MEMS digital microphone and Arduino compatible microcontroller: an embedded system for noise monitoring

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EAC
ACOUSTICAL ENGINEERING | UFSM

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Outline

Introduction: main goals

The **main goals** of this presentation are:

- Show a brief overview about sound pressure, sound pressure level, and sound level meters;
- Expose a brief discussion about noise monitoring;
- Describe the prototype of **a compact and cost-effective sound level meter** based on a **digital MEMS microphone** and the **Teensy 4.0 microcontroller**; and
- Present and discuss the **prototype performance** and **algorithm validations**.

Introduction

- The objective of this work is to design an embedded system focusing on **sound pressure level** (SPL) and **equivalent continuous sound level** (L_{eq}) measurements.
- The **direct application** is **sound/noise monitoring** according to SLM standards.

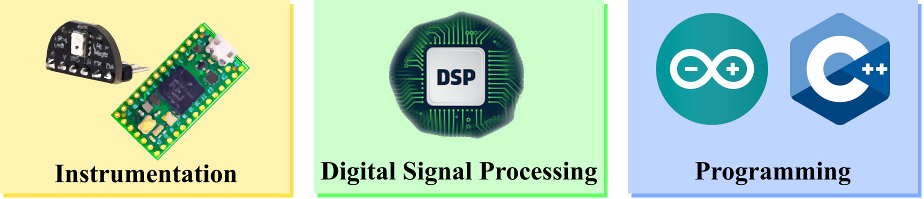


Figure 1: Three pillars of this work.

Sound Pressure

- **Sound pressure** is created by **variations over the static pressure** of the medium due to a **wave propagation** caused by some disturbance [1, 2, 3].

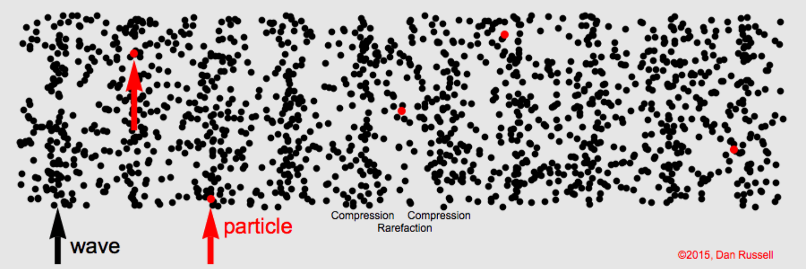


Figure 2: Sound pressure and particle displacement animation (credits to Dan Russel [4]).

Effective Sound Pressure (RMS)

- **RMS** is a suitable mathematical tool to deal with **time-varying quantities**, such as sound pressure and voltage.
- The **effective sound pressure** is closely related to the **energy content of a sound wave**.
- The **root mean square** (RMS) of sound pressure or **effective sound pressure** is graphically depicted below.

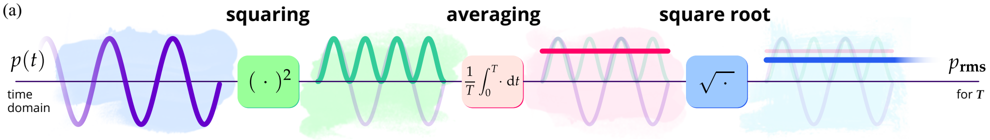


Figure 3: Step-by-step root mean square (RMS) calculation.

SPL and L_{eq}

- Sound pressure may range between micro to hundreds of Pascals. Thus, to ease reading and comparisons, sound pressure levels (SPL) are often used.
- **Sound pressure levels** are evaluated with a **logarithmic scale**, which **compresses the values**. The reference 20 µPa sets the 0 dB.
- Sound pressure levels correlate with the sensation of how loud a sound is.

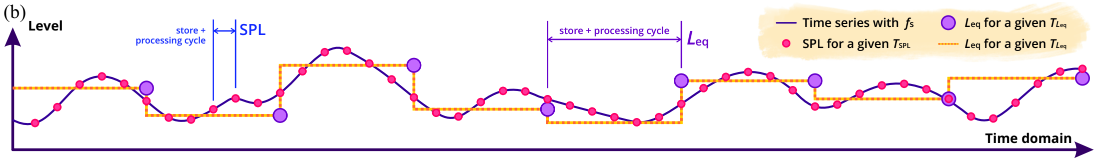


Figure 4: Time series with f_s, SPL, and L_{eq} measurement examples.

SPL and L_{eq}

Sound pressure level

$$\text{SPL} = 10\,\log_{10}\left(\frac{p_{\text{rms}}}{p_0}\right)^2 \;\text{dB}$$

Equivalent continuous sound level

$$L_{\text{eq}} = 10\,\log_{10}\left(\frac{1}{T}\int_0^T \frac{p^2(t)}{p_0^2}\,\mathrm{d}t\right)$$

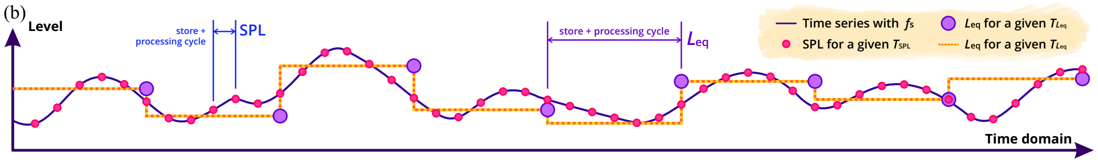


Figure 4: Time series with f_s, SPL, and L_{eq} measurement examples.

Sound Level Meter

- The sound level meter (SLM) is an instrument designed to **measure sound pressure level (SPL) in a standardized way** [5].
- It comprises a microphone, a conditioning circuit and a signal processing stage.
- Modern SLMs can measure a variety of acoustic parameters, ranging from simple noise measurements to building acoustics, vibrations, spectral analysis, etc.

Figure 5: B&K sound level meters.

Noise monitoring

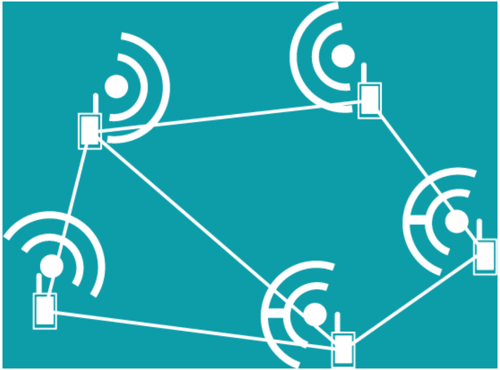


Figure 6: Drawing of a wireless acoustic sensor network (image from Spat blog).

- Noise and noise pollution assessments are generally made using L_{eq} measurements.
- It is common to assess the desired area using a sound level meter. Carrying out this way, it has some **disadvantages**, such as being **expensive** and **time consuming**.
- Innovation has trended towards the development of **wireless acoustic sensor networks** for noise pollution monitoring [6, 7, 8].

Outline

1. Introduction & Basic theory
2. The prototype
3. Algorithms validation
4. Performance tests
5. Conclusions

Prototype: components & assembled unit

In this section, the following **prototype components are** described:

1. **Digital MEMS microphone** used for sound acquisition;
2. **Teensy 4.0 microcontroller** (MCU) used for data acquisition;
3. Arduino **SD card module** used for data storage; and
4. **Portable batteries** used to power the system.

- Finally, the **fully assembled prototype is shown**.

Sound acquisition (MEMS mic)

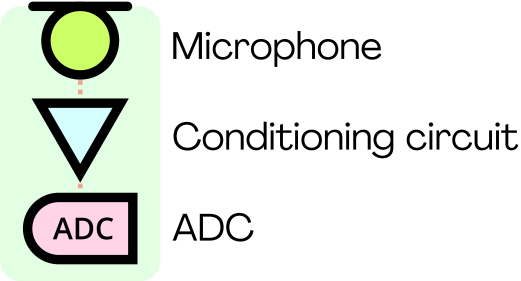
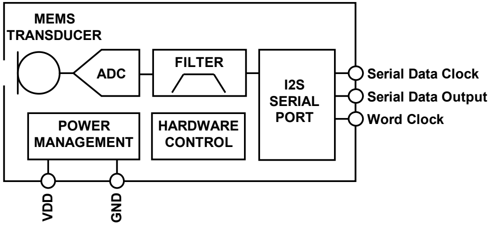


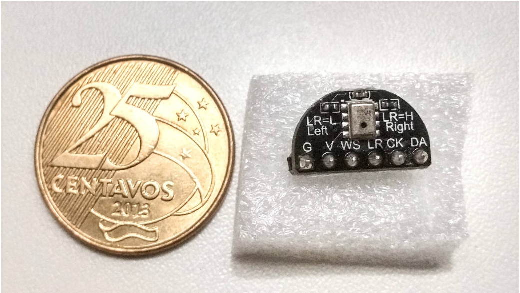
Figure 7: MEMS mic diagram.

- For the sound acquisition, the **Sipeed MSM261S4030H0** breakout board was used, which contains an I^2S [9] **digital MEMS microphone**.
- The device comprises, **on a single chip**, a condenser microphone, a conditioning circuit and a analog-to-digital converter (ADC).
- According to the datasheet, the micro-phone has a **flat frequency response** from 100 Hz to 10 kHz [10].

Sound acquisition (MEMS mic)



(a) I²S MEMS microphone block diagram [11].



(b) Picture of the breakout board near a Brazilian coin with a 25 mm diameter.

Figure 7: Block diagram and picture of the MEMS microphone onto the breakout board.

Processing (MCU) — Teensy

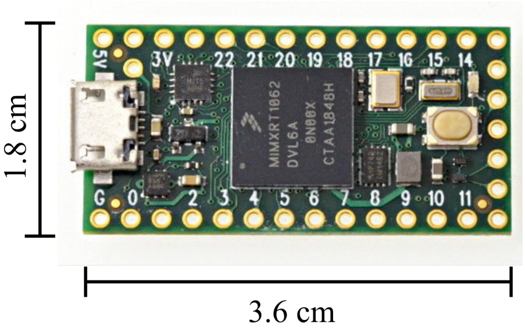


Figure 8: Teensy 4.0 MCU.

- For the processing stage, the **Teensy 4.0** Arduino compatible microcontroller (MCU) was used [12].
- It was chosen due to its **low-cost**, **low-power consumption**,**high computing power** (ARM Cortex M7 600 MHz), and **small size**.
- It comes with an open-source built-in **library for sound acquisition and processing** (it also has I^2S compatibility).

Teensy: Audio System Design Tool

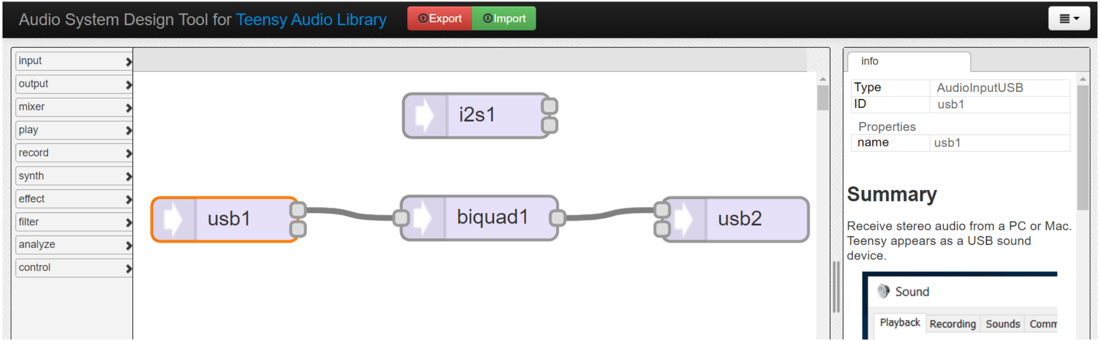
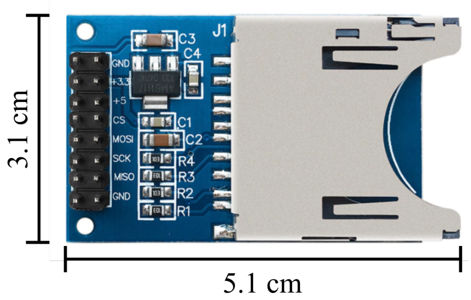


Figure 9: Audio System Design Tool, a guided user interface (GUI) to build audio programs with Teensy's audio library.

Saving & Powering

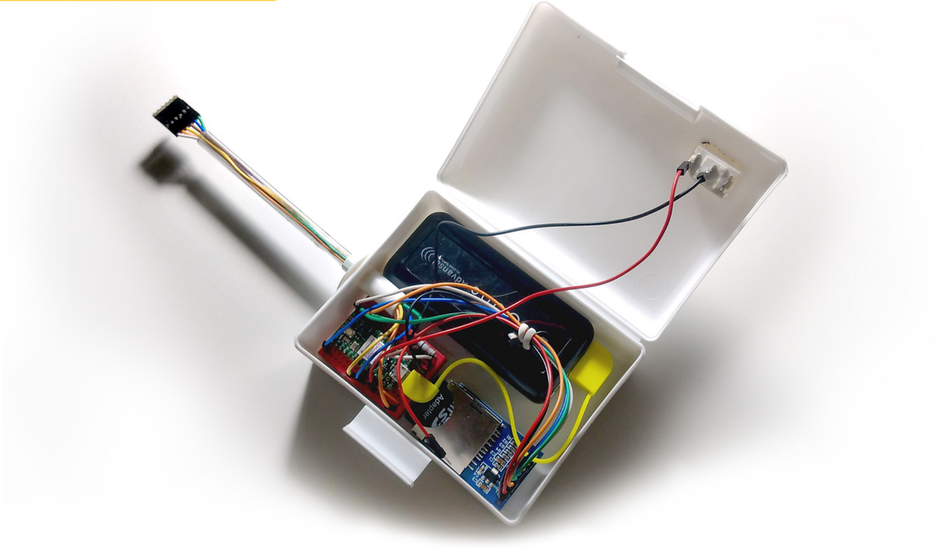


(a) Arduino SD card module.

(b) Portable batteries tested (4400 mAh and 10000 mAh).

Figure 10: Saving module and powering components.

Final prototype



Final prototype

Signal chain and features

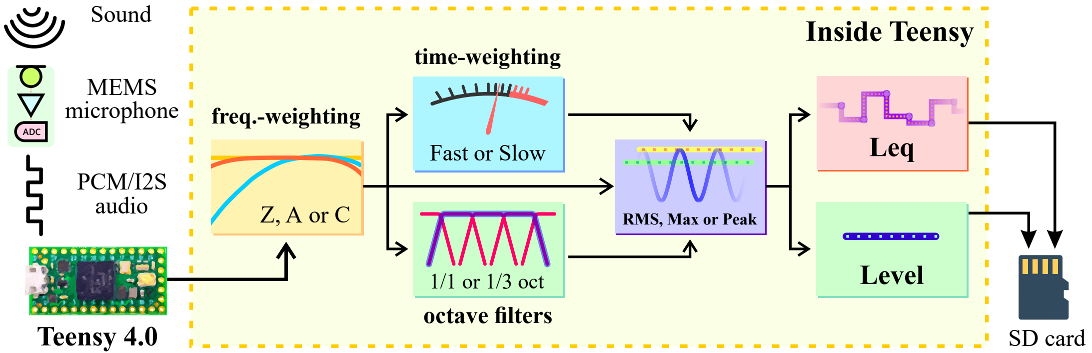


Figure 11: Signal chain of the designed prototype.

Outline

Filtering & Standards

In this section are presented the **evaluation tests** performed to validate the implemented filters, such as:

1. **Time-weighting filters**
   - (according to IEC 61672:2013, Parts 1 and 2 [13, 14])
2. **Frequency-weighting filters**; and
   - (according to IEC 61672:2013, Parts 1 and 2 [13, 14])
3. **Octave filters**.
   - (according to ANSI S1.11-2014, IEC 61260-1:2014 and IEC 61260-2:2014 [15, 16, 17])

Signal chain and method

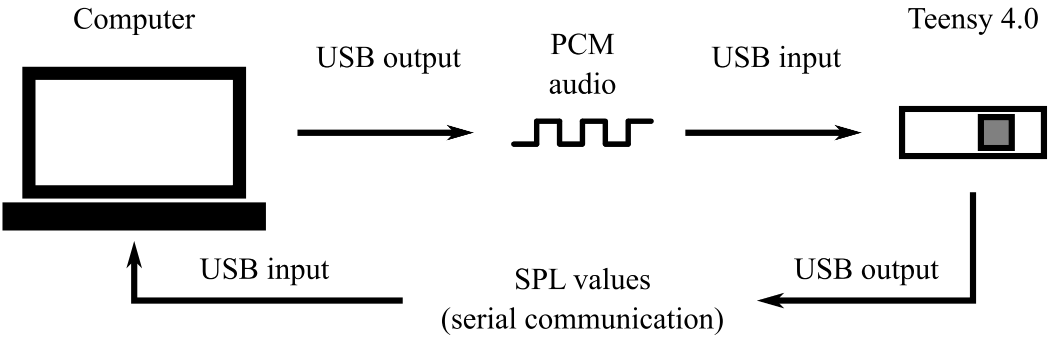


Figure 12: Signal chain for the algorithm validations.

Time-weighting validation

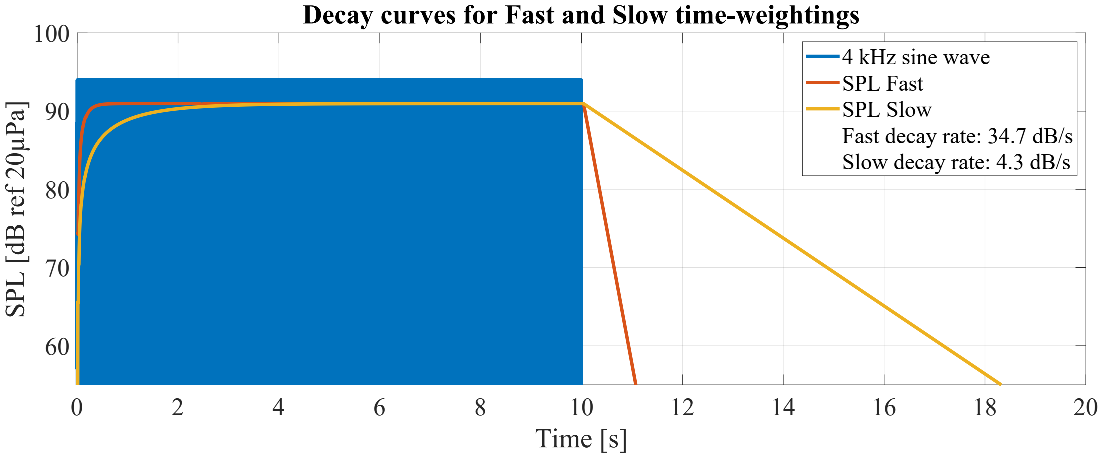


Figure 13: Time-weighting filter validations.

Frequency-weighting validation

A-weighting

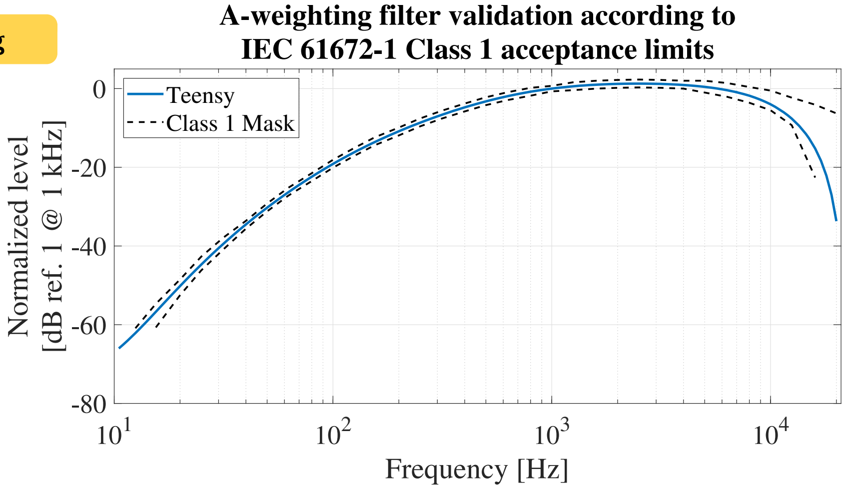


Figure 14: A-weighting filter validation.

Frequency-weighting validation

C-weighting

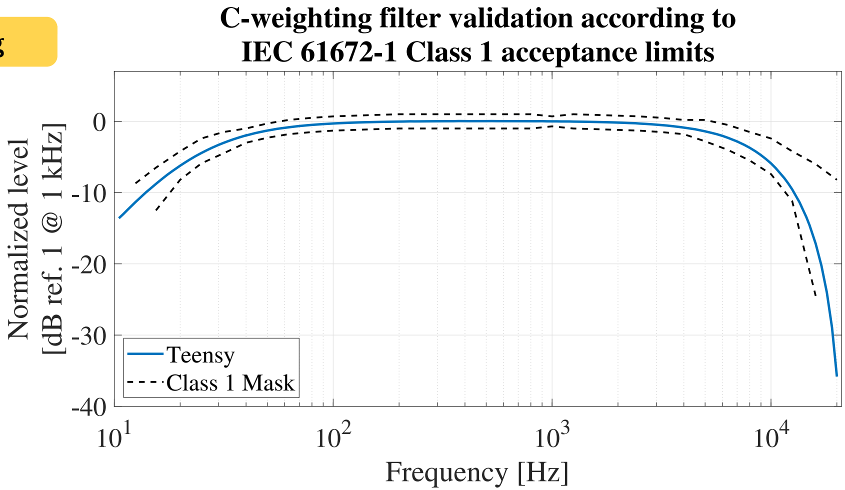
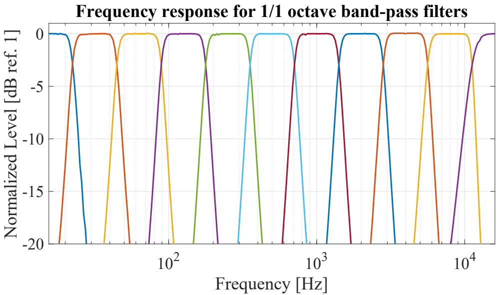


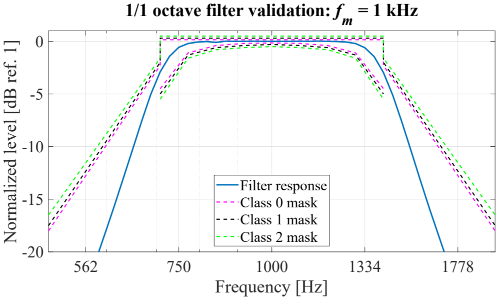
Figure 14: C-weighting filter validation.

Octave filters

One-octave filters validation



(a) All 1/1 octave filters plotted together.

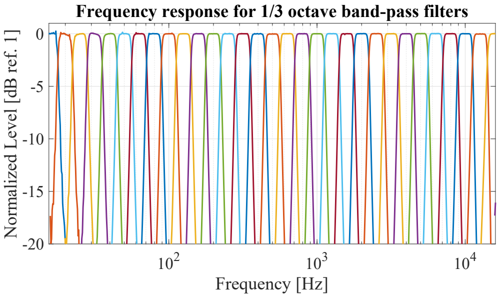


(b) Class 1 validation of 1/1 octave filter with mid-band frequency of 1 kHz.

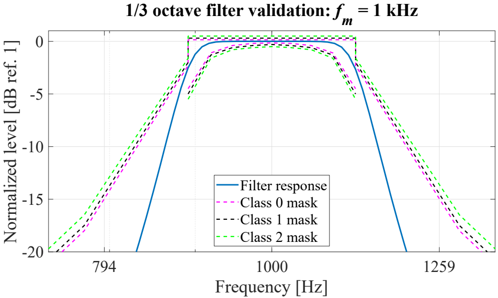
Figure 15: One-octave filter bank and validation for the 1 kHz band.

Octave filters

Third-octave filters validation



(a) All 1/3 octave filters plotted together.

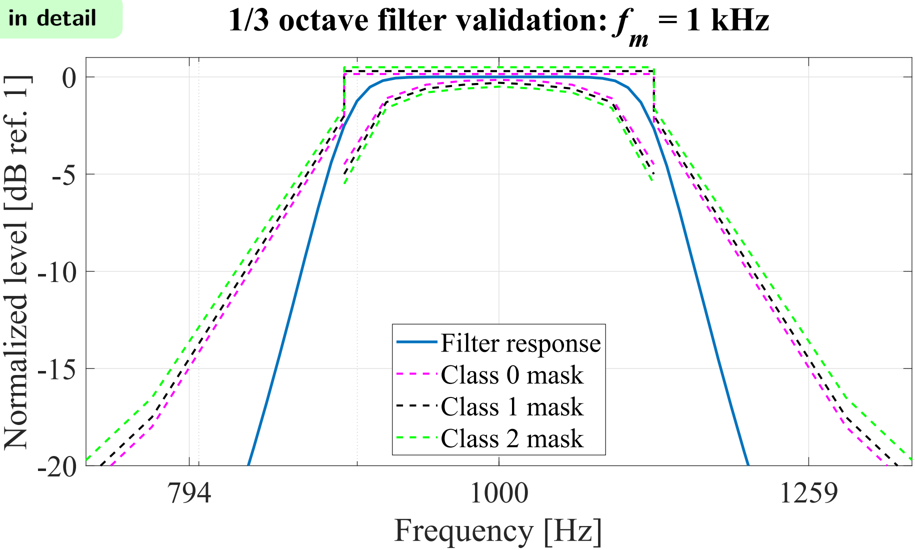


(b) Class 1 validation of 1/3 octave filter with mid-band frequency of 1 kHz.

Figure 15: Third-octave filter bank and validation for the 1 kHz band.

Octave filters

Filter mask in detail



Outline

Performance

In this section are presented the **prototype performance tests** carried out, namely:

1. Power consumption and CPU usage evaluation;
2. **Acoustic comparison** measurements against a Class 1 SLM; and
3. **Noise monitoring** for long periods.

Power and CPU consumption

- Power and CPU consumption were tested considering several configurations.
- The USB digital power meter shown in Figure 15 was used.
- Running at 150 MHz and considering a 4000 mAh battery, **the prototype can measure continuously for up to four days**.

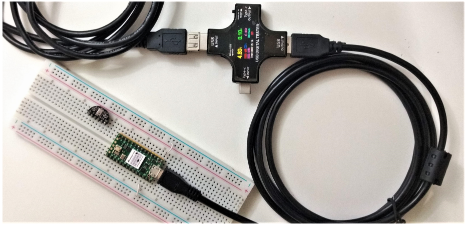
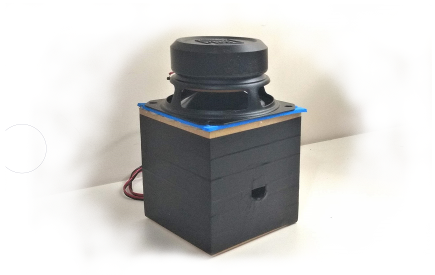


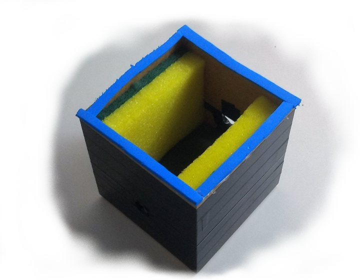
Figure 15: Teensy 4.0 connected to an USB digital power meter.

Comparison against a Class 1 SLM — Introduction

- A set of **parallel measurements** against a Class 1 B&K Type 2240 SLM was carried out.
- The measurements took place in a simple room using a test bench comprised of a **small chamber with a loudspeaker on top**.



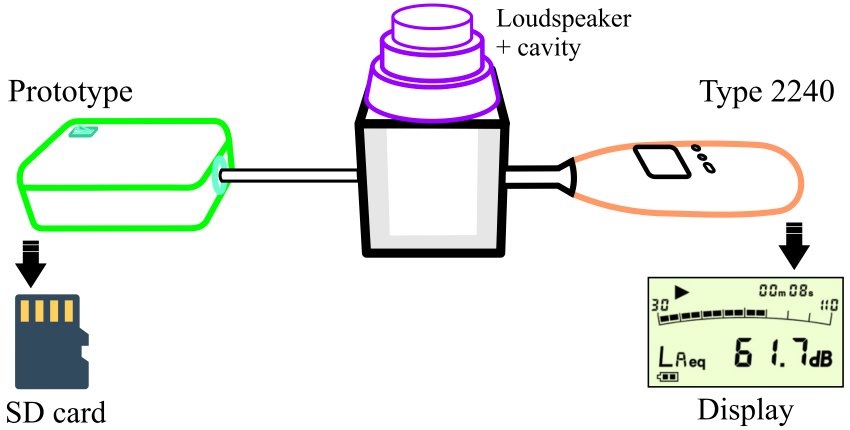
(a) Loudspeaker mounted on the chamber.



(b) Inside of the test chamber.

Figure 16: Acoustic pressure relative response (instrumentation).

Comparison against a Class 1 SLM — Test bench



Comparison against a Class 1 SLM — Method

- For all tests, L_{Aeq}, L_{AFmax} and L_{Cpeak} were evaluated considering the following signals:

Comparison against a Class 1 SLM — Method

- For all tests, L_{Aeq}, L_{AFmax} and L_{Cpeak} were evaluated considering the following signals:

  1. A series of flat-noise filtered into $^1/_6$-octave bands (performance across spectrum). **The results were used to generate a correction filter for the microphone frequency response**.

Comparison against a Class 1 SLM — Method

- For all tests, L_{Aeq}, L_{AFmax} and L_{Cpeak} were evaluated considering the following signals:

  1. A series of flat-noise filtered into $1/6$-octave bands (performance across spectrum). **The results were used to generate a correction filter for the microphone frequency response**.

  2. A series of flat-noise filtered into $1/3$-octave bands. **This test was repeated three times and a statistical analysis was held**.

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  3. A series of flat-noise filtered into $1/1$-octave bands;

Comparison against a Class 1 SLM — Method

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  2. A series of flat-noise filtered into $1/3$-octave bands. **This test was repeated three times and a statistical analysis was held**.
  3. A series of flat-noise filtered into $1/1$-octave bands;
  4. A broadband signal (flat-noise); and

Comparison against a Class 1 SLM — Method

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  2. A series of flat-noise filtered into $1/3$-octave bands. **This test was repeated three times and a statistical analysis was held**.
  3. A series of flat-noise filtered into $1/1$-octave bands;
  4. A broadband signal (flat-noise); and
  5. A soundscape recording considering seven reproduction levels.

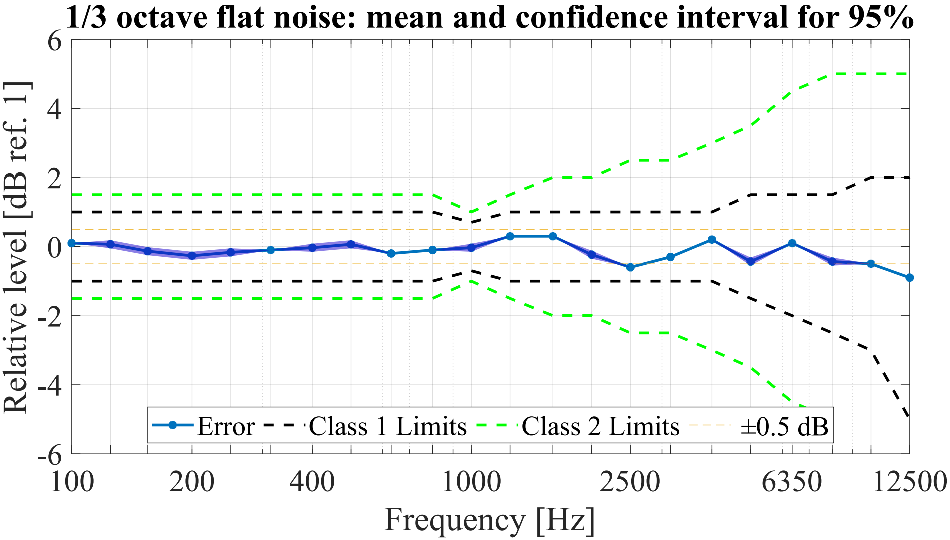
Comparison against a Class 1 SLM — Method

- For all tests, L_{Aeq}, L_{AFmax} and L_{Cpeak} were evaluated considering the following signals:

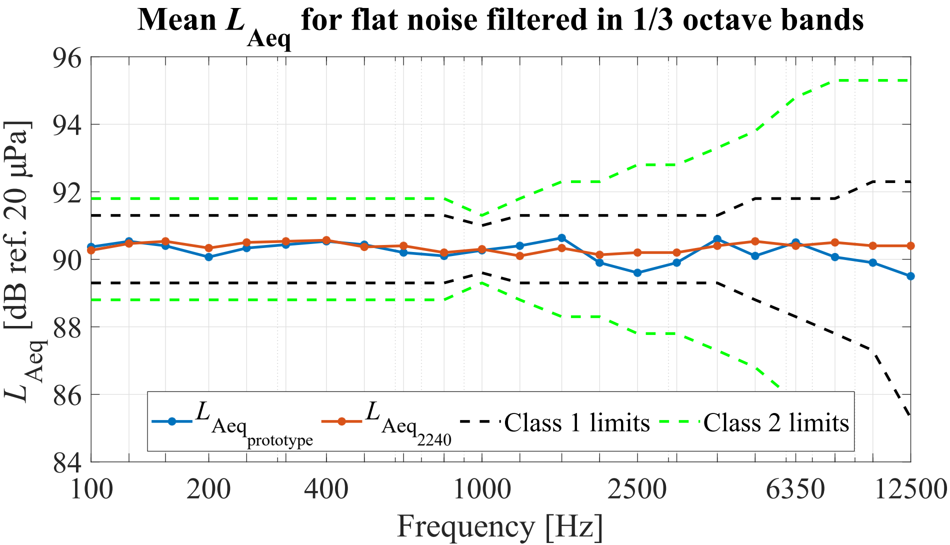
  1. A series of flat-noise filtered into 1/6-octave bands (performance across spectrum). **The results were used to generate a correction filter for the microphone frequency response**.
  2. A series of flat-noise filtered into 1/3-octave bands. **This test was repeated three times and a statistical analysis was held**.
  3. A series of flat-noise filtered into 1/1-octave bands;
  4. A broadband signal (flat-noise); and
  5. A soundscape recording considering seven reproduction levels.

- The **frequency range** for all tests **was limited between 100 Hz and 12.5 kHz.**

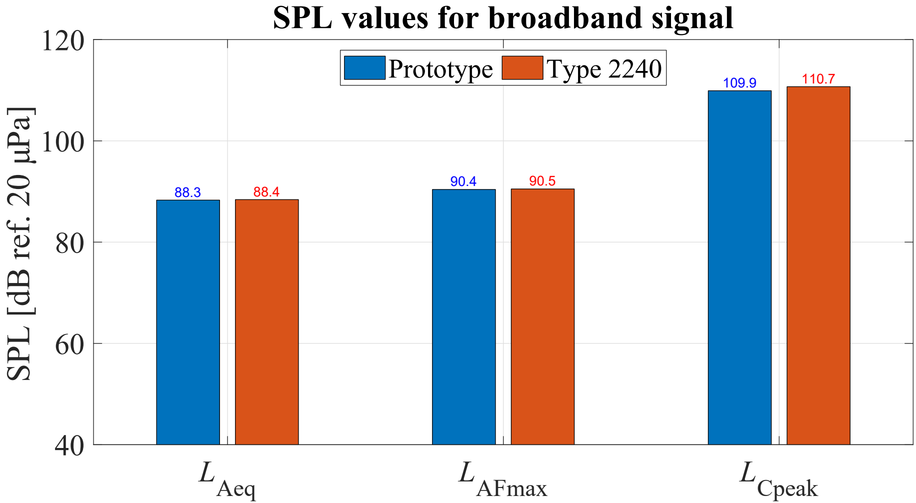
Comparison against a Class 1 SLM — Results



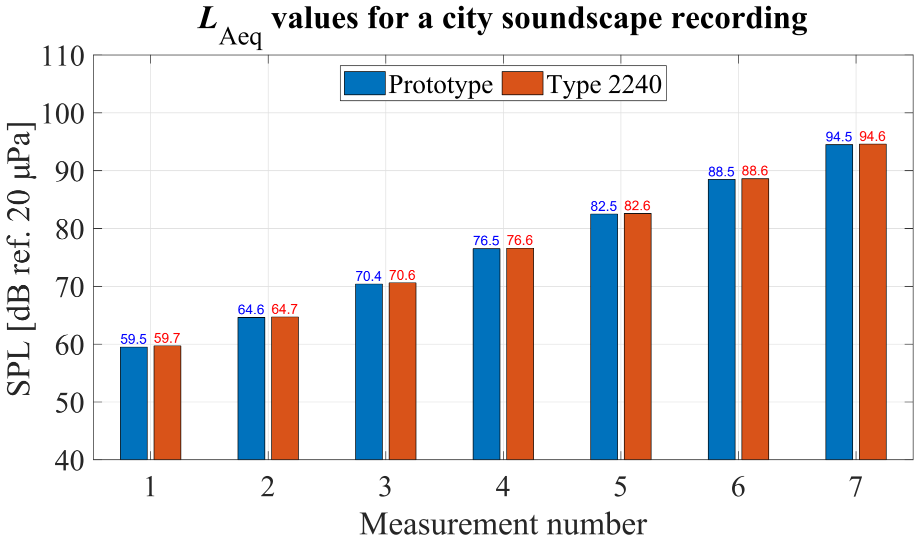
Comparison against a Class 1 SLM — Results



Comparison against a Class 1 SLM — Results



Comparison against a Class 1 SLM — Results

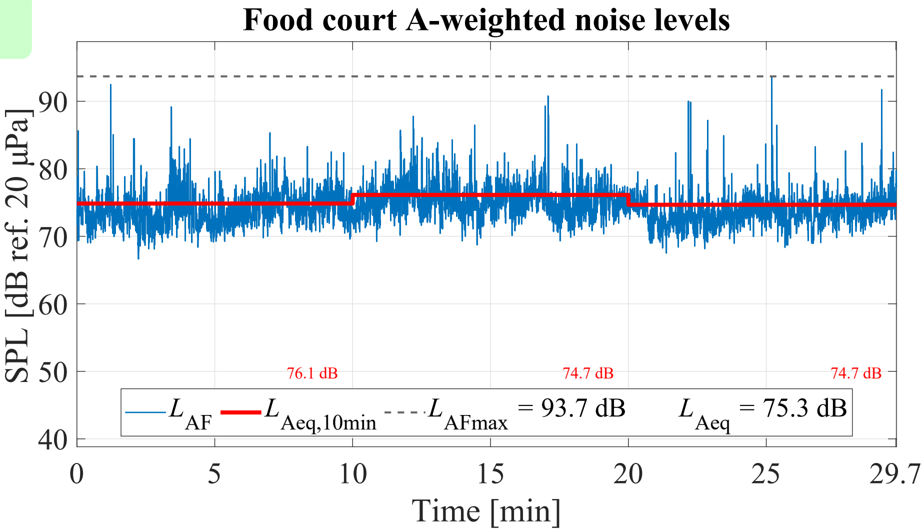


Noise monitoring for long periods

- **Four scenarios** were considered:
  1. A shopping mall food court (30 minutes measurement);
  2. The facade of a residence (1 hour during morning and evening periods); and
  3. Inside a bedroom (8 hours measurement);
- The device was powered by a 4400 mAh power bank; and
- All data was saved into a SD card in `ASCII` (`.txt`) format.

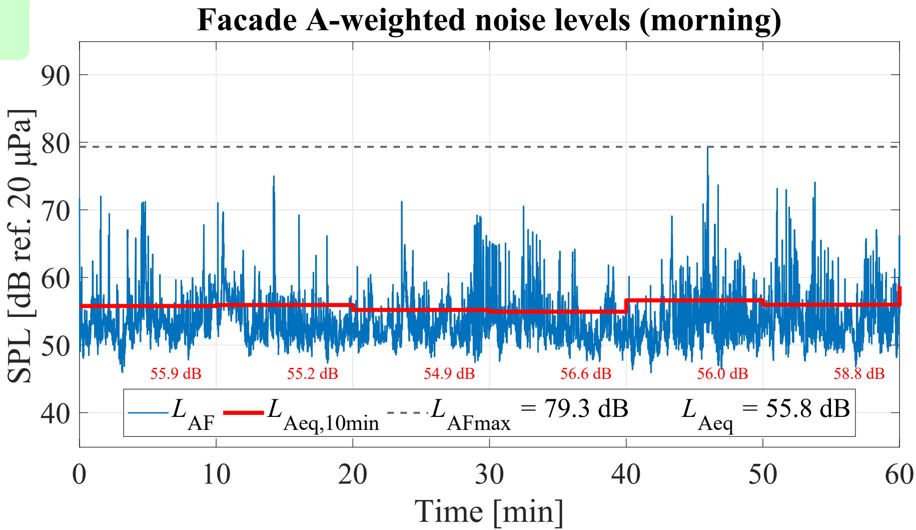
Noise monitoring for long periods — Results

Food court 30 min



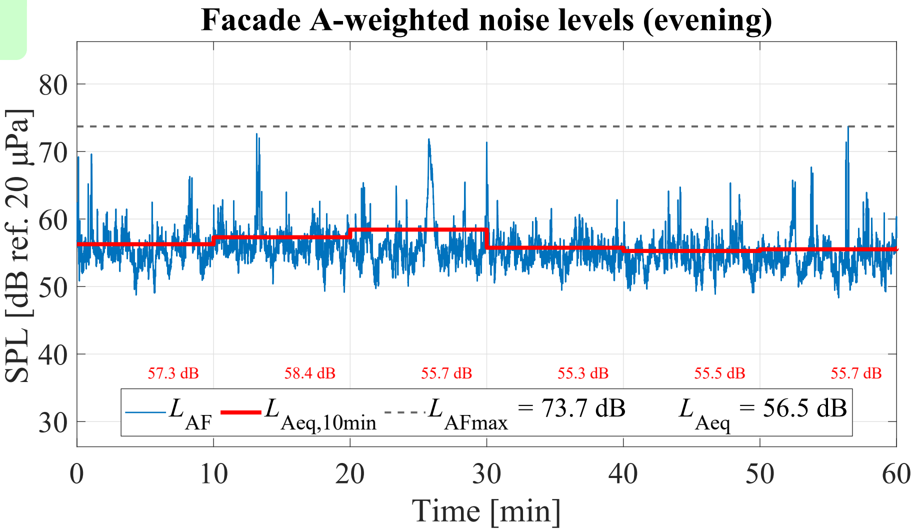
Noise monitoring for long periods — Results

Façade (m)
1 hour



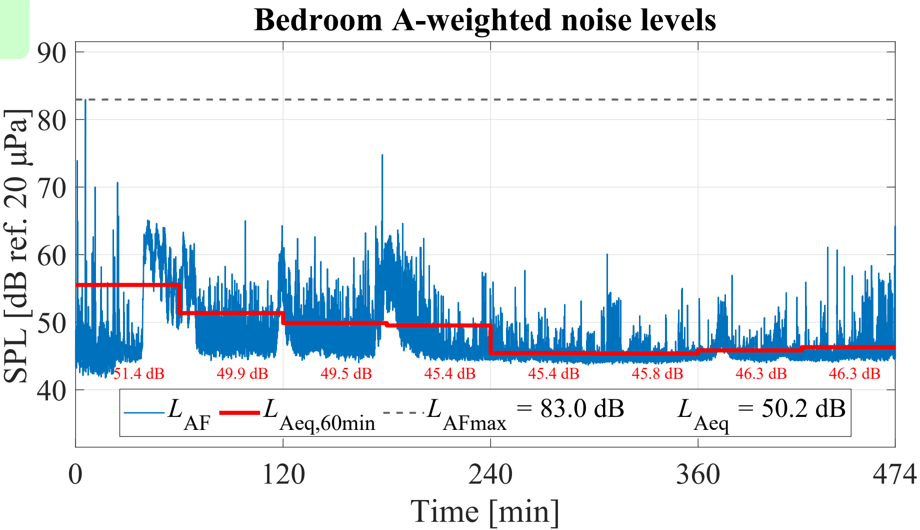
Noise monitoring for long periods — Results

Façade (e)
1 hour



Noise monitoring for long periods — Results

Bedroom
8 hours



Outline

Conclusions

- This study presented a **small embedded system based on a MEMS digital microphone** and **Teensy microcontroller** for applications in **noise monitoring** (or general SPL measurement).
- Tests showed that **implemented filtering algorithms fulfills Class 1 IEC standards**.
- Relative levels between the prototype and a Class 1 SLM ranged ± 0.5 dB in general.
- Field measurements revealed **adequate performance with low-power and CPU consumption**, enabling long-term measurements.
- Further testing will be carried out in laboratory.
- Additional data of this project can be found in the GitHub repository https://github.com/eac-ufsm/internoise2021-MEMS.

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Acknowledgment

- **Acoustical Engineering** Program at the **Federal University of Santa Maria** (UFSM, **Brazil**), as well as its scholarship programs FIPE and FIEX, which assisted this project.
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- Thanks to Denison Oliveira and Fernando Diaz from HBK/Brüel & Kjær for the support concerning the SLM Type 2240.
- Joseph Lacey for insightful comments on the text.

Thank you!

If you have any questions, suggestions or comments, feel free to contact me.

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Amplifiers, Bolling Field, 1921.

Cite us!

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  title     = {{MEMS digital microphone and Arduino compatible microcontroller: an embedded system for noise monitoring}},
  year      = {2021},
  address   = {Washington, DC, USA},
  month     = {Aug.},
  pages     = {1--12},
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