

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

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inter  
noise 2021

① Introduction & Basic theory

② The prototype

③ Algorithms validation

④ Performance tests

⑤ Conclusions

# Outline

① Introduction & Basic theory

② The prototype

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# 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.

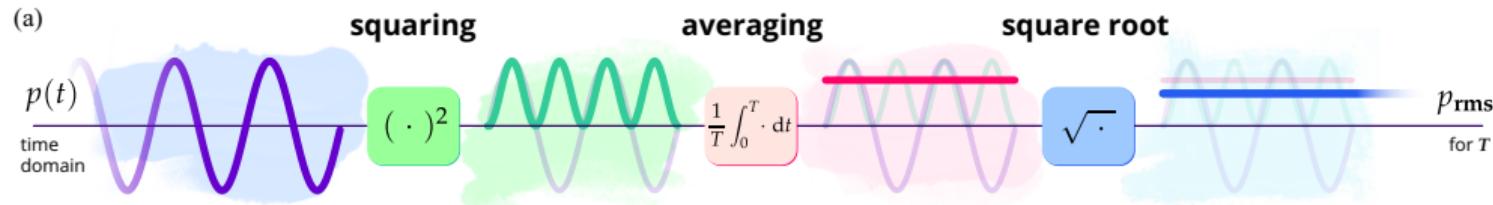


Figure 3: Step-by-step root mean square (RMS) calculation.

# 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  $\mu\text{Pa}$  sets the 0 dB.
- Sound pressure levels correlate with the sensation of how loud a sound is.

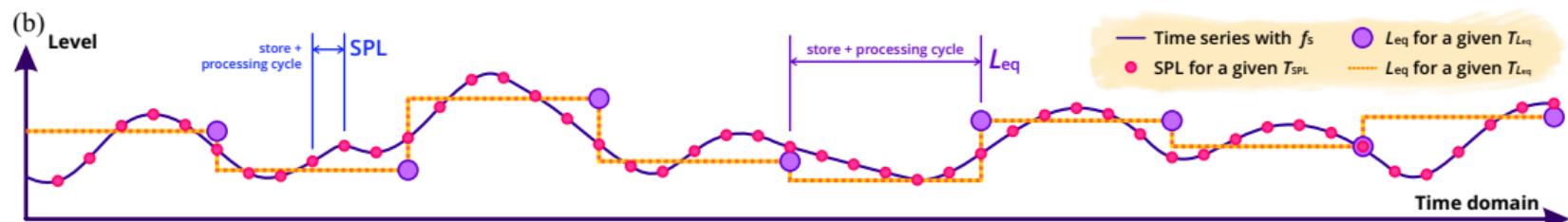


Figure 4: Time series with  $f_s$ , SPL, and  $L_{eq}$  measurement examples.

SPL and  $L_{\text{eq}}$ 

## Sound pressure level

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

## Equivalent continuous sound level

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

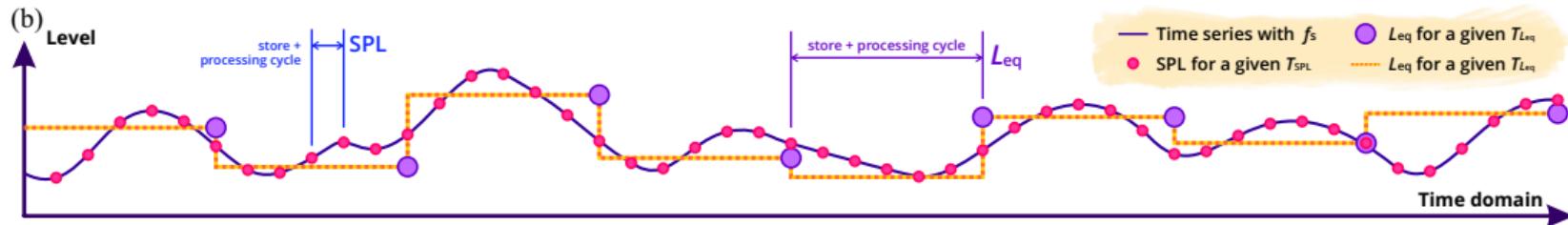


Figure 4: Time series with  $f_s$ , SPL, and  $L_{\text{eq}}$  measurement examples.

# 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].

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# 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**.

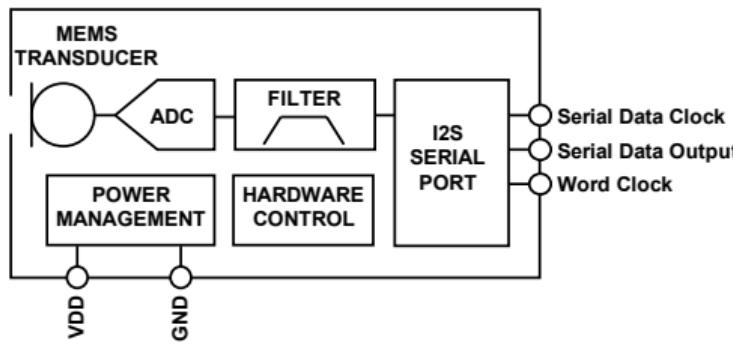
# Sound acquisition (MEMS mic)



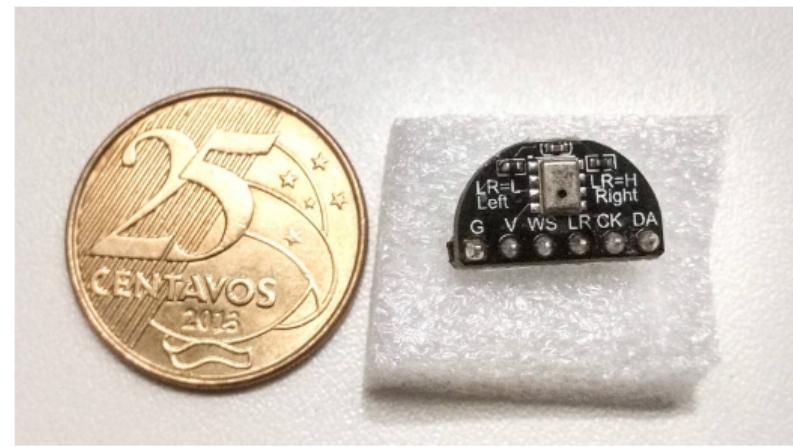
Figure 7: MEMS mic diagram.

- For the sound acquisition, the **Sipeed MSM261S4030H0** breakout board was used, which contains an I<sup>2</sup>S [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 microphone has a **flat frequency response** from 100 Hz to 10 kHz [10].

# Sound acquisition (MEMS mic)



(a) I<sup>2</sup>S 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

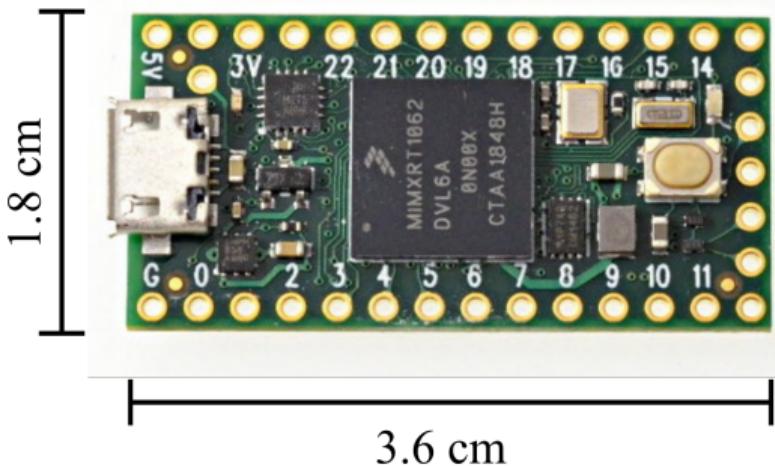


Figure 8: Teensy 4.0 MCU.

- 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<sup>2</sup>S compatibility).

# Teensy: Audio System Design Tool

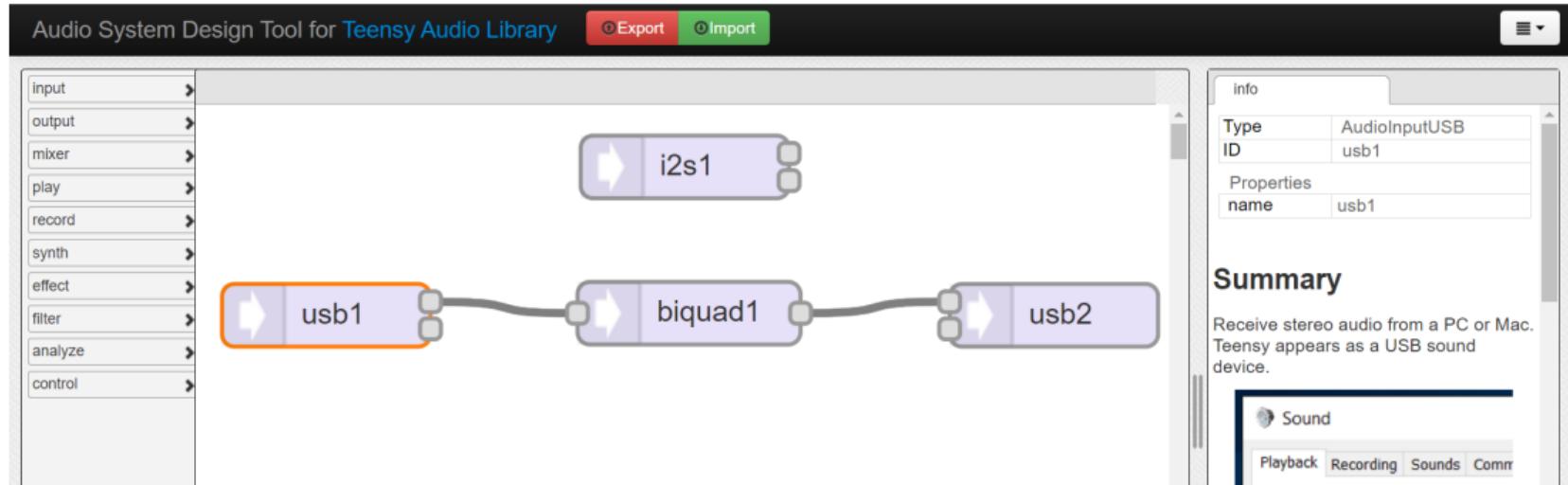
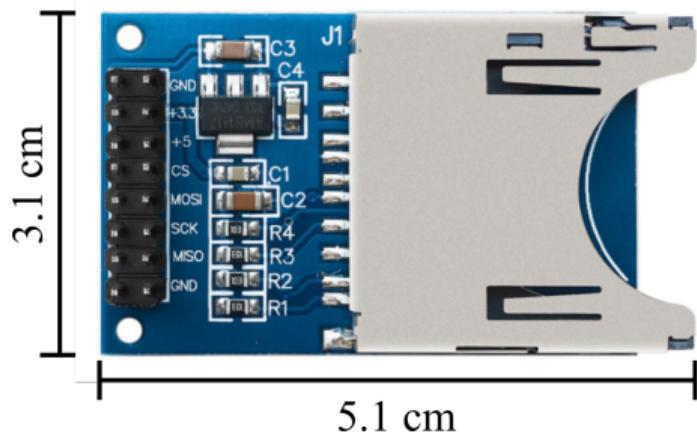


Figure 9: Audio System Design Tool, a guided user interface (GUI) to build audio programs with Teensy's audio library.

# Saving & Powering



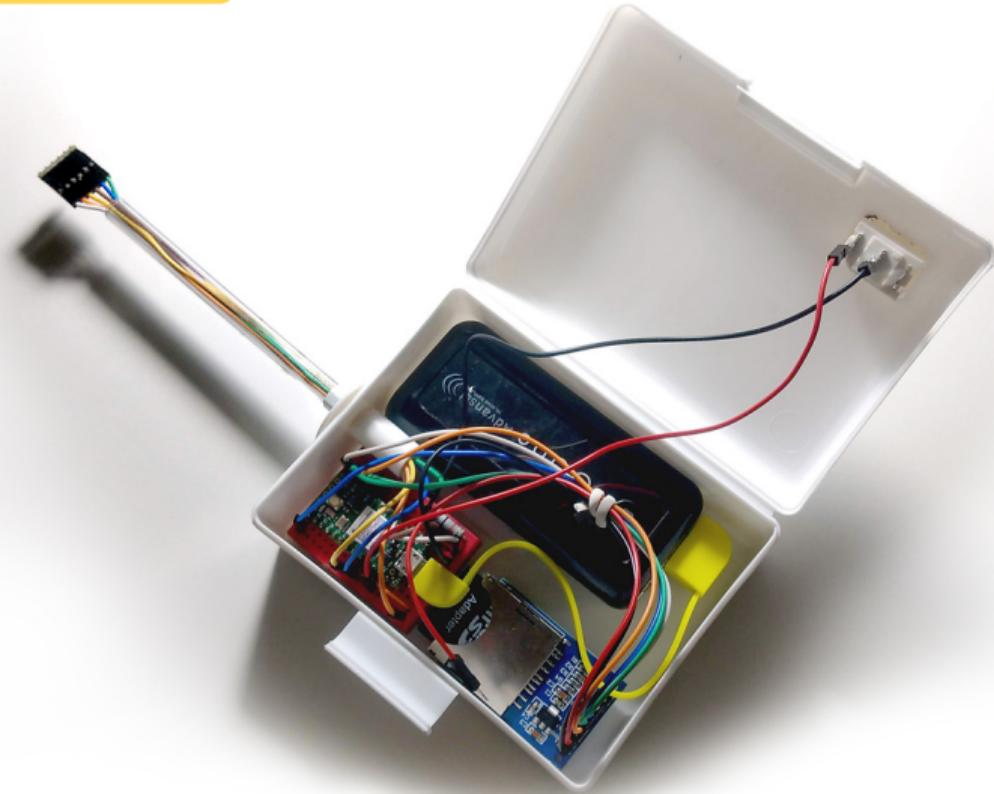
(a) Arduino SD card module.



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

Figure 10: Saving module and powering components.

## Final prototype



## Final prototype



# Signal chain and features

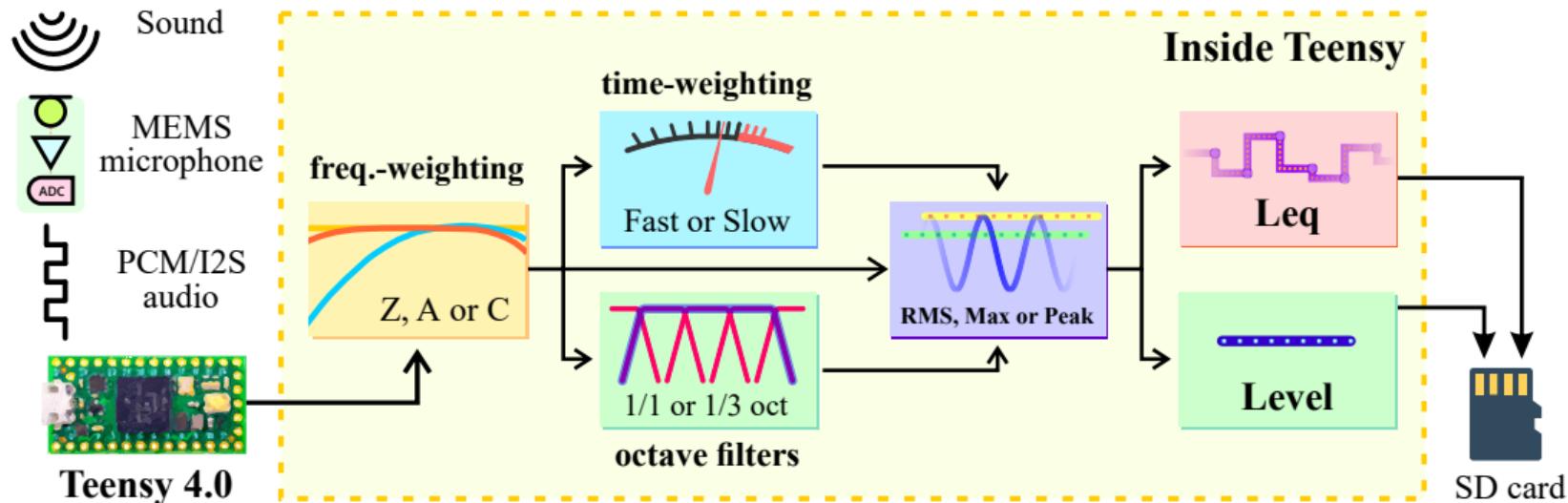


Figure 11: Signal chain of the designed prototype.

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# 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

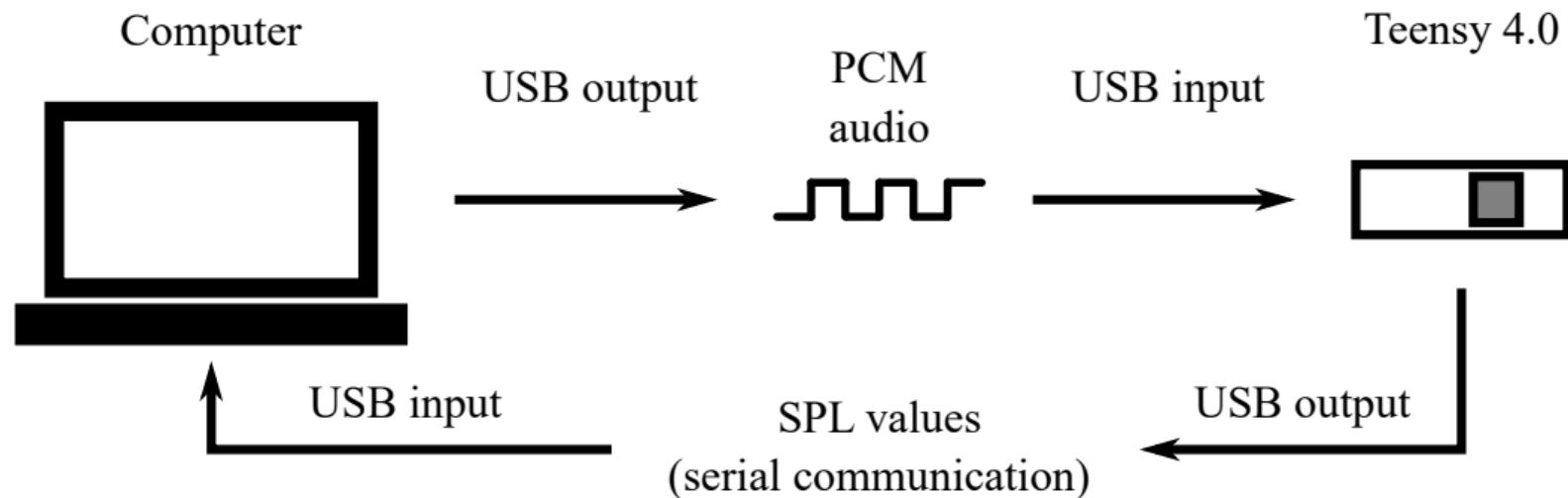


Figure 12: Signal chain for the algorithm validations.

# Time-weighting validation

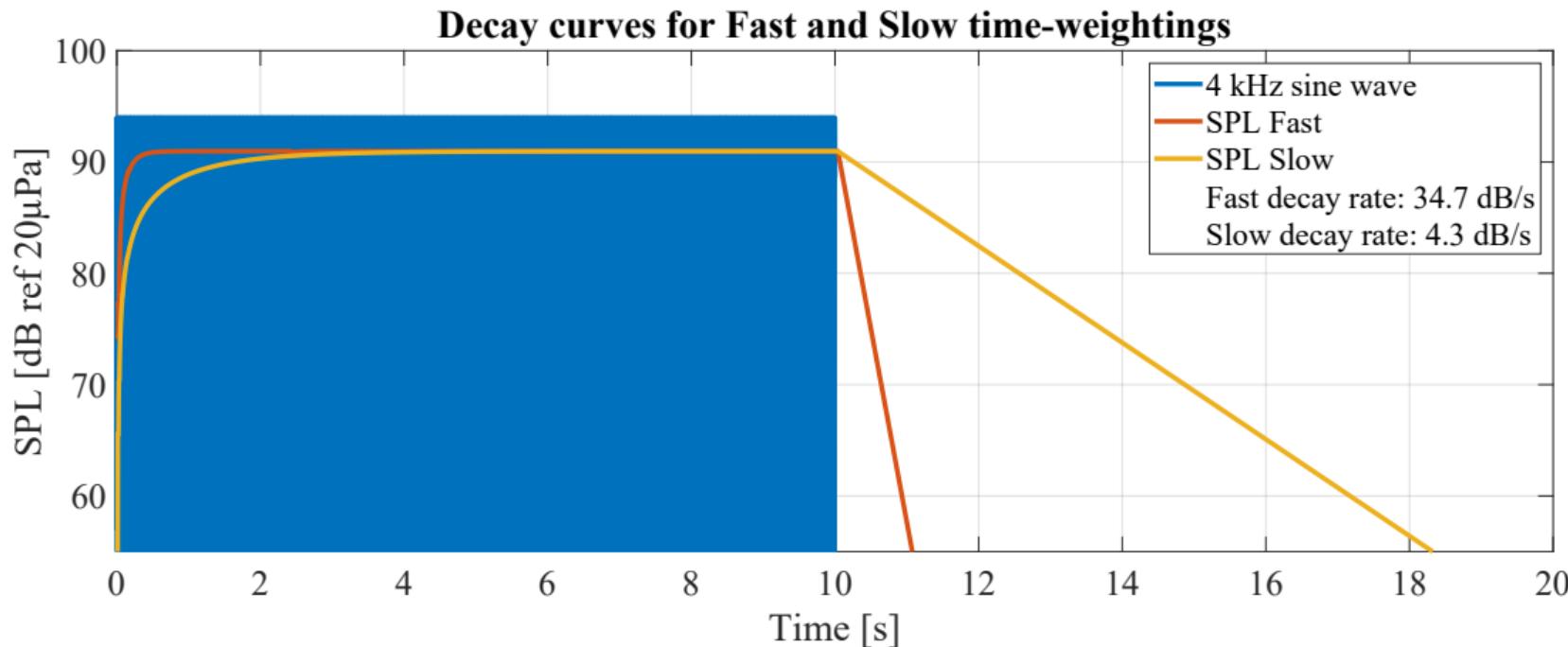


Figure 13: Time-weighting filter validations.

# Frequency-weighting validation

## A-weighting

### A-weighting filter validation according to IEC 61672-1 Class 1 acceptance limits

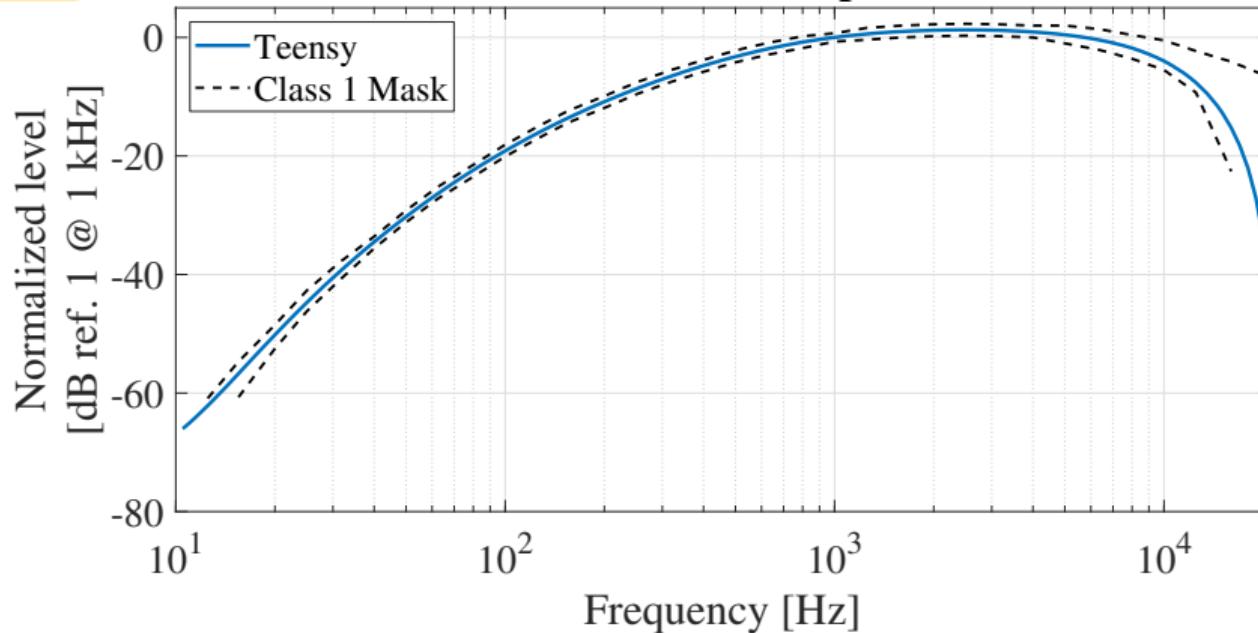


Figure 14: A-weighting filter validation.

# Frequency-weighting validation

C-weighting

## C-weighting filter validation according to IEC 61672-1 Class 1 acceptance limits

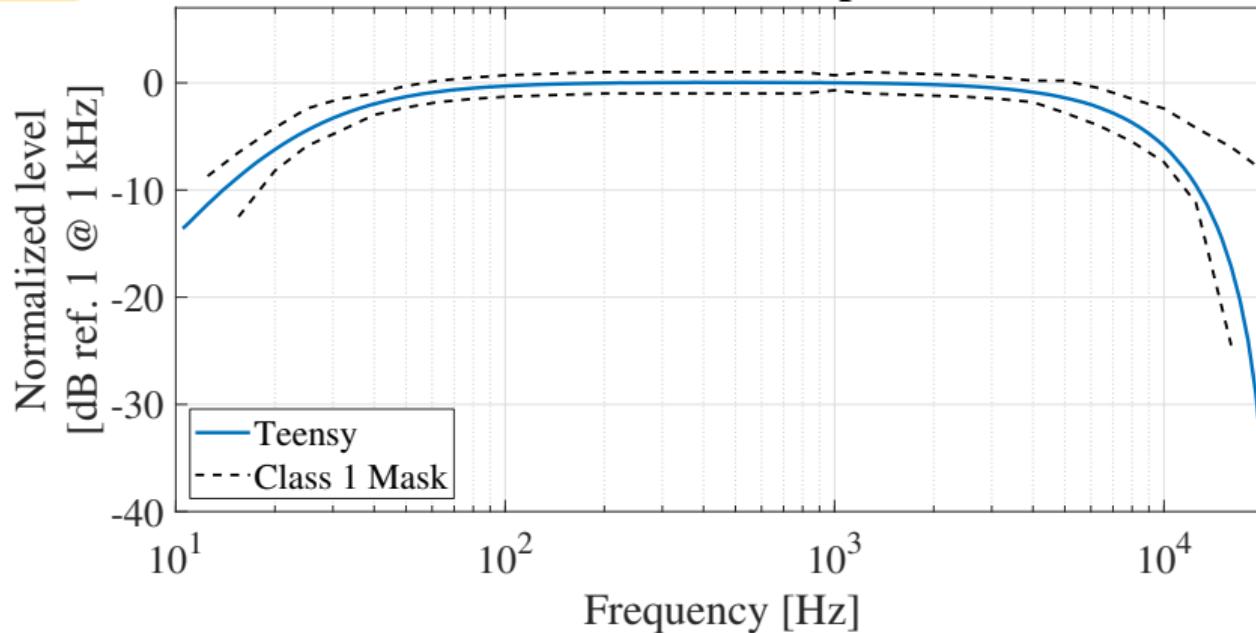
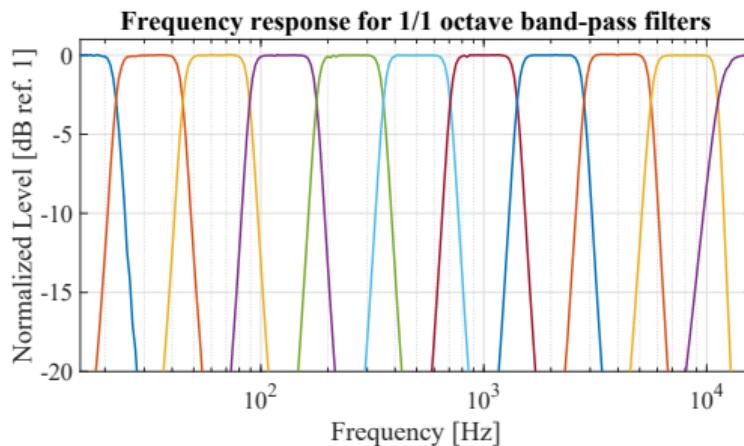


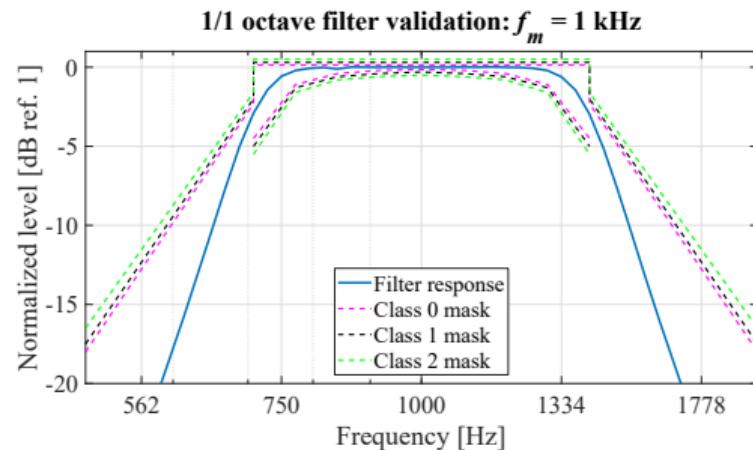
Figure 14: C-weighting filter validation.

# Octave filters

## One-octave filters validation



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

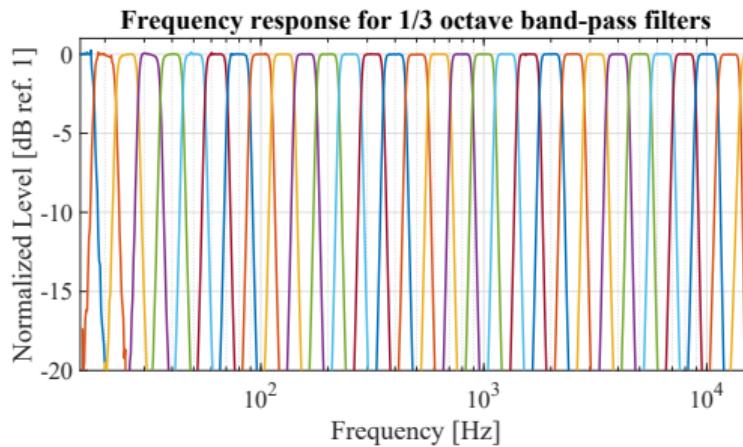


(b) Class 1 validation of 1/1 octave filter with mid-band frequency of 1 kHz.

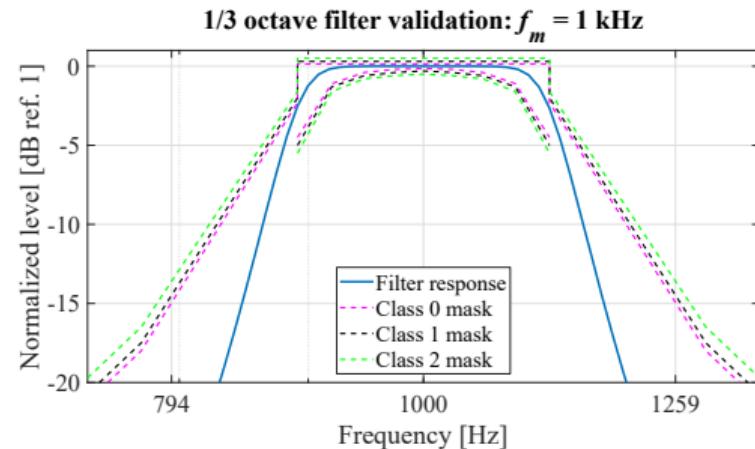
**Figure 15:** One-octave filter bank and validation for the 1 kHz band.

# Octave filters

## Third-octave filters validation



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



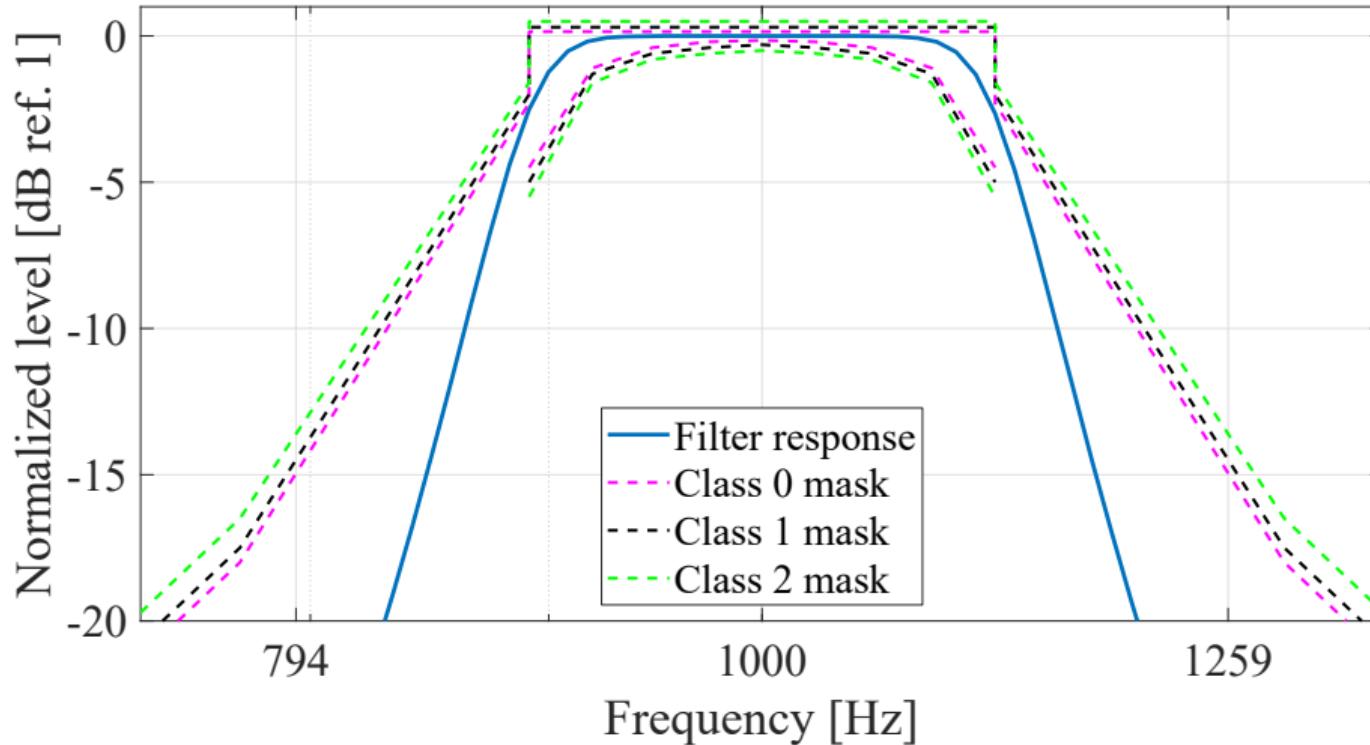
(b) Class 1 validation of 1/3 octave filter with mid-band frequency of 1 kHz.

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

# Octave filters

Filter mask in detail

1/3 octave filter validation:  $f_m = 1 \text{ kHz}$



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# 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

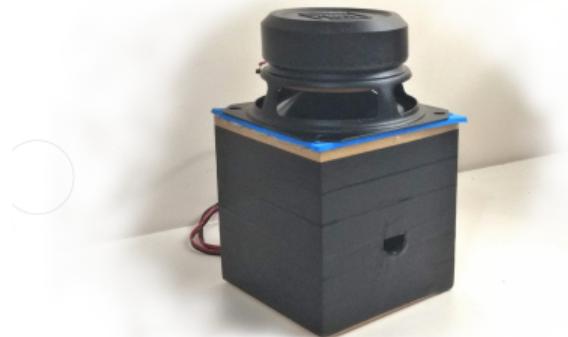
- Power and CPU consumption were tested considering several configurations.
- The USB digital power meter shown in Figure 15 was used.
- Running at 150 MHz and considering a 4000 mAh battery, **the prototype can measure continuously for up to four days.**



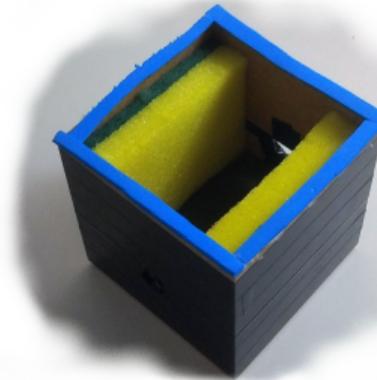
Figure 15: Teensy 4.0 connected to an USB digital power meter.

# 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:

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  - ③ A series of flat-noise filtered into 1/1-octave bands;
  - ④ A broadband signal (flat-noise); and

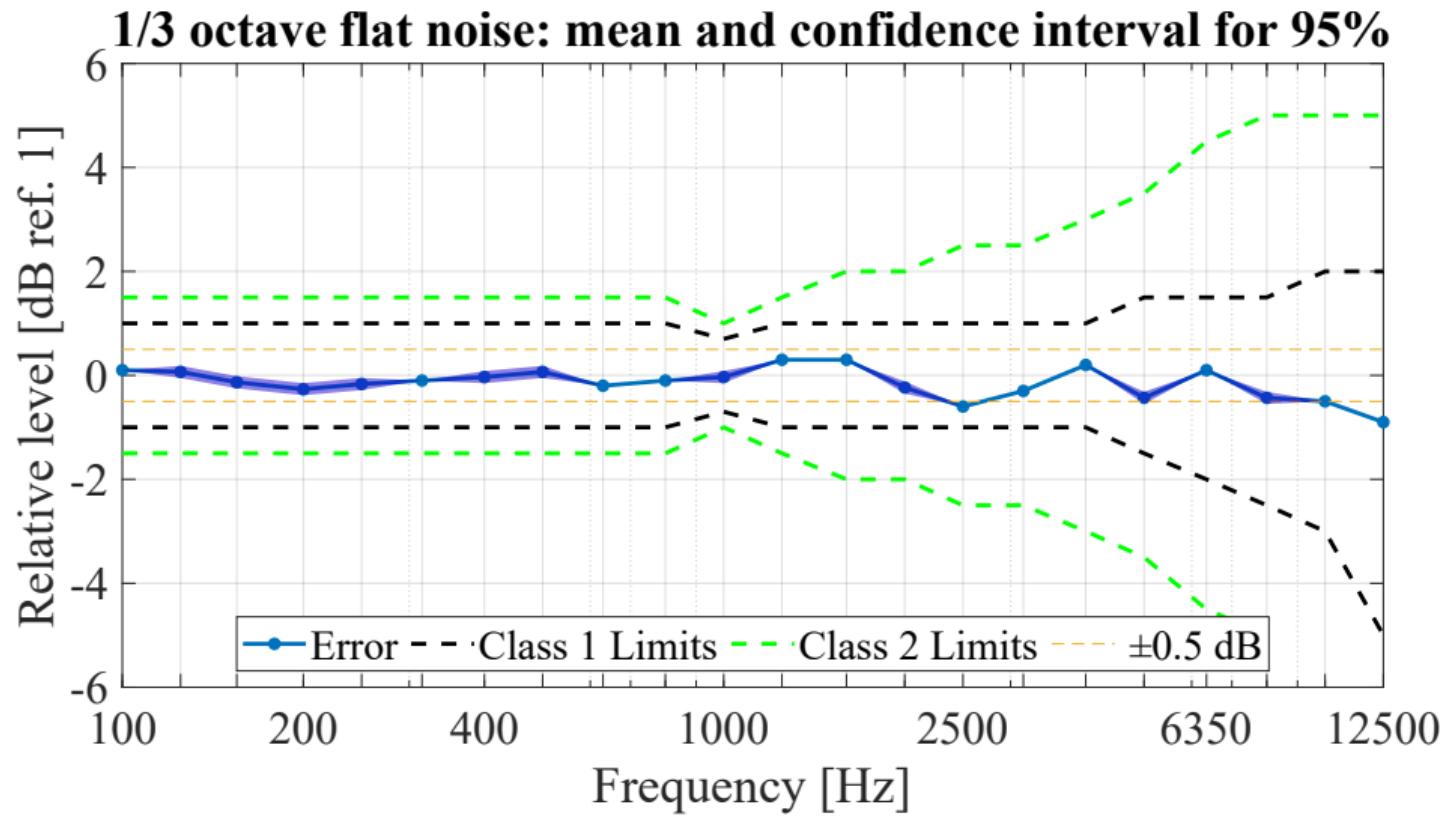
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  - ③ A series of flat-noise filtered into 1/1-octave bands;
  - ④ A broadband signal (flat-noise); and
  - ⑤ A soundscape recording considering seven reproduction levels.

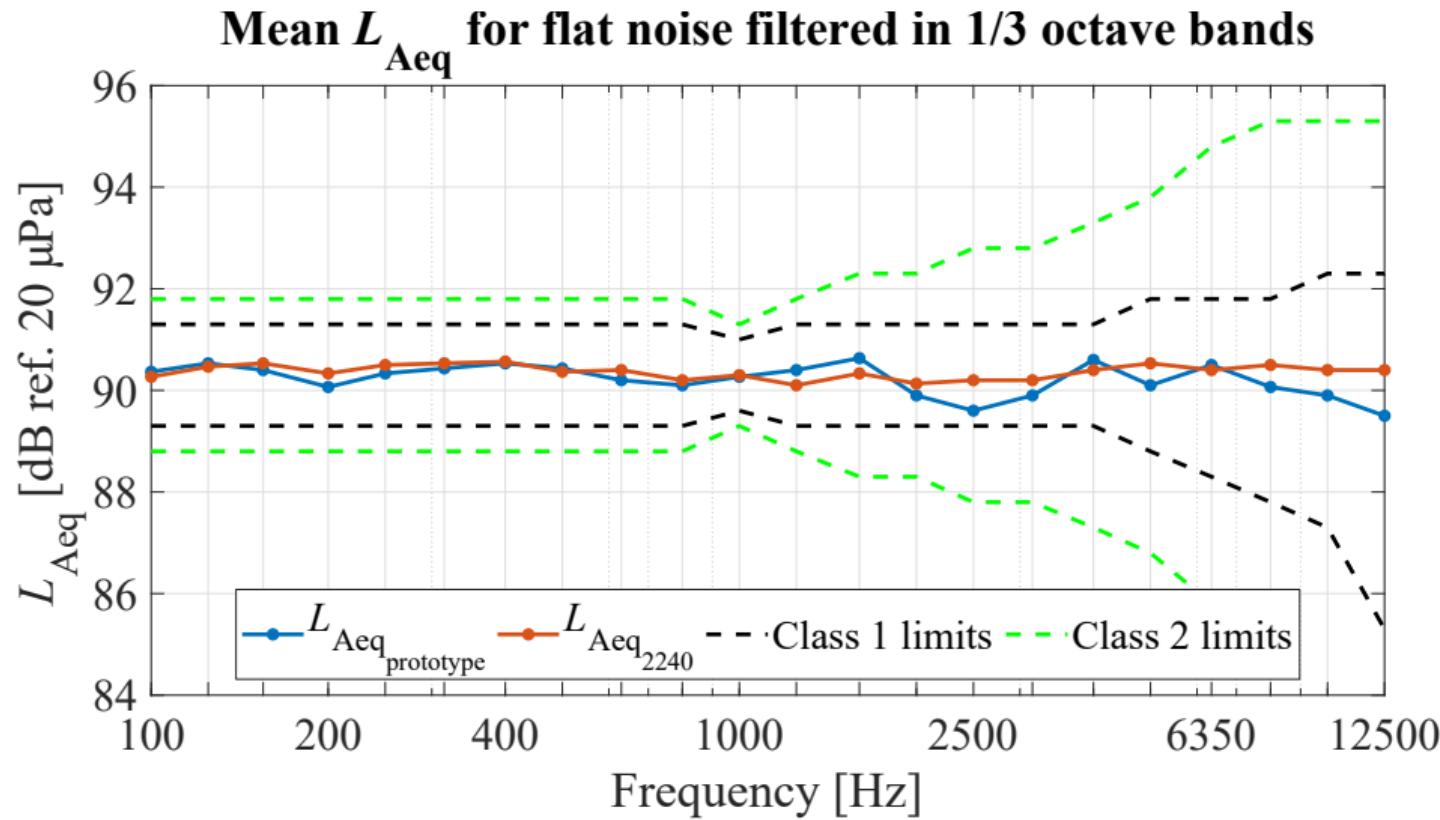
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  - ④ A broadband signal (flat-noise); and
  - ⑤ A soundscape recording considering seven reproduction levels.
- The **frequency range** for all tests **was limited between 100 Hz and 12.5 kHz.**

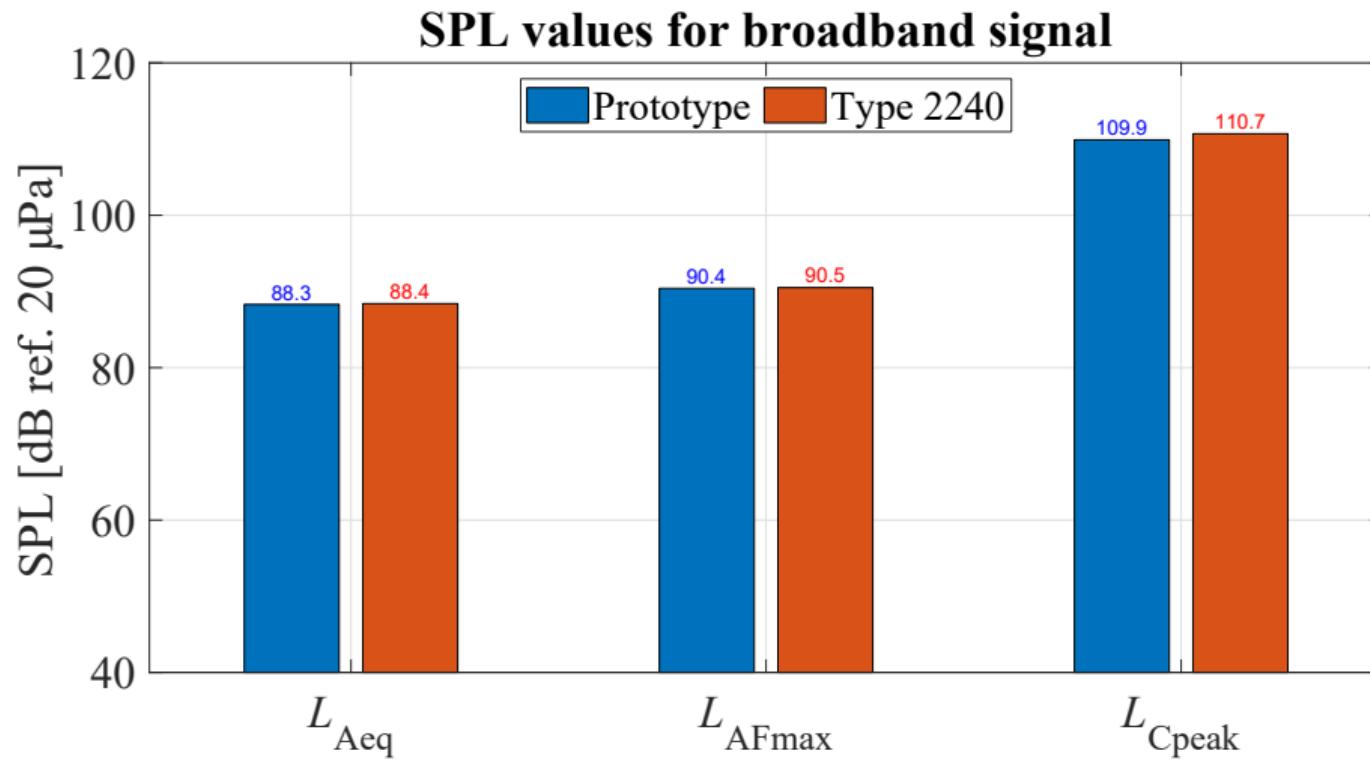
## Comparison against a Class 1 SLM — Results



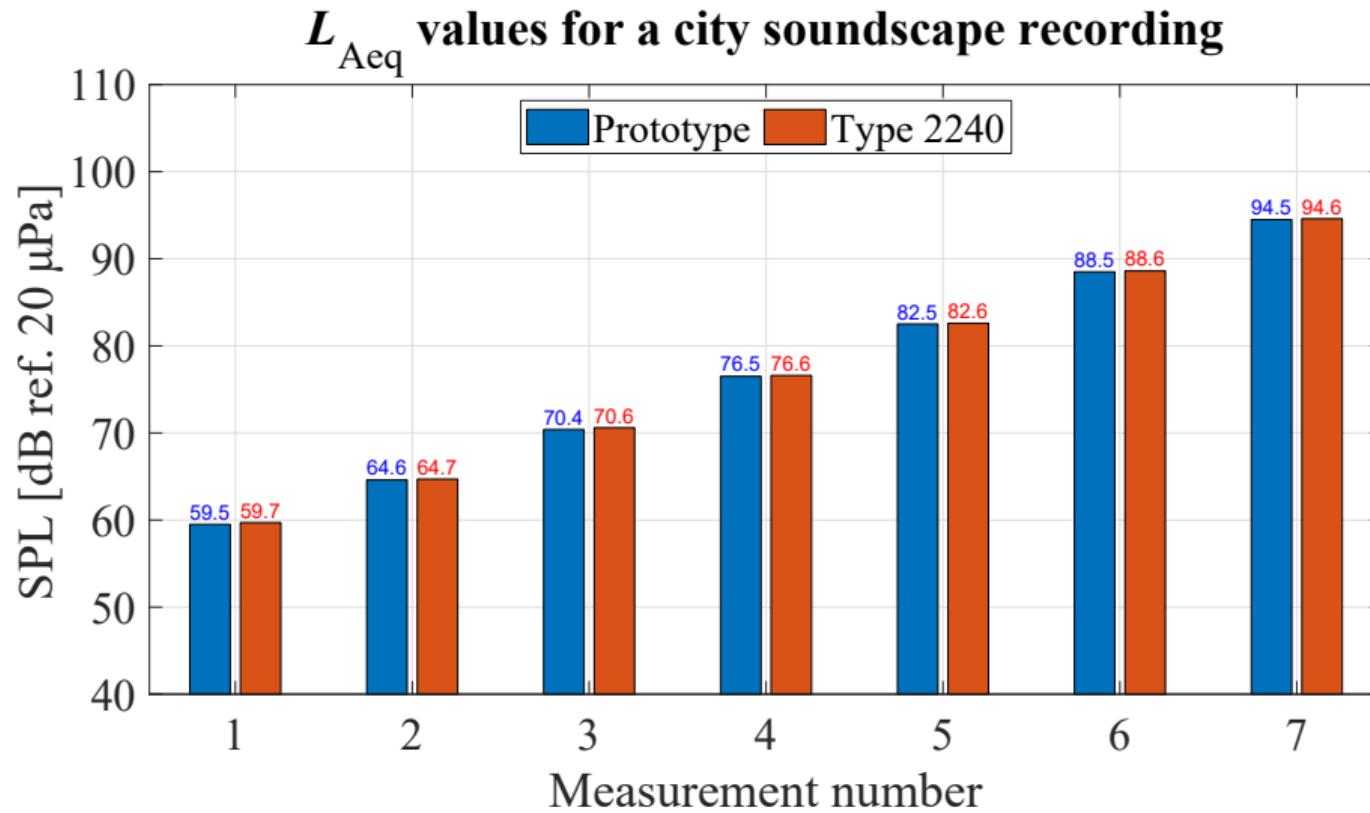
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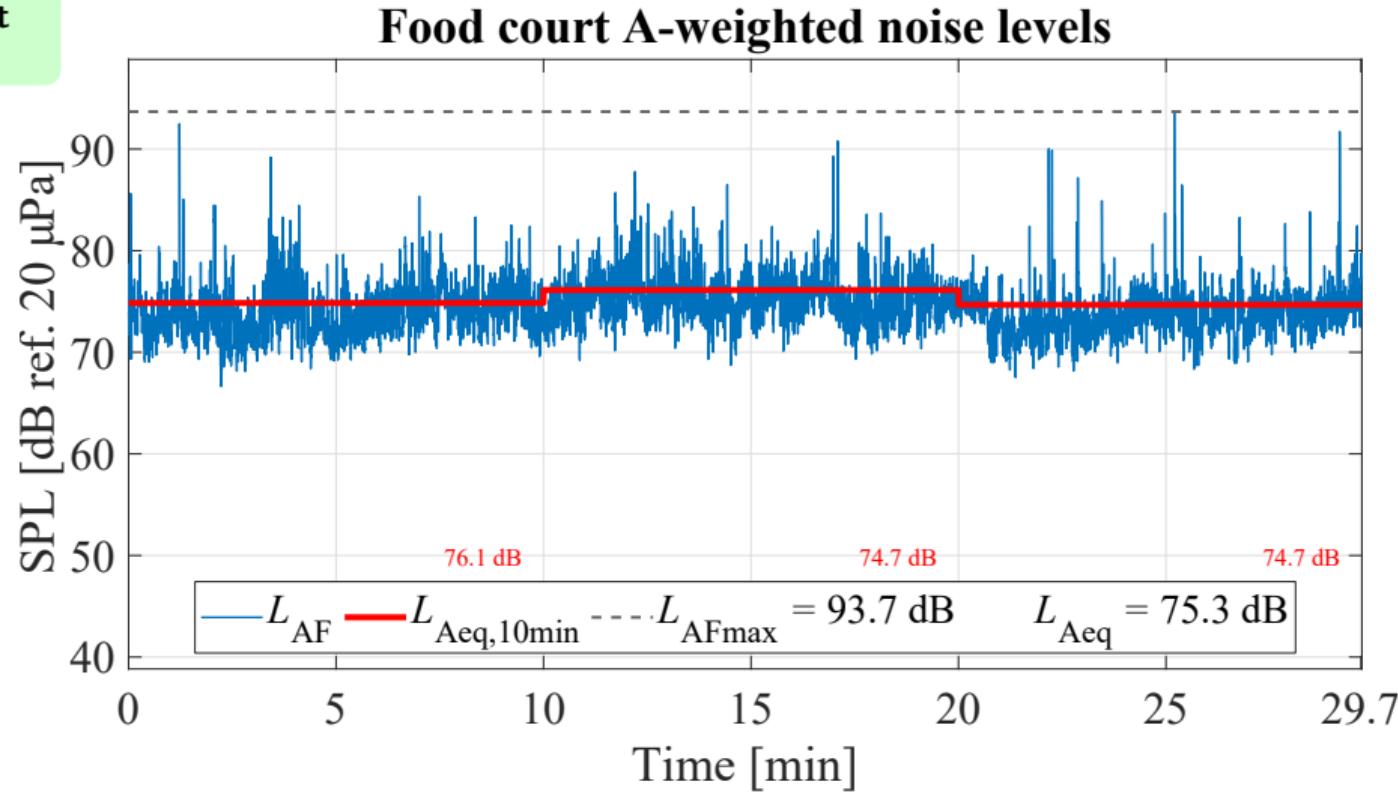


# Noise monitoring for long periods

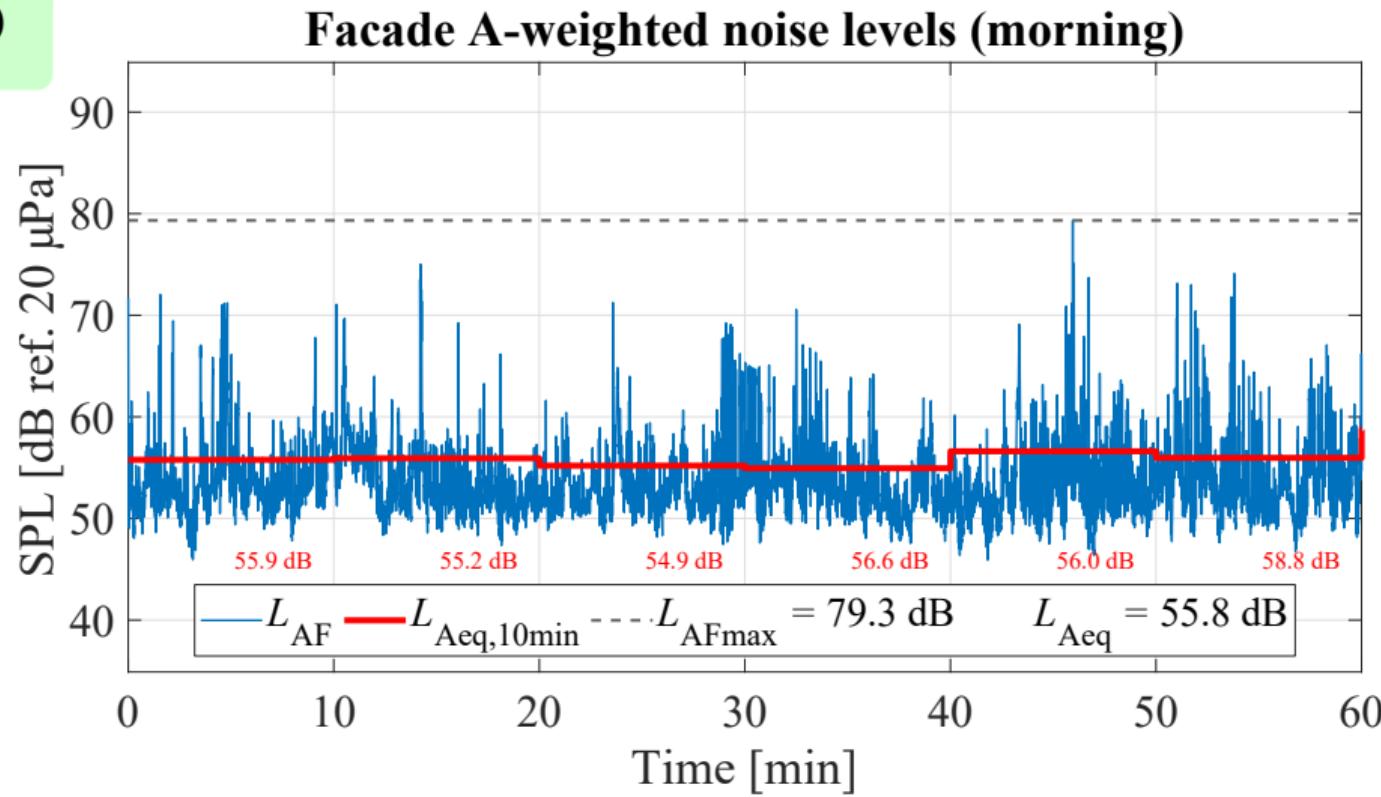
- Four scenarios were considered:
  - ① A shopping mall food court (30 minutes measurement);
  - ② The facade of a residence (1 hour during morning and evening periods); and
  - ③ Inside a bedroom (8 hours measurement);
- The device was powered by a 4400 mAh power bank; and
- All data was saved into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

# Noise monitoring for long periods — Results

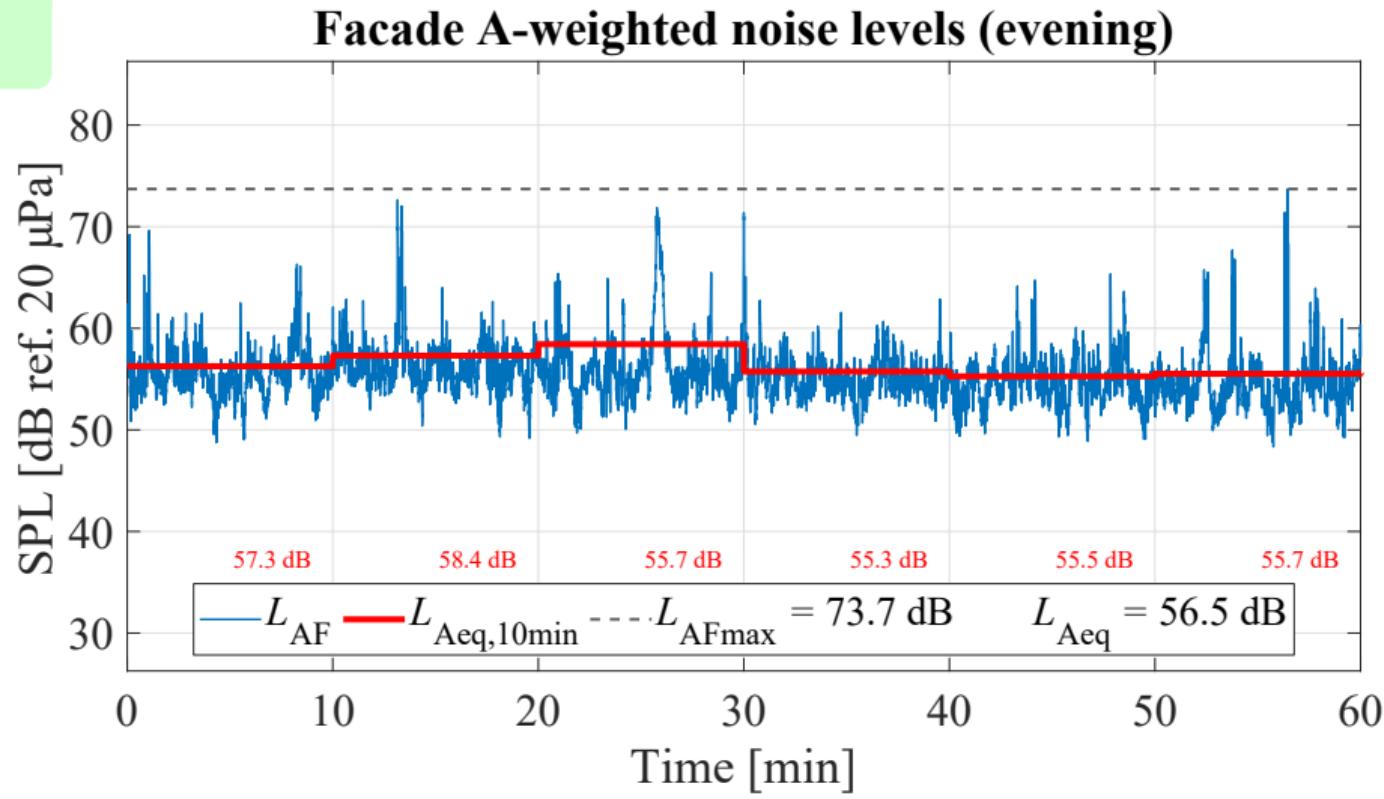
Food court  
30 min



## Noise monitoring for long periods — Results

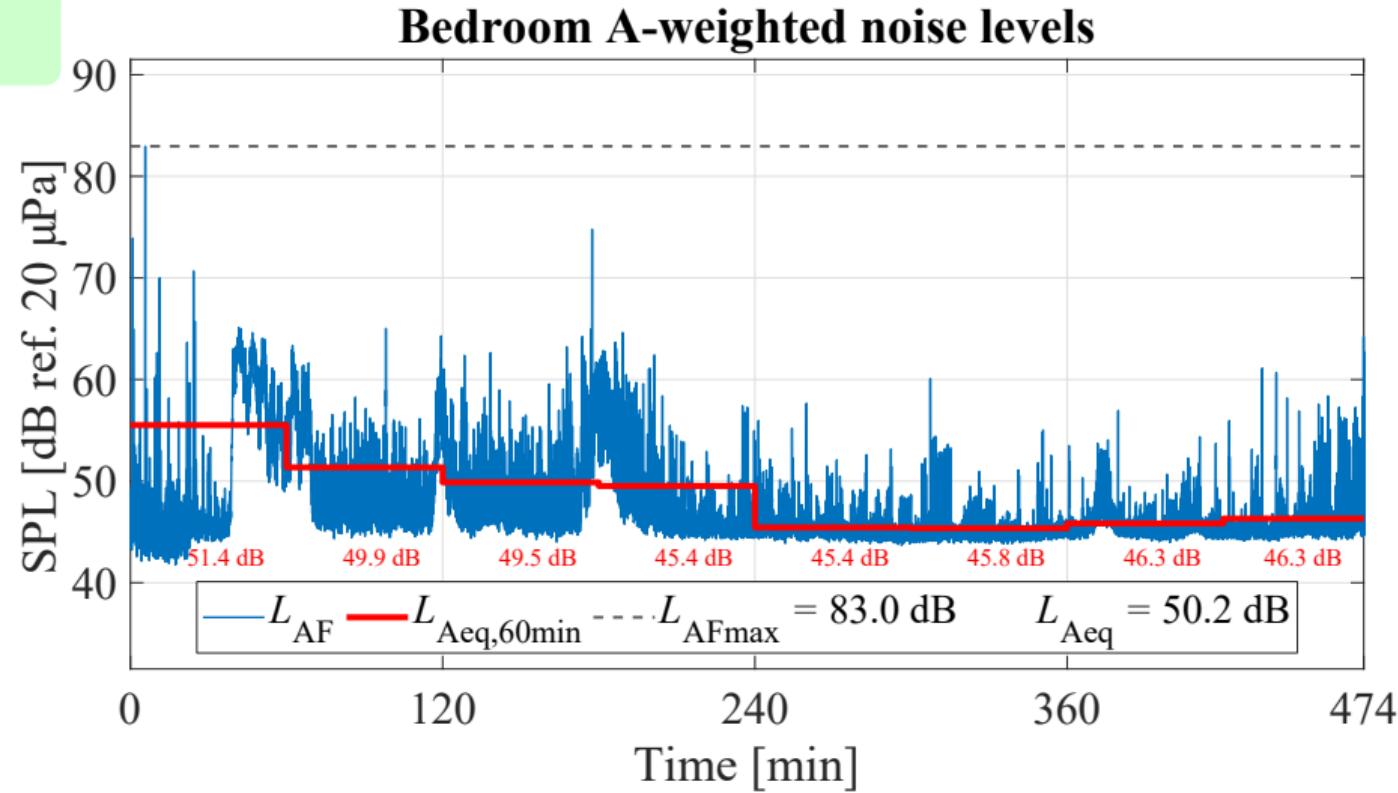
Façade (m)  
1 hour

## Noise monitoring for long periods — Results

Façade (e)  
1 hour

# Noise monitoring for long periods — Results

Bedroom  
8 hours



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# 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  $\pm 0.5$  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> 

## 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.
- The first author wants to acknowledge the Internoise 2021 for the grants for students of Latin America and for electing this project as a winner.
- 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!

- F. R. Mello; W. D'A. Fonseca; P. H. Mareze. MEMS digital microphone and Arduino compatible microcontroller: an embedded system for noise monitoring. In *50th International Congress and Exposition on Noise Control Engineering - Internoise 2021*, pages 1–12, Washington, DC, USA, Aug. 2021.

BibTeX: [18]

```
@InProceedings{MEMS:internoise2021,
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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.},
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