 accuracy of a Type 2 sound level meter. Moreover, in order to test the
 191 actual precision of the GNSs when measuring real traffic noise, 30 minutes
 192 of measurements were taken outside of an open window at an approximated
 193 height of 6 m. The setup of the microphones was the same as the one used
 194 for the laboratory tests, but the array of microphones was protected by a
 195 wind shield.

196 2.1.4. Uncertainty evaluation

197 A complementary analysis to assess the reliability of the L_{Aeq} data pro-
 198 vided by the GNSs is performed. Thus, the standard uncertainty Type A,
 199 $u(L_{Aeq})$, is computed according to the procedure stated in [38]. The variance
 200 of the observations is first computed as:

$$s^2(L_{Aeq}) = \frac{1}{N-1} \sum_{i=1}^N (L_{Aeq}(i) - \overline{L_{Aeq}})^2 \quad (1)$$

201 where N , which depends on the signal input, is the number of samples for
 202 the whole testing time, and $\overline{L_{Aeq}}$ is the equivalent level of the signal for the
 203 whole testing time as well. Then, the $u(L_{Aeq})$ is computed as:

$$u(L_{Aeq}) = \sqrt{\frac{s^2(L_{Aeq})}{N}} \quad (2)$$

204 The signals used to calculate the uncertainty are, on one hand, the white
205 and pink noise at 70 dBA and 80 dBA ($N = 300$) which are the same used
206 for the calibration validation and, on the other hand, the 94 dB@1 kHz signal
207 ($N = 180$) which is used for the global calibration test (Section 2.1.3). The
208 Type A standard uncertainty is computed for the whole set of GNSs and for
209 the sound level meter for comparison.

210 *2.2. Mobile measurements*

211 *2.2.1. Study area*

212 The second part of this research consists in the mobile sampling and the
213 comparison to the static one. The selected street is a main avenue with 3
214 lanes by each side of the road and a two-way bicycle exclusive lane in the
215 center. The width of the street is approximately 33 m including sidewalks
216 (22 m of traffic lanes) with an approximated traffic flow of 1000 vehicles per
217 hour. Both, fixed and mobile measurements were taken simultaneously in
218 the area under assessment. To ensure the reliability of the measurements,
219 under the laboratory conditions as stated in Section 2.1.3, the calibration of
220 the devices was performed before and after the whole measurement process.
221 Thus, three GNSs were put at an approximated height of 1.5 m in an L-
222 shaped segment of the avenue, with buildings on one side and a soccer field
223 on the other. Thus, one GNS was located in the free field conditions, another
224 one at the middle of the avenue and the last one was put at 1 m from the
225 façade. The measurement configuration and more information about the
226 place under study is shown in Figure 5.

227 Five passes-by for each side of the road were taken using one GNS mounted
228 in a bicycle (Figure 6). Special care was taken about speed, road irregular-

Figure 5: Map of the place under study (Abat Marcet, Terrassa, Spain). The road is highlighted in red and the fixed measurement points are indicated as a circle: 1) Free field, 2) Center and 3) Façade.

Figure 6: Bike with the GNS mounted in the lower part of the seat. The microphone is located at the top of a tube at an approximated height of 2 m.

ities and self generated noise by the bike to avoid external noise sources.
 Thus, the speed of the bike was always below 5 m/s to avoid applying any
 corrections. The microphone was also provided with a windshield.

2.3. Measurements analysis

A comparison of the noise level measured by the mobile GNSs when
 passes near to the static receiver is proposed. The procedure is based on the
 one shown in [24], where an analysis of mobile (walking person) and static
 measurements is done. It is proposed to join mobile samples to compute its
 equivalent level (aggregation of mobile samples) according to a distance of

238 aggregation which ensures that both, the fixed and the mobile receivers are
239 measuring the same acoustic environment.

240 To compare the A-weighted ($L_{Aeq,fix}$) and the $1/3$ OB ($Leq_{fc,fix}$) equivalent
241 noise levels sampled by the static GNS, and the A-weighted ($L_{Aeq,mob}$) and the
242 $1/3$ OB ($Leq_{fc,mob}$) equivalent noise levels sampled by the mobile one, the data
243 should be synchronized in time and space to study the data representative
244 of the same sound environment. The following procedure is carried on to
245 perform the analysis for each pass-by:

- 246 1. **Time and space synchronization:** The closest point between the
247 mobile measurement and the fixed station is obtained. Then, for 20 s of
248 measurements centered at the closest point, the mobile signal is shifted
249 in time until the maximum correlation coefficient between $L_{Aeq,fix}$ and
250 $L_{Aeq,mob}$ is obtained.
- 251 2. **Spatial aggregation:** To ensure the spatial representativeness, the 35
252 m radius suggested in [24] is then used for the aggregation of mobile
253 noise measurements taking the static receiver position as a reference.
254 The $L_{Aeq,mob}$ and $Leq_{fc,mob}$ of the set of samples within this aggregation
255 radius is computed for the mobile measurements.
- 256 3. **Fixed-Mobile noise levels:** The $L_{Aeq,fix}$ and $Leq_{fc,fix}$ are computed
257 for the same time-lapse as the aggregated mobile noise measurements.
258 Thus, the noise level difference as $L_{Aeq,fix} - L_{Aeq,mob}$ and $Leq_{fc,fix} -$
259 $Leq_{fc,mob}$ are finally computed.

260 The process is repeated 10 times (10 passes-by) for the three static re-
261 ceivers.

262 3. Results

263 3.1. Laboratory tests

264 3.1.1. Calibration

265 The frequency response of the microphone with the compensation filter
266 response is shown in Figure 7a. The standard deviation of the global cali-
267 bration value was 0.27 dBA, which ensures that the same value can be used
268 for the 5 GNSs. The calibration validation is shown as a box-plot in Fig-
269 ure 7b. It is performed using white and pink noise signals to validate the
270 $1/3$ OB equivalent levels as well as the Leq and L_{Aeq} . It can be observed that
271 the variability within GNSs is, for most of the frequencies, under ± 1 dB.
272 Furthermore, all the $1/3$ OB are within ± 1 dB from the reference sound level
273 meter.

274 3.1.2. Accuracy and standard uncertainty evaluation

275 A summary of the testing results is presented in Table 2. It is observed
276 that the GNS is able to measure noise levels with an equivalent accuracy
277 as a Class 2 sound level meter for frequencies between 63 Hz to 10 kHz,
278 which is suitable for typical environmental noise evaluation. Furthermore,
279 it is observed that the Type A standard uncertainty brought similar results
280 for the 5 GNSs compared to the reference sound level meter, that under the
281 testing conditions, it would suggest that the trustworthiness of the noise level
282 recorded by the proposed measuring devices is comparable to the one of the
283 sound level meter. Due to their wider spectral content, it is also observed
284 that the uncertainty is slightly higher for the case of the Pink and White
285 noise signals. The close values of the GNS to the sound level meter confirms

Figure 7: (a) Mean frequency response of 5 SPH0645LM4H-B microphones. The frequency response of the compensation filter is also shown. (b) Box plot showing the 25%-75% percentiles, the data range and the mean differences of the Leq , $LAeq$ and Leq_{fc} , between the sound level meter and the 5 GNSs (white and pink noise signals at 70 and 80 dBA, 20 samples in total).

Table 2: Results of the accuracy test compared to the requirements for a Class 2 sound level meter indicated in IEC61672 [37, 39]. The Type A standard uncertainty computed for the L_{Aeq} according to [40] is also shown.

Frequency weighting			
Frequency	Measure (dB)	Limit (dB)	Comply
63 Hz	-24.4	-26.2 ± 2	Passed
80 Hz	-21.8	-22.5 ± 2	Passed
100 Hz	-18.2	-19.1 ± 1.5	Passed
125 Hz	-15.7	-16.1 ± 1.5	Passed
160 Hz	-13.3	-13.4 ± 1.5	Passed
200 Hz	-10.9	-10.9 ± 1.5	Passed
250 Hz	-8.6	-8.6 ± 1.5	Passed
315 Hz	-6.5	-6.6 ± 1.5	Passed
400 Hz	-4.7	-4.8 ± 1.5	Passed
500 Hz	-3.2	-3.2 ± 1.5	Passed
630 Hz	-1.8	-1.9 ± 1.5	Passed
800 Hz	-1.0	-0.8 ± 1.5	Passed
1 kHz	0.0	0 ± 1	Passed
1.25 kHz	0.5	0.6 ± 1.5	Passed
1.6 kHz	0.9	1 ± 2	Passed
2 kHz	1.2	1.2 ± 2	Passed
2.5 kHz	1.3	1.3 ± 2.5	Passed
3.15 kHz	0.9	1.2 ± 2.5	Passed
4 kHz	0.9	1.0 ± 3	Passed
5 kHz	0	0.5 ± 3.5	Passed
6.3 kHz	-1.5	-0.1 ± 4.5	Passed
8 kHz	-3.2	-1.1 ± 5	Passed
10 kHz	-5	-2.5 [+5;-∞]	Passed
Level linearity			
Frequency	Measure (Min,Max) (dBA)	Range	Comply
1 kHz	44.2, >115	70.8	Passed
4 kHz	42.1, >117	74.9	Passed
8 kHz	43.3, >116	72.7	Passed

Tone-burst			
Time (ms)	Δ (dB)	Target (±lim (dB))	Comply
1000	0.0	0 (± 1)	Passed
500	0.0	-0.1 (± 1)	Passed
200	-0.1	-1.0 (± 1)	Passed
100	-2.3	-2.6 (± 1)	Passed
50	-4.3	-4.8 (+ 1, -1.5)	Passed
20	-8.6	-8.3 (+ 1, -2.0)	Passed
10	-11.6	-11.1 (+ 1, -2.0)	Passed
5	-14.6	-14.1 (+ 1, -2.5)	Passed
2	-18.6	-18.8 (+ 1, -2.5)	Passed
1	-21.4	-21.0 (+ 1, -3.0)	Passed
0.5	-23.3	-24.0 (+ 1, -4.0)	Passed
0.2	-26.2	-27.0 (+ 1, -5.0)	Passed

Self generated noise			
Measure	Min	Max	Std
33.5 dBA	31.5 dBA	35.5 dBA	1.6 dBA

Long-term stability			
Measure (Init/End)	Error	Limit	Comply
94.5 dBA	0.2E ⁻³ dBA	± 0.3 dBA	Passed

Type A standard uncertainty					
Device	Pink Noise		White Noise		1 kHz
	@70 dB	@80 dB	@70 dB	@80 dB	@94 dB
SC-310	0.014	0.014	0.008	0.009	<0.001
GNS ₁	0.014	0.015	0.009	0.009	0.003
GNS ₂	0.014	0.014	0.009	0.009	0.001
GNS ₃	0.015	0.015	0.008	0.009	0.002
GNS ₄	0.014	0.014	0.009	0.009	0.002
GNS ₅	0.015	0.014	0.009	0.009	<0.001

the proper operation of the frequency compensation filter.

3.1.3. Traffic noise static measurements

A segment of 100 s of the 1 hour sampled noise (each second samples) is shown in Figure 8. It is observed that the $L_{Aeq,1s}$ measurements of the GNSs are quite similar to the sound level meter ones.

Figure 9 shows the Leq_{fc} of the GNS and the sound level meter for the

Figure 8: 100 s of urban audio sampled at 1 s, the noise level measured by SC-310 sound level meter compared to the average value of the 5 GNSs and its standard deviation.

half hour of traffic noise sampling. A box plot showing the mean value, 25%-
75% percentiles and data range of the estimation error is also shown. It can
be seen that the L_{Aeq} and Leq mean estimation errors are below ± 0.5 dB,
being the second one almost zero. For the Leq_{fc} , for frequencies below 5
kHz, the estimation error is under ± 1 dB from the reference. For the higher
frequencies, the obtained difference is due to the low noise levels at these
frequency bands, which are below the noise floor of the GNSs and also below
the minimum level to ensure linearity (33.5 dB and 44.2 dB, respectively, as
shown in Table 2).

3.2. Mobile measurements

3.2.1. GPS position accuracy

The position error was calculated based on the perpendicular distance of
the actual measurement location to the closest point of the bicycle exclusive
lane (Figure 10). The average position error of the whole set of sampled

Figure 9: Box-plot of the mean, the data range and the 25%-75% percentiles of the noise level difference between the GNDs and the sound level meter. The average of the Leq_{fc} measured by the 5 GNDs and the one sampled by the SC310 sound level meter is also shown.

points is 7.8 m with a standard deviation of 6.2 m (the position accuracy specified by the GPS module manufacturer is 3 m). The difference in the accuracy position could be due to the placement of the GNS and its antenna, that were put under the seat of the bicycle driver, which would probably affect the signal reception as the sky-view is reduced [41]. The difference obtained between the actual position and the one obtained by the GPS is accurate enough to georeference the receiver to its corresponding street, which is the objective of adding the positioning information. The speed was also computed for the whole measurement time obtaining an average of 3.1 m/s.

3.2.2. Fixed/Mobile comparison

As stated in Section 2.2.1, the calibration of the devices was performed before and after the whole mobile sampling procedure obtaining almost the same values. Thus, Figure 11 shows a box-plot of the Leq_{fc} and L_{Aeq} dif-

Figure 10: Perpendicular distance of actual measurement to the closest point in the bicycle exclusive lane.

ference between the static noise sensors minus the noise level of the mobile one for the 10 passes-by. As can be observed, the equivalent levels of the mobile measurement are most of the time higher than the fixed ones, which could be expected since the bicycle is just next to the source. Furthermore, a different pattern is observed in the noise levels measured by the GNS placed near the façade (Figure 11c) compared to the free-field and the center ones (Figure 11a and 11b, respectively), for the frequency bands under 250 Hz, an increase in the noise level around 4 dB is seen, which is probably caused by the façade reflections [42]. The observed variability between the passes-by, i.e. high data range in Figure 11, could be caused due to the relative position of the sources and the static and mobile receivers is different for each pass-by.

4. Analysis and discussion

The present study encourages a change in the static measurement approach by designing a noise sensor to perform mobile measurements. The huge amount of static receivers previously required, could be replaced by a small set of GNSs which would cover larger areas. Depending on the place under assessment, with just a few devices, that could be mounted in different type of vehicles, a noise map could be produced with less resources and without compromising accuracy, since the proposed noise sensor was tested to have an equivalent accuracy as a Class 2 sound level meter [26, 37].

The design of the device incorporates a digital microphone to acquire the acoustic signals, thus, the pre-amplification stage is avoided which reduces the size of the prototype, the possible sources of electrical noise and the final production price. Compared to other low-cost proposed hardware [8, 25,

(a)

(b)

(c)

Figure 11: Noise level difference between free field (a), central (b) and façade (c) fixed stations to the mobile one for Leq_{fc} and L_{Aeq} .

26, 43, 44], the cost for assembling one unit is greatly reduced (in most of the cases around 40%), which could be decreased even more if the whole set of components are integrated in a single PCB rather than using the manufacturers evaluation boards. Additionally, the incorporation of a GPS module into the system, enables the device to perform the georeferencing of samples automatically.

The capability of the GNS to produce $1/3$ OB spectrum, which is not common for low-cost sensor, can be used to produce an algorithm for outliers detection, which is very important for the mobile sampling since many external factors could affect the noise levels sampled. Furthermore, the $1/3$ OB spectrum could be useful when analyzing the noise measured while moving compared to static measurements, since the attenuation at each $1/3$ OB are observed to be different depending on the position of the static receiver. The noise level measured at the center of the avenue is very near to the one measured with the mobile GNS. Thus, a transfer function between a static receiver at the center of the street and one located at the façade, could be developed to estimate the perceived noise level at the façade, which is the parameter required by the normative [45]. A wider set of static and mobile measurements that could also be based on simulations, which expands the variety of street configurations, could confirm that the spectrum difference between the fixed and mobile measurements follows a pattern, which has been suggested to be affected by the distance to the façade and the height of the measurement as well [24].

The preliminary tests performed in this research confirmed that several factors should be addressed before making a noise map based on mobile

368 measurements, which could be related to the selected vehicle such as:

- 369 • Microphone/GNS position [22]₁ • Max speed [46]
- 370 • Self generated noise [25]

372 or related to the data processing, such as

- 373 • Samples aggregation [23, 47] ₃₇₆ • Equivalent façade level [24]
- 374 • Crossway uncertainty [48, 49] ₃₇₇ • Outlier detection [20]
- 375 • Sampling routes [25] ₃₇₈ • Required samples (pass-by) [50, 51]

380 Mounting the GNS in a bike has been shown to be a good option to deal
381 with the noise of the vehicle itself and the max speed limitation. For the
382 case of the GNS position, it was observed that the GPS antenna should be
383 placed trying to avoid the screening of the bike driver to improve the position
384 accuracy as suggested in [41].

385 Since the scope of the present research is limited to the design and testing
386 of the device when taking mobile samples rather than the post-processing of
387 the mobile samples themselves, the outlier detection was not included in this
388 paper but it was actually performed. Few outliers were found during the
389 mobile measurements. Some of them were related to the traffic itself, which
390 only increased the noise level measured but keeping similar spectrum shape
391 as the rest of the measurements. Other type of outliers were detected that,
392 apart from an increase in the noise levels, they had a different shape in the
393 spectrum, characterized by an increase in noise levels at high frequencies.

394 The cause of the latter ones could not be found and they were removed, only
395 2 of this type were found during the whole measurement time.

396 Finally, for the case of the nocturnal noise measurements where the back-
397 ground and the actual traffic noise are very low, since the levels measured
398 by the GNS are expected to be above 40 dB as seen in Section 3.1.2 (linear-
399 ity and self generated noise), a technique based on street categorization and
400 a short number of long-term static measurements could be used to estimate
401 the L_{night} from the day-time measurements [52], instead of performing mobile
402 measurements at night that, apart from being more expensive and resources
403 demanding, would require longer measurement time to acquire representative
404 values.

405 5. Conclusions

406 The development of a noise sensor designed to perform mobile noise mea-
407 surements was introduced. The inclusion of a digital microphone simplifies
408 the design of the noise sensor and reduces its cost since only 4 core elements
409 are required: Microcontroller, Micro SD card, GPS and Microphone.

410 It was confirmed that with low-cost hardware it is possible to generate
411 reliable noise measurements, with an equivalent accuracy to a Class 2 sound
412 level meter for L_{Aeq} , and with a Type A standard uncertainty very similar
413 to the one observed by the reference equipment. Furthermore, more complex
414 tasks such as the $1/3$ OB spectrum computation was also shown to be possible
415 with accurate results. Since the hardware and programming of the GNS is the
416 same, a very low variability within the set of GNSs was observed during the
417 calibration and accuracy tests. Moreover, the same parameters were used

418 for the calibration of the 5 GNSs tested, which suggest that the obtained
419 calibration parameters could be used for further devices produced.

420 It was shown that the bicycle is a good option to perform mobile mea-
421 surements. Anyway vehicles that are already in transit such as public trans-
422 portation or delivery services, could also be used to perform the mobile mea-
423 surements but further consideration should be taken.

424 Finally, the preliminary tests confirmed practically that in order to pro-
425 duce a noise map based on mobile measurements, several factors should be
426 considered that could be related to the vehicle where the device is mounted
427 or to the data processing to produce the noise map.

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