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MEASUREMENT OF THE SOUND FIELD OVER A GREEN ROOF USING SIMULTANEOUS SOUND PRESSURE RECORDINGS

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ABSTRACT

Green roofs provide a distinct acoustic environment with reduced sound pressure levels (SPL) compared to conventional roofs. These levels arise from a combination of direct sound, diffraction, reflection, and absorption effects—strongly influenced by measurement height. Simultaneous SPL measurements at eight heights were carried out to examine how roof geometry and materials affect SPL through absorption and diffraction. Results show that SPL decreases with decreasing measurement height, particularly when greenery covers wall parapets, highlighting the role of vertical surfaces in shaping rooftop soundscapes.

Keywords: *green roofs, sound absorption, soundscape, height dependency of SPL, sound diffraction* .

1. INTRODUCTION

Urban noise pollution is a widespread source of discomfort, with potential medical implications [1]. Among other benefits, urban greenery contributes to noise reduction and improves acoustic comfort [2]. To achieve these effects, densely built cities with limited space for ground vegetation, such as Barcelona, must integrate greenery into the architectural envelope. This study examines the acoustic effects of a semi-intensive green roof comprising $350\,\mathrm{m}^2$ of horizontal vegetation and $200\,\mathrm{m}^2$ of vertical greenery, located primarily along the walls of the roof parapet; and of a conventional roof with no vegetation. The conventional roof refers to a typical Mediterranean solution with ceramic tiles.

A preliminary study at the same location [3] explored differences in soundscape between the two aforementioned roofs. That study, along with subsequent field observations, led to the hypothesis that noise reduction exhibited a marked dependence on height, meriting further investigation. Subjective experience suggested a substantial change in perceived sound when standing versus sitting: from an open, noisy soundscape—where multiple urban sources were clearly identifiable—to a rooftop soundscape characterised by significantly lower sound levels. This contrast, though still present, was less pronounced on the conventional roof.

The soundscape of green roofs has been the subject of numerous studies [4]. In addition, the acoustic absorption properties of green roofs and green walls have been analysed both in laboratory [5] and in situ [6], confirming the expected good sound absorption behaviour due to both, substrate and vegetation.

The experienced sound field results from a combination of direct, diffracted, and reflected components.

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While previous models describe insertion loss behind sound barriers due to diffraction [7] [8], the geometric and absorptive particularities of the green roof—such as the highly absorbent wall parapet/barrier walls and substrate—warrant specific analysis. This experimental study investigates the dependence of SPL on both height and distance to the parapet, with a focus on the diffracted field within the acoustic shadow cast by the roof's parapet walls.

2. MATERIALS AND METHODS

2.1 Roofs under analysis

The selected roofs are located in a peripheral district, with a sparse population, approximately 500 m from an extensive green zone along the Besòs river. The immediate environment consists of a noisy, heavily motorised industrial park. The green and conventional roofs are separated by about 100 m and are part of the same industrial complex. The green roof, beneath its soil, water-proofing and drainage layers, features a thin roof system, while the conventional roof has a standard roofing solution. The dimensions of the green roof are $37 \times 13\,\mathrm{m}^2$ with a height 20 m, while the conventional roof measures $27 \times 6\,\mathrm{m}^2$ with a height of 12 m.

Figure 1 shows the floor plans of the two roofs, indicating the locations of the microphone arrays and their respective planes. Figure 2 shows a photo collage featuring five key scenes from the study.

2.2 In-situ sound absorption coefficient

Acoustic absorption measurements were conducted in situ using an impedance gun from Microflown Technologies [9–11]. This device consists of a spherical loudspeaker and a PU probe that simultaneously detects acoustic pressure and particle velocity. White noise is generated by the loudspeaker, placed 23 cm from the probe. The probe is positioned near the surface to be measured, as shown in the bottom-right image of Figure 2. The absorption coefficient is obtained from the impedance, that is, the complex ratio between acoustic pressure and particle velocity. The frequency range analysed spans from 200 Hz to 8000 Hz, and the results are presented in third-octave bands.

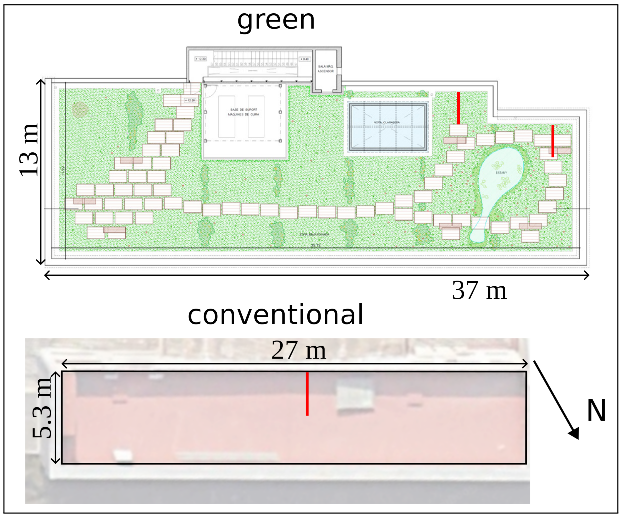


Figure 1: Floor plans of the green (top) and conventional (bottom) roofs. The red stripes indicate the locations and planes of the microphone arrays.

2.3 8-Microphone Array

A special arrangement of eight microphones was used to simultaneously measure sound variation at different heights and distances from the wall, as the background noise was highly variable. The microphone configuration was employed both vertically, with a fixed distance to the wall, and horizontally, with a fixed distance to the floor. These configurations are shown in the diagram of Figure 3. The measurements were recorded using 8 free-field Roga MI-17 microphones and a Rion DA-40 8-channel data recorder, and processed with the Rion AS-70 waveform analysis software.

3. RESULTS AND DISCUSSION

3.1 Acoustic absorption

The acoustic absorption coefficient is determined following the procedure described in Section 2.2, in different areas of the green roof. The results obtained for two representative areas of the roof are shown in Figure 4. The results are presented in third-octave bands between 200 Hz and 8000 Hz. In both cases, relatively high absorption coefficients are observed, with values approaching 1 for frequencies above 2500 Hz in the area with the most vegeta-

Figure 2: Photo collage of five key scenes. Left: vertical array of microphones in front of a conventional wall parapet. Middle top: vertical array of microphones in front of a photovoltaic glass of width $0.02\,\mathrm{m}$. Middle bottom: horizontal array of microphones along a vegetated zone. Right top: acoustic camera facing a conventional wall parapet. Right bottom: impedance gun measuring absorption of a vegetated surface.

tion (right image).

3.2 Acoustic camera

We use an acoustic camera to localise the sources of noise in order to characterise the incident sound field. The equipment used was the SevenBel Sound Scanner with the P132 sensor, capable of measuring down to 250 Hz. Figure 5 shows three images of the three wall parapets.

3.3 Sound pressure levels

Figure 6 shows the results for three different fixed heights, where in each case the sound is recorded simultaneously by the eight microphones located at 8 distances from the barrier. The sound levels remain approximately constant with height while changing the distance. Figure 7 displays the A-weighted equivalent continuous sound level for measurements taken at three different positions, with simultaneous measurements from eight microphones at

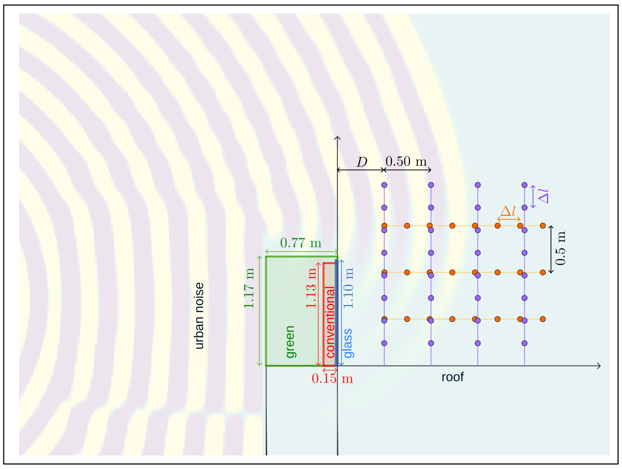


Figure 3: Diagram of wall parapets and microphone array positions (arrays are dots connected by lines). Two types of parapets are shown on the green roof: one wide and vegetated (green in the figure), and another thin, made of photovoltaic glass (blue in the figure). The wall parapet of the conventional roof is shown in red. Vertical microphone array positions are indicated in violet, while horizontal arrays are shown in red. The spacing between microphones in each array is Δl =24.2 cm, with recordings within a given array being simultaneous. The background wavefront represents sound propagation, depicted artistically from a 2D sound-wave simulation using Python Matplotlib. The distance D between the wall parapet and the first microphone of a horizontal array is $50.2\,\mathrm{cm}$ for the green roof and $54.2\,\mathrm{cm}$ for the conventional roof. For vertical arrays, the first microphone is located $50.0\,\mathrm{cm}$ from the parapet.

varying heights above the ground. The three graphs correspond to the three barriers analysed. For a fixed distance, the difference in sound level with height exhibits different behaviour in each case. The difference between the maximum height, h =$1.94\,\mathrm{m}$, and the lowest height, h =$0.25\,\mathrm{m}$, is 10 dB(A) in the green roof-green wall configuration, 6 dB(A) in the green roof-glass wall configuration, and 2 dB (A) in the conventional roof-brick wall configuration.

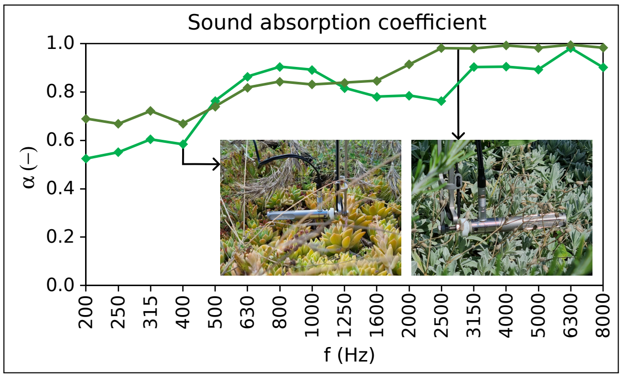


Figure 4: Acoustic absorption coefficients as a function of frequency measured with the impedance gun. Light green represents absorption coefficients for low vegetation, such as Sedum, and dark green for intermediate vegetation, such as leaf plants.

3.4 Noise level dependency on the frequency

To understand which frequency bands contribute to the overall decrease in sound level, sound levels in third-octave bands between 50 Hz and 10.000 Hz are analysed for eight different heights at a distance of d=1.0 m from the wall in the three roof-barrier configurations (Figure 8). Additionally, for each configuration, the variation in noise levels in some selected third-octave bands with respect to height is plotted in Figure 9.

The spectrum of the conventional roof (Figure 8 c) does not depend on the height of the receiver, and the noise level decreases monotonically with frequency. The green-green case (Figure 8 a) exhibits a behaviour similar to the conventional one at low frequencies, while at medium and high frequencies the curves diverge, clearly decreasing the sound level. Low frequencies at different heights appear to have similar values of L_p, but as the frequency increases, so does the difference between the sound levels at difference heights. The green-glass roof (Figure 8 b) displays intermediate behaviour between the two previous ones. To illustrate this, a closer look at the variations in different third-octave frequency bands for a selected position, as a function of height, is provided in Figure 9. At low frequencies, the level decreases slightly with height across all three configurations. In contrast, at higher frequencies (from 500 Hz onward), the level increases with height. This increase is greater for the green-green roof

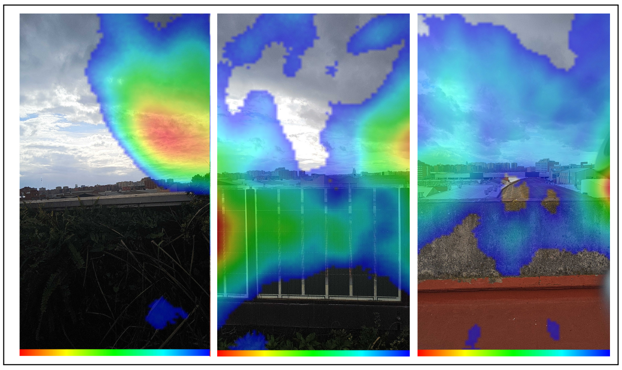


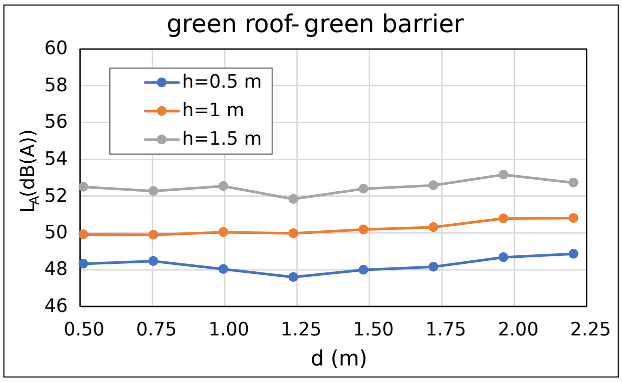
Figure 5: Acoustic camera measurements. From left to right: green roof with green barrier; green roof with glass barrier; conventional wall with brick barrier. The optical image is overlaid with a sound level map, where blue and red represent lower and higher sound levels, respectively. The dynamic range is 3dB. In the left image the sound source is perceived to be slightly higher than the noise source. In the centre image, the two original noise sources are perceived but are out of the frame. The same happens at the conventional wall

and modest for the conventional one.

The difference in sound levels for eight different heights in the 125 Hz and 1000 Hz third-octave bands, for two selected distances d=1 m and d=2 m, is shown in Figure 10. For each position, the difference in level of each microphone is determined in relation to the highest microphone, which is taken as the reference level.

In all three cases, the 125 Hz band increases at lower heights, contrary to expectations based on diffraction models. This behaviour could be explained by the low absorption at low frequencies in both the green roof and conventional configurations, allowing the sound to reflect off the barrier walls and the floor at these heights. In the case of the 1000 Hz band, which behaves similarly to the 500 Hz, 2000 Hz, and 4000 Hz bands, the difference between roof-barrier configurations is much clearer.

The difference between the reference level (highest microphone) and the lowest microphones ranges from $14-16$ dB in the green roof-green barrier configuration. The same measurement on the glass barrier shows a difference of $10-12$ dB between the extremes. In both



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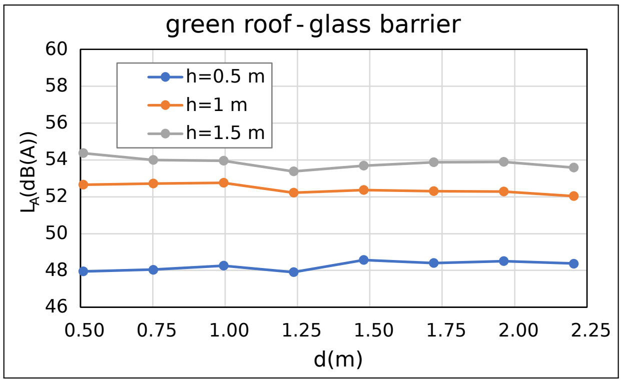

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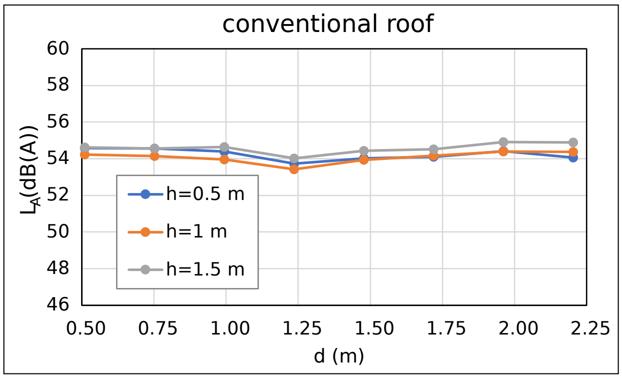
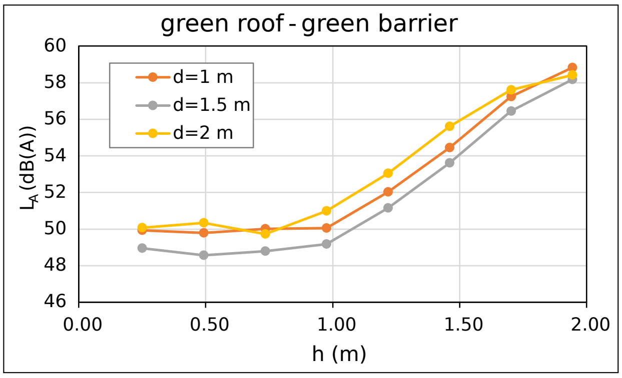


(c)

Figure 6: L_A vs d. Panels (a), (b), and (c) show the A-weighted sound pressure level, L_A, as a function of distance to the wall, for three different fixed heights h. The measurements are performed at the green roof-green barrier case (a), the green roof-glass barrier case (b), and the conventional roof (c).



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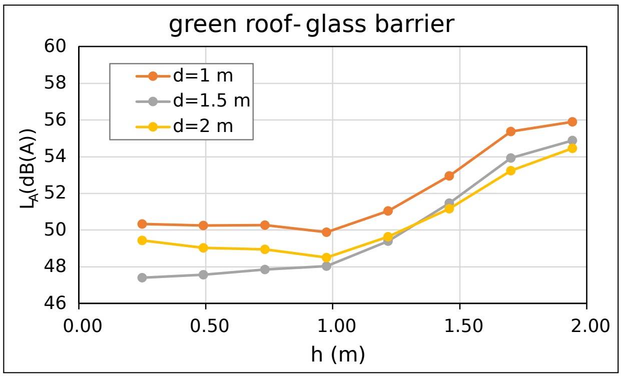

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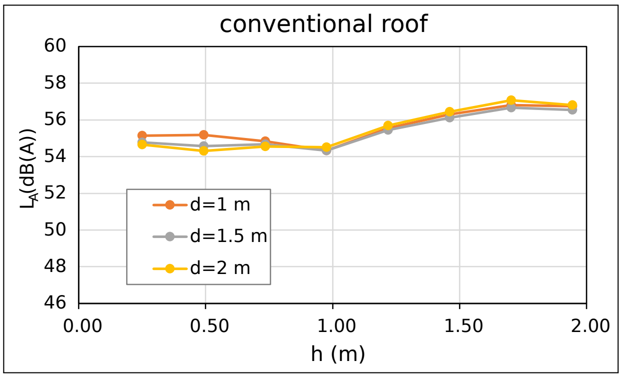
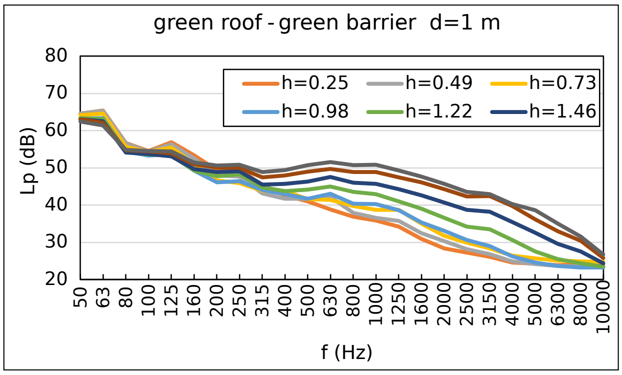


(c)

Figure 7: L_A vs h. Panels (a), (b), and (c) show the A-weighted sound pressure level, L_A, as a function of height, for three different fixed distances d from the wall. The measurements are performed at the green roof-green barrier case (a), the green roof-glass barrier case (b), and the conventional roof (c).



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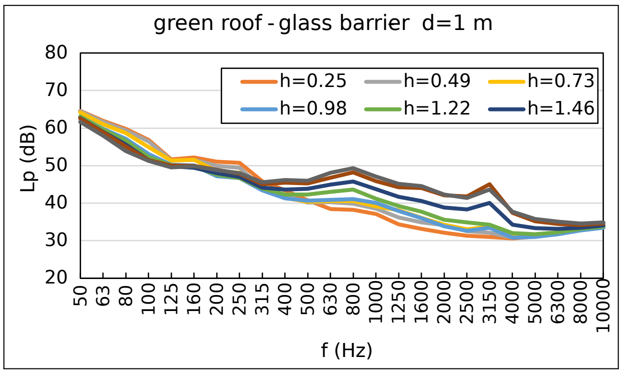

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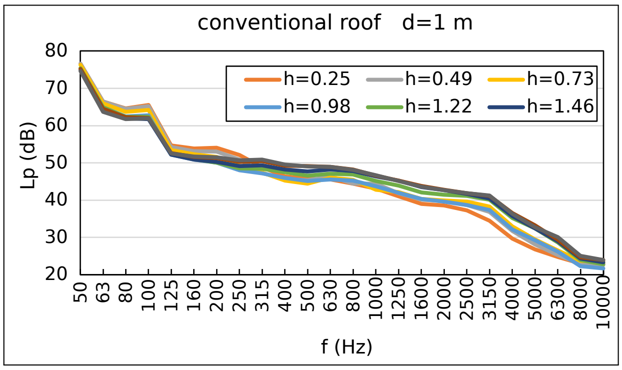


(c)

Figure 8: Panels (a), (b), and (c) show the sound pressure level, L_p, in third-octave bands as a function of frequency, for a fixed distance d=1 m from the wall. The measurements are taken at different heights for the green roof-green barrier case (a), the green roof-glass barrier case (b), and the conventional roof (c).

cases, the trend is relatively linear. Finally, the conventional roof-brick wall configuration shows differences of $4 - 5$ dB between the highest and lowest microphones.

From these measurements, it can be inferred that the L_A level differences presented in Section 3.2 are mainly driven by medium and high frequencies, from 500 Hz to 4000 Hz, as also evident from the graphs in Figure 8.

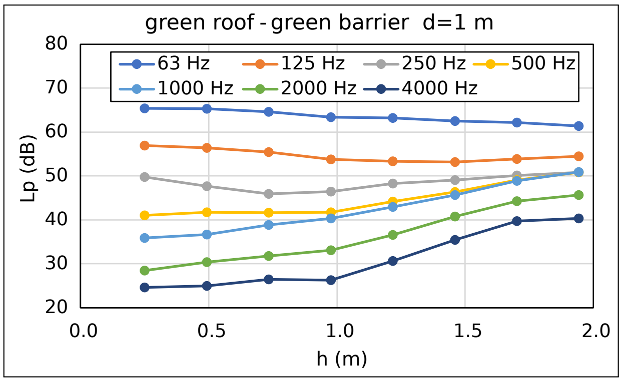
4. CONCLUSIONS

Three different cases were analysed: a green roof with a green wall parapet, a green roof with a glass barrier, and a conventional roof with a brick parapet. The green roof with a green barrier exhibited the largest difference in sound levels between the highest measurement point and the lowest, with level differences of up to 15 dB in medium to high frequencies, from the 500 Hz band up to 4000 Hz. The glass barrier showed a similar behaviour but with smaller differences, up to 10 dB. The conventional roof showed a maximum difference of 5 dB. This comparison is shown in Figure 10 (b).

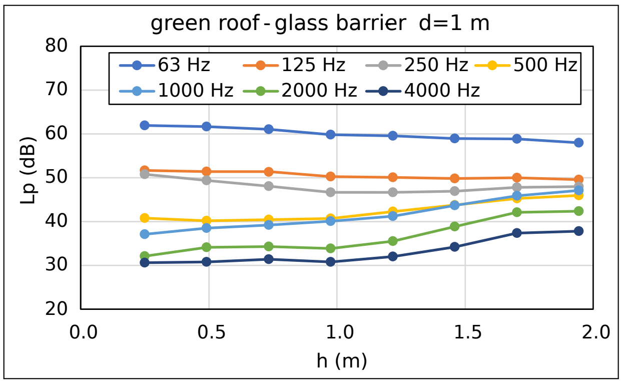
This contrasting behaviour was also observed when measuring the A-weighted global sound levels. In this case, the green roof with a green wall parapet exhibited differences of 10 dB(A), the green roof with a glass barrier 6 dB(A), and the conventional roof with a brick parapet 2 dB(A).

Much smaller variations between roofs were observed at low frequencies ($125 - 250$ Hz), as shown in Figure 10 (a). The three configurations show similar behaviour, reaching 4 dB as the measurement height decreases. Therefore, the trend is reversed at higher frequencies. The effect of internal sound reflections inside the roof is hypothesised, as there is low absorption coefficients of the walls and plants at low frequencies, along with the possibility of additional inter-reflections of sound inside the roof walls.

The hypothesis is confirmed: greenery on the roof, particularly when covering wall parapets, results in a reduction of overall sound levels with decreasing measurement height. Future work will involve numerical modelling of diffraction, absorption and reflection to better understand and predict the mechanisms shaping rooftop soundscapes.



(a)



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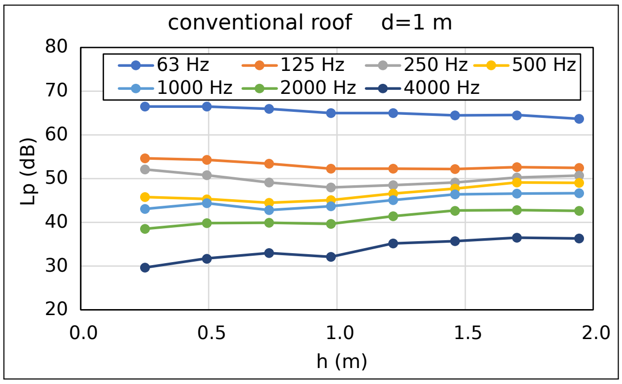
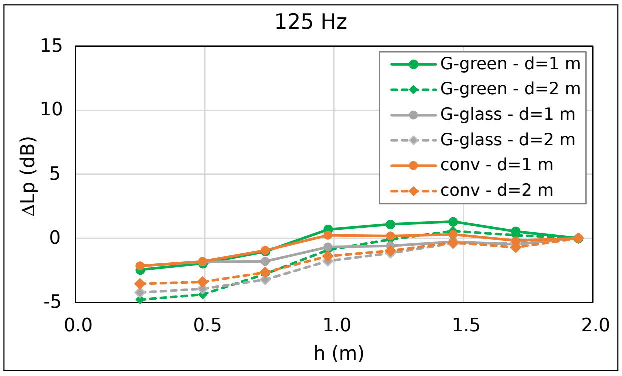
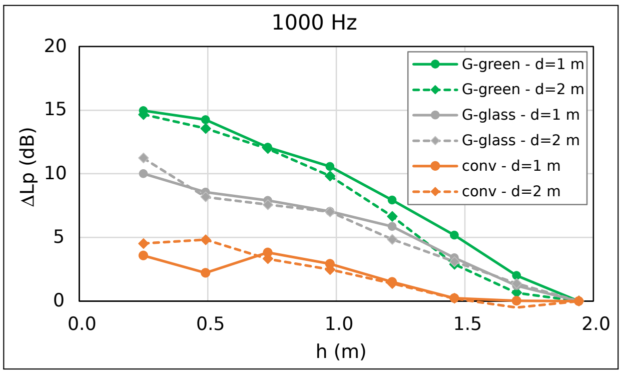


(c)

Figure 9: Panels (a), (b), and (c) show the sound pressure level, L_p, in different third-octave bands (63 Hz-4000 Hz) as a function of height, for a fixed distance d=1 m from the wall. The measurements are taken at varying heights for the green roof-green barrier case (a), the green roof-glass barrier case (b), and the conventional roof (c).



(a)



(b)

Figure 10: ΔL_p vs h. Panels (a) and (b) show the variation of the sound pressure levels with height ΔL_p, for two different distances of the microphone array to the wall in each of the roof-barrier configurations. ΔL_p represents the difference between the value at the higher microphone and each of the other microphones.The 125 Hz band case is represented in panel (a) and the 1000 Hz band in panel (b)

5. ACKNOWLEDGEMENTS

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