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# ASSESSING FOREST ACOUSTICS: A COMPARISON OF IN-SITU AND SCALE MODEL ACOUSTIC IMPULSE RESPONSES

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### ABSTRACT

Acoustic impulse responses (IRs) can be used for the analysis of a space's acoustic properties and for convolution based auralisation (which has many applications, including in music production and sound design). However, the vast majority of impulse responses are recorded indoors, typically in musical performance spaces. As a result there are relatively few IRs available recorded in outdoor conditions. This paper presents an analysis of IRs recorded in a forest environment, comparing in-situ results with those recorded using a scale model. The in-situ recordings were measured in mono and B-format, and are analysed in terms of reverberation parameters and spatial characteristics. A 1:10 scale model of the forest environment was then constructed and measured. This work aims to contribute to the understanding of sound propagation in a forest environment (particularly in terms of the acoustic effect of tree trunks of different diameters at different positions relative to the listener, which previous studies have determined to be of particular importance) and to assess the suitability of scale modelling in this context. The resultant impulse responses are available online.

**Keywords:** *forest acoustics, acoustic impulse response measurement, scale model*

## 1. INTRODUCTION

An understanding of the acoustic properties of forest environments is of great importance to many fields, including noise propagation, soundscape evaluation, and sound design [1, 2]. There is existing literature focussing on different aspects of forest acoustics, but work remains to be done in developing a full understanding of how the different physical characteristics of a forest (the layout, number of trees, tree trunk diameters, bark material) combine and result in a particular acoustic. This work investigates the acoustics of a forest environment, by assessing in-situ impulse responses and scale model measurements, and aims to answer the following questions:

1. What are the acoustic properties of tree trunks in a forest environment?
2. Is a scale model a good approach to studying forest acoustics?

The structure of this paper is as follows: Section 2 presents a review of relevant prior research; Section 3 presents the method of impulse response recording used in the forest and the scale model; Section 4 presents the analysis and comparison of the impulse responses from both environments; and Section 5 concludes the paper, considering the above questions.

## 2. BACKGROUND

This section presents a brief review of the relevant existing literature, include material on the study, analysis, and modelling of forest acoustics, and acoustic scale modelling.

### 2.1 Forest acoustics

Sound attenuation by vegetation has been investigated since at least 1946, when Eyring investigated the acoustic properties of a Panamanian jungle [3]. It has been proposed that trees can be used as noise barriers near sources such as highways and railroad tracks [4,5]. The form and layout of a forest have been indicated as important properties in determining sound attenuation [6, 7]. This is related to the interaction of various acoustic phenomena in a forest environment. Noise attenuation can occur due to sound energy absorption and scattering effects by branches, foliage, and shrubbery [5, 8]. The effect of sound propagation in a forest environment has been shown to be highly frequency dependent [9]. A relatively small sound attenuation in a frequency range between 1 and 2 kHz was observed by Fricke, and a similar reduction in attenuation was found by Kragh, typically between 500 Hz and 2 kHz [7, 10].

Previous IR measurement work has been conducted in a forest environment, where Shelley et al. conducted a study at Koli

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National Park in Finland using a B-format microphone and a single speaker [11]. This method followed ISO 3382 IR measurement procedure (designed for indoor measurement) [12]. The analysis of acoustic parameters, including reverberation time (T30) and clarity (C50) was conducted, and a reverberation time of between 1.3s and 1.7s was found in the 1 kHz octave band. Previous studies have indicated that tree trunks are a key factor in sound scattering above 1 kHz in a forest environment [9, 13–15]. Chobeau determined that the scattering caused by tree trunks is dependent on the apparent diameter of the trunk and the relationship between the diameter and the frequencies present in the incident sound [16]. Generally, tree trunks scatter sound frequencies with wavelengths equal to or smaller than their diameters [9].

Previous studies in modelling forest acoustics have considered tree trunks as the key factor in sound propagation. *Treeverb*, a digital reverberator, simulates acoustic reverberation in a forest environment, modelling the scattering of acoustic waves among trees in a simplified forest model [17]. Fig. 1 shows a simple example of a forest modelled in this way, where T1, T2, and T3 are the interconnected tree-nodes, S is the source and R is the receiver. In this work an image-source model, along with Morse's solution to the acoustic scattering from a cylinder [18], was used to generate IRs. In [19] a similar approach was used to model forest acoustics, using a set of waveguides to connect the tree nodes (extending the scattering delay network approach in [20]).

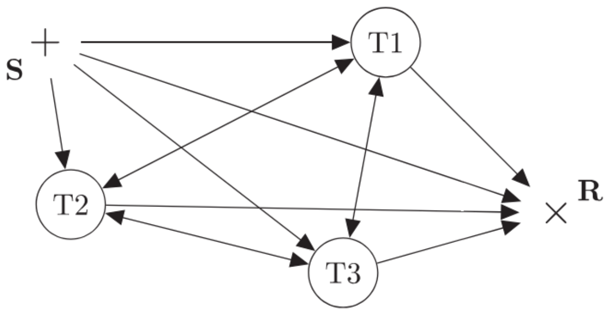


**Figure 1**. An example of a simplified model of a forest, consisting of three tree-nodes, T1, T2, T3, a source, S, and a receiver, R. From [19].

### 2.2 Scale modelling

Acoustic scale modelling was first used in the design of concert halls and opera theatres in the 1930s [21]. This method allows for the prediction of the acoustic properties of a full-scale space as it captures complex wave effects such as diffusion, diffraction, and ground interference [22, 23]. The model scale factor ($k$) determines the relationship between the scale frequency ($f_{\text{scale}}$) and the corresponding full scale frequency ($f_{\text{real}}$) [24]:

$$f_{\text{scale}} = k \times f_{\text{real}} \tag{1}$$

When determining the scale factor there is a trade-off between the capability of the available recording equipment [25], the space available, and the increased air absorption at higher frequencies [26]. When constructing a scale model, the materials used should closely approximate sound absorption coefficients (SACs) at the scaled frequencies [27].

Scale modelling has previously been used to study sound propagation in outdoor spaces. Cox et al. studied the acoustic properties of Stonehenge using an acoustic scale model [23]. This research used a scale factor of 12, and IR measurement and analysis were conducted in accordance with ISO 3382 [12]. The Exponential Sine Sweep (ESS) method was used with frequencies ranging from 800 Hz to 96 kHz. Four compact tweeters, arranged in a square configuration, and an ultrasonic microphone were used to approximate an omnidirectional source and receiver. The model stones were designed and constructed to minimise sound absorption (given the typically low SAC of stone), and unvarnished Medium Density Fibreboard (MDF) was used to model the ground, to match the SACs of grassland in a true scale frequency range of 125 Hz to 1 kHz. The scale modelling work presented in this paper draws on Cox et al.'s approach.

## 3. METHODOLOGY

This section covers the methods of IR measurement used in the real forest (Section 3.1), the design and construction of the scale model (Section 3.2), and the scale model IR measurement (Section 3.3).

### 3.1 Forest IR Measurement

The chosen measurement site was in Wheldrake Woods, c. 8 miles south-east of York [28]. Fig. 2 shows the chosen environment. The trees are all the same species (*Abies Grandis*), and consist primarily of tall, straight, trunks with no large branches. The ground surface is relatively flat with no additional low vegetation.

Two source and two receiver positions were selected for measurement. Source *S1* was placed with clear sight lines to Receivers *R1* and *R2*. *S2* was placed with a tree obstructing its view of both receivers. Each position was at least 1m away from the nearest tree. The positions and diameters of the trees within an area of 20m × 20m around the sources and receivers were measured, the layout of which is shown in Fig. 3. The size of the surveyed area was determined by the maximum scale model size, as discussed in Sections 3.2 and 3.3.

The IRs were measured with the ESS method, using a Genelec 8130A loudspeaker to reproduce a sine sweep of 15s duration with a frequency range of 60 Hz - 20 kHz ($f_s = 48$ kHz). Recordings were made using two microphones: an Earthworks M30 omnidirectional measurement microphone (mono), and a

**Figure 2**. The forest environment considered in this study. The measurement setup can be seen: an Earthworks M30 omnidirectional measurement microphone and a Genelec 8130A loudspeaker.

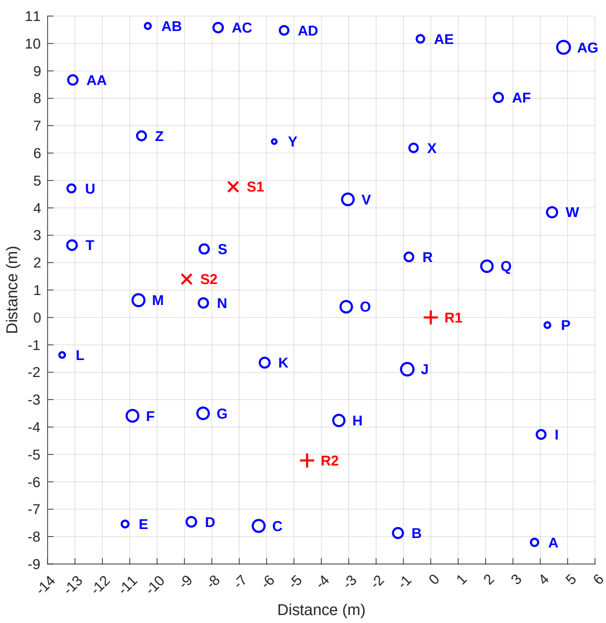


**Figure 3**. Diagram of the layout of the forest environment, showing source, receiver, and tree positions. Within the measurement area there were 33 trees with diameters ranging between 0.17m to 0.47m.

Soundfield ST450 MkII (B-Format). The speaker and microphones were placed at a height of 1.5m. For each source position, four measurements were made: first recording a sweep

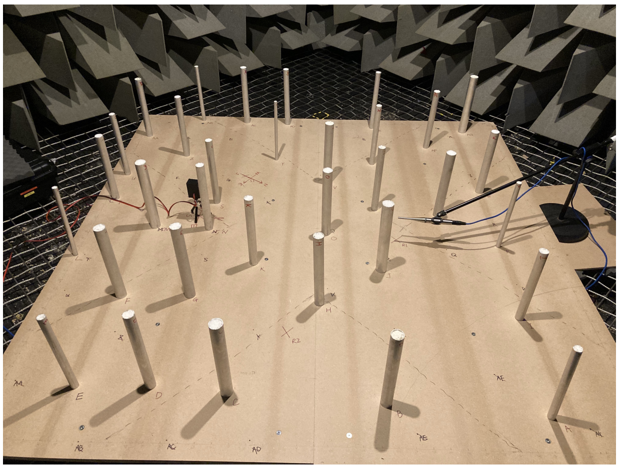

**Figure 4**. A picture of the forest scale model setup in the anechoic chamber, formed by 33 aluminium tubes (filled with plaster) and an MDF board. Here source and receiver are at position S2R1.

with the speaker facing *R1*, then three further recordings with the speaker rotated clockwise 90° each time. These four orientations were then averaged to approximate an omnidirectional source [11].

### 3.2 Design of the scale model

The scale model was constructed with a scale factor of 10. This was determined by the maximum usable area of the anechoic chamber in which the recording took place, and the microphone in use (an Earthworks M30) having a flat response up to 30 kHz. This allowed for useful measurement up to $f_{real} = 3\,\text{kHz}$, and the use of available materials with SACs appropriate to this scale.

Aluminium tubes were used to model the trees, due to their smooth surface which is reflective at high frequencies. To avoid capturing the resonant frequencies of the tubes, each was filled with plaster. The tubes were chosen from available diameters, resulting in some minor error (maximum 6.85%).

In this experiment, the height of each tube was 40cm. This was chosen as it is more than twice height of the source/receiver in the scale model (15cm). Unvarnished MDF was used to model the ground, as in [23].

To construct the scale model, a square MDF board (with side length of 2.1m) was mounted to the floor of the anechoic chamber. Dowels were then used to attach the model trees in their correct positions. The final forest scale model setup is shown in Fig. 4.

### 3.3 Scale Model IR Measurement

A Peerless OC20SC14-04 tweeter with a diameter of 33.2mm, and a frequency response from 750 Hz to 38 kHz was used as the source in the scale model measurements, with the Earthworks M30 used to record the signals produced. A 15s duration ESS ($f_s = 96$ kHz) was used with a frequency range from 1 kHz to 30 kHz, allowing for IR analysis of octave bands from 125 Hz to 2 kHz at full scale. For each source/receiver pair, 16 recordings were made: four speaker orientations (as in the in-situ measurement), each recorded four times (in an attempt to improve the signal-to-noise ratio [23]). These 16 takes were then averaged and equalised for the speaker's response using an inverse filter based on a free-field measurement of the speaker.

## 4. EVALUATION

This section presents analysis of the IRs measured in-situ and using the scale model. This includes ISO 3382 analysis and spatial analysis of the B-format recordings. The full sets of recorded IRs are available online [29, 30].

### 4.1 Forest IR Analysis

Fig. 5 shows the reverberation time (T30) results for the four forest IRs. They each show a similar trend, with a pronounced peak across the 500 Hz, 1 kHz, and 2 kHz octave bands, where the values are above 1.5s. These results are partly due to the measured tree trunk diameters (ranging between 0.17m and 0.47m), which correspond to wavelengths from 735.6 Hz to 2072.5 Hz, this is an expected result given the importance of tree trunk reflections identified in the literature [9, 13–16].

Ground interference is likely to have an impact below 500 Hz [13, 31], resulting in constructive and destructive interference in the 125 Hz, 250 Hz, and 500 Hz octave bands [32]. Low-frequency wind noise in the recordings may result in overestimation of reverberation time, particularly for the 125 Hz octave band. The significant drop in reverberation time for the 4 kHz and 8 kHz octave bands is due to the open nature of the forest and absorption by tree bark [19, 33].

Fig. 6 shows a comparison of Definition (D50) results for the four forest IRs. D50 values are generally above 80%, suggesting significant sound attenuation at high frequencies and good speech intelligibility. A reduction in D50 is observed for the 1 kHz and 2 kHz octave bands of each IR, due to the increased reverberant energy. At position S2R1, the source is occluded by *Tree O*, and at position S2R2, the source is occluded by *Tree N*. Without a clear line of sight between source and receiver there is no true direct sound present in the IR, resulting in a decrease in D50 [34]. This is particularly evident in the results for S2R1.

Fig. 7 shows a waveform plot of the S1R2 IR. Alongside the IR, red lines indicate the timings of reflections from the tree trunks in the environment (calculated using the forest layout data). It can be seen that a number of strong early reflections in the IR line up with these predicted timings, confirming the impact that tree trunks have on a forest's acoustic properties.

The spatial information captured in the B-format IRs can be evaluated by spatial impulse response rendering (SIRR) analysis. Here the signals are divided into discrete time frames, and then a short-time Fourier transform (STFT) is performed on each channel. A instantaneous intensity vector **I** vector can then be estimated according to:

$$\mathbf{I}(\omega) = \frac{\sqrt{2}}{Z_0}\Re\{W^*(\omega)U(\omega)\} \tag{2}$$

where U($\omega$) is vector [X($\omega$), Y($\omega$), Z($\omega$)], $Z_0$ is the char-

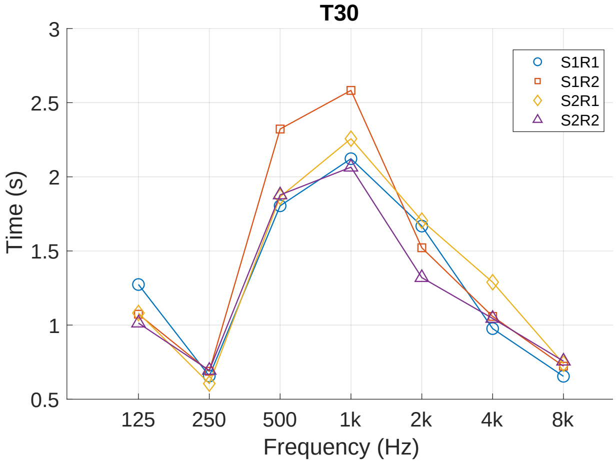


**Figure 5**. Reverberation time (T30) results for the four forest IRs.

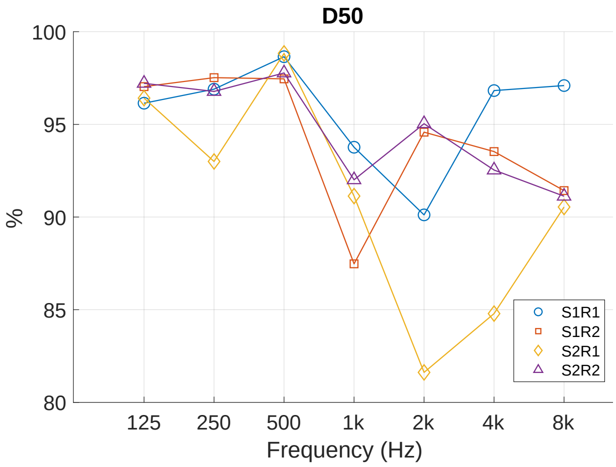


**Figure 6**. Definition (D50) results for the four forest IRs.

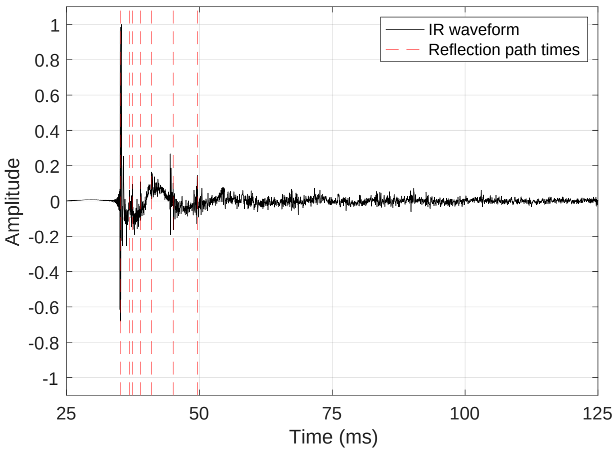


**Figure 7**. Waveform plot of the S1R2 IR recorded in the forest. The red lines indicate the timing of first-order reflections from nearby trees.

acteristic acoustic impedance of air, and $*$ denotes the complex conjugate [35].

Fig. 8 shows a SIRR plot for the IR at position S1R2. Only the horizontal plane is considered in this SIRR analysis, due to the open nature of the forest environment precluding significant directional information in the vertical plane [36]. The arrows indicate the direction of arrival of sound in each frequency bin for each frame. An arrow pointing to the right corresponds to a sound arriving straight-on to the microphone (0°); an arrow pointing down corresponds to a sound coming from the right to the microphone (90°). These arrows are overlaid on a spectrogram of W-channel of the IR, allowing for concurrent analysis of the magnitude and direction of arriving acoustic energy.

The SIRR plot shows a strong direct sound followed by a set of early reflections coming from different directions. At certain points in time, clusters of arrows can be found pointing in the same direction. These indicate reflections from particular tree trunks, and a summary of the first-order reflections (with suggestions of the particular trees contributing to them) is given in Table 1. This analysis could be continued to include further reflection paths; previous work has shown the importance of reflections of up to third-order in outdoor environments [36].

### 4.2 Scale Model IR Analysis

The scale model IRs were interpolated to be 10 times longer, in order to conduct analysis at true scale. Fig. 9 shows the waveform plot of the IR recorded at position S1R2 in the scale model. As before, red lines indicate the estimated reflection path times calculated using the forest layout data. The results show that the reflections indicated in the waveform align well with the potential reflections indicated in the actual layout, and the error range is small. The waveform shows a strong direct sound followed by clusters of early reflections, which is similar to the IR recorded in the real forest (as shown Fig. 7).

**Table 1**. Details of the first-order reflections identified in the SIRR analysis in Fig. 8.

| Timing | Direction of arrival | Frequency | Relevant Tree(s) |
|---|---|---|---|
| 12-16ms | 0° | 0-5 kHz | *K, S, H, N, O* |
| 20-22ms | 315° | 1-5 kHz | *M* |
| 22-26ms | 45° | 1-4 kHz | *V, Y* |
| 28-30ms | 225° | 2-5 kHz | *C* |

Fig. 11 shows the early decay time (EDT) results for the four scale model IRs, which can be compared with Fig. 10 (which shows the EDT results for the in-situ forest IRs). EDT was chosen for comparison here as it has previously been shown to be useful when comparing scale model and real-world IRs [23]. EDT results in the scale model show generally low values due to the limited number of model trees and the anechoic environment. Although a similar trend can be found in both results: higher EDT values in the 250 Hz octave band than at 500 Hz, then a general increase for higher bands.

Spectral plots of the IRs are shown in Fig. 12 (in-situ) and Fig. 13 (scale model). Results were calculated by filtering the IRs into one-third octave bands and then calculating the dBFS values (decibels relative to full scale) for each band. There are similarities in the spectra, with a decrease in magnitude centred around the 250 Hz band, and an increase above this range.

The spectrum of the forest shows another small decrease in response of 2 to 4 dB around 800 Hz, and the results from the scale model show a similar reduction at positions S1R2 and S2R1. In the case where the source and receiver are obstructed by a tree, the frequencies are greatly pronounced below 800 Hz in the real forest. For these receiver positions in the scale model, the magnitudes are higher at the tree-obstructed (*S2*) position below this frequency. Above 250 Hz, the scale model magnitudes are generally higher than in the real forest.

## 5. CONCLUSION

This paper has presented the measurement and analysis of IRs recorded in a forest environment, comparing in-situ IRs with those recorded using a scale model. The questions posed in Section 1 will now be considered:

1. What are the acoustic properties of tree trunks in a forest environment?

2. Is a scale model a good approach to studying forest acoustics?

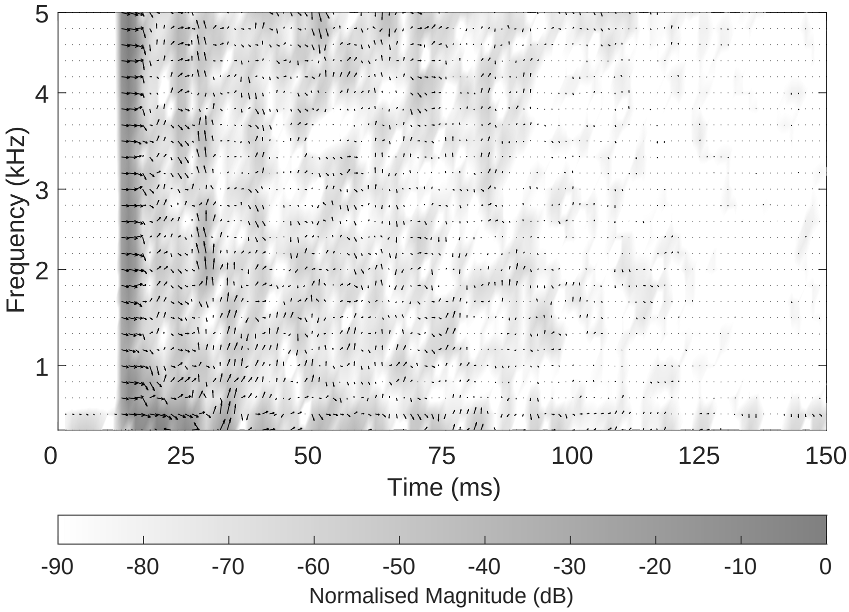


**Figure 8**. SIRR analysis plot of the B-format IR reorded at position S1R2 in the forest, where a spectrogram of the IR's W-channel is overlaid with arrows representing the direction of sound arrival (in the horizontal plane) in different frequency bins for each time frame.

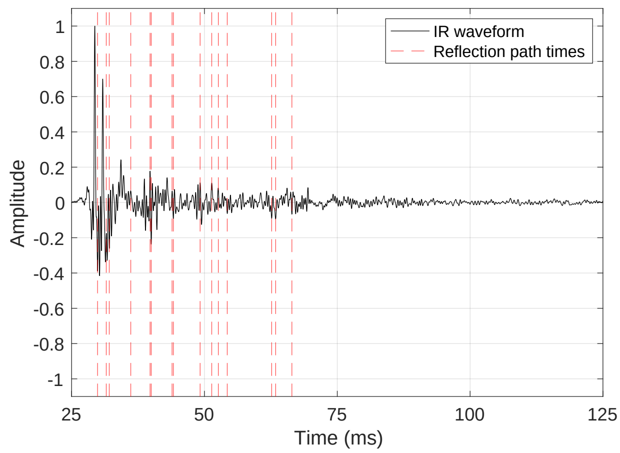


**Figure 9**. Waveform plot of impulse response recorded at position S1R2 in the scale model. The red lines indicate the estimated timing of early reflections.

The presented IR analysis has demonstrated the impact that tree trunks have on the acoustic of a forest environment. The presence of tree trunks results in strong early reflections (as shown by the SIRR analysis results), and can occlude sound paths reducing the acoustical clarity (as shown by the D50 results), and can increase reverberation time in 1 kHz and 2 kHz octave bands (as shown by the T30 results). The results presented here are limited by the small number of source and receiver positions, and the area of the forest environment surveyed and measured.

The results from the scale modelling work indicate that this may be a useful approach to the study of forest acoustics, as there are similarities between the scale model and in-situ results presented in the evaluation. That said, there are still a number of unanswered questions that bear consideration. There is further work to be done in assessing the appropriateness of the materials used in the scale model, and whether they correctly represent the full scale acoustic behaviour. The scale model used here is also limited to 33 trees in a 20m $\times$ 20m area (as determined by the chosen scale factor and model size limitations). Further work investigating the effect of the scale factor on the results, and the impact of the number of modelled trees, should be conducted.

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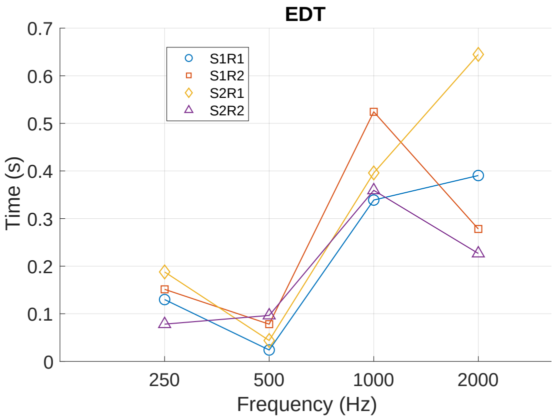


**Figure 10**. Early decay time (EDT) of four forest IRs at octave bands ranging from 125 Hz to 2 kHz.

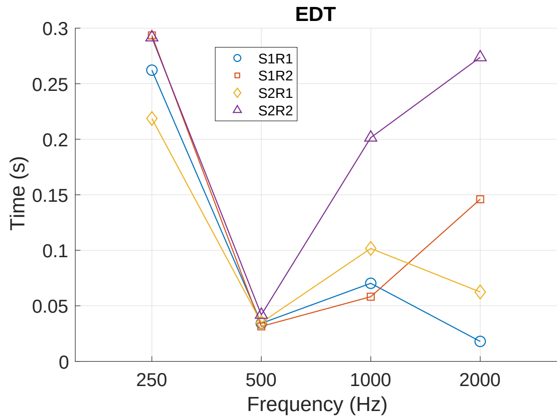


**Figure 11**. Early decay time (EDT) of four scale model IRs at octave bands ranging from 250 Hz to 2 kHz.

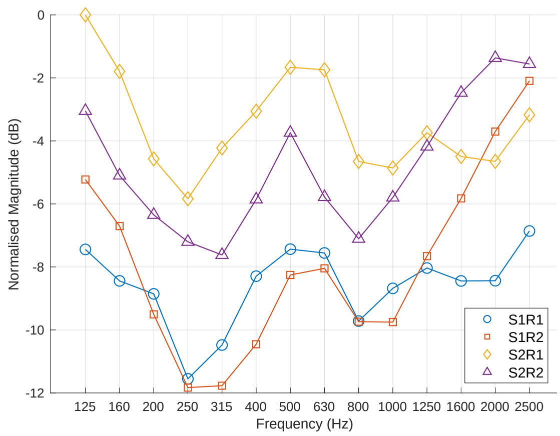


**Figure 12**. Spectral plots (1/3 octave bands) of the four in-situ IRs.

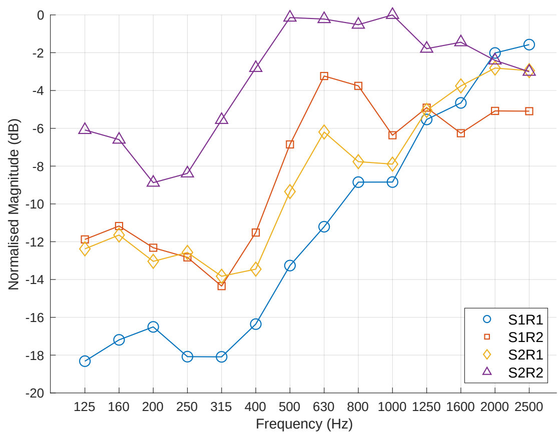


**Figure 13**. Spectral plots (1/3 octave bands) of the four scale model IRs.

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