SUGIRA: 3D RIRS SOFTWARE DEVELOPMENT

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SUGIRA, a novel software to visualize 3D impulse responses, is introduced. It generates a hedgehog plot from loaded Ambisonic measurements, useful to locate the direction and relative amplitude of direct sound and reflections, as well as displaying their arrival time. Additionally, the hedgehog plot can be placed over an image, for example a plan view, in order to deepen the analysis. SUGIRA's Graphic User Interface provides an immersive and intuitive experience. Measurements processing of Central Hall (University of York), Clifford's Tower (York) and San José Theatre (Buenos Aires) are shown in this work. The validation of SUGIRA was performed comparing results with Marshall Day Acoustics' software IRIS.

Keywords: 3D Impulse Response, Hedgehog Plot, Ambisonic, Software Development.

1. Introduction

The examination of 3D impulse responses can make one gain crucial insights into the acoustics of complex sound systems and spaces, which is vital for designing and optimizing concert halls, theaters, recording studios, audio systems for virtual reality, and other immersive sound environments. Traditionally, room acoustics were analyzed using omnidirectional monophonic impulse response measurements, which provide data on sound reflections in terms of magnitude and time. However, they do not offer directional information about the reflections. Comparing different room impulse responses (RIRs) for the same room can reveal the impact of variables such as diffusers location and microphone positioning.

Another method involves binaural impulse responses, which account for the time and level differences between the acoustic waves reaching the left and right ears. These differences allow the brain to perceive the direction and distance of sounds. However, this technique assumes that reflections come from a single direction and emphasizes temporal over spatial information, making it accurate for horizontal angle (azimuth) reflections but less so for vertical angle (elevation) reflections.

To conduct a more thorough analysis of sound reflections, considering magnitude, time, and direction, a 3D impulse response measurement is necessary. Formats like Ambisonics provide directivity measurements by combining signals from various microphone capsules within a Soundfield transducer.

The goal of this project is to develop a software for processing such responses. SUGIRA (Sea Urchin Grapher - Impulse Response Ambisonic) accepts Ambisonics signals (A or B format) or a sine sweep measurement with its corresponding inverse filter as input. After processing, the software generates an interactive 'hedgehog' plot that details the timing, direction, and intensity of direct sound and reflections at a specific point. This plot can also be displayed on a plan view of the studied room for easier interpretation of the results.

To enhance user-friendliness, a graphical user interface (GUI) was developed in Python. This interface includes the aforementioned features and additional options for analysis, visualization, and exporting of the results.

2. State of art

3D impulse response measurement systems have been developing since 1980's by Yamasaki & Itow [1], Farina & Tronchin [2], and many other authors. However, it was not until 2013 that the company Marshall Day Acoustics presented a 3D impulse response analysis tool called IRIS [3], which consisted in a conventional measurement system that used a matrix of tetrahedral microphones, an audio interface and a dedicated software.

Nowadays, many software calculate and display a 3D analysis of an impulse response. Some of them, like EASE, are based on geometric simulations of a designed enclosure, and allow one to see the arrival of a certain order of rays at a particular seat. Another softwares are focused in the processing of signals recorded by a Soundfield microphone. The results delivered by those softwares are hedgehog plots, that can be used to relate sound rays to physical characteristics of the room, observe the directional distribution of early and late sound energy, and identify surfaces causing undesired reflections. ODEON [4] and IRIS are dedicated to this kind of processing.

The IR360, developed by the sound engineer Federico N. Cacavelos as thesis, is another software dedicated to this analysis [5]. Some other software were inspired by this thesis, like Zonic and AIRA, developed by students of the Universidad Nacional de Tres de Febrero. All of them, including SUGIRA intend to be a better version of their predecessors.

3. Theoretical framework

3.1 Ambisonics

Gerzon and Craven developed Ambisonics in the 1970s, which is a set of surround sound recording and storage techniques. This technology covers the sound field in a full sphere, rather than the classic horizontal plane that is formed by a stereo pair, 5.1 or any other typical surround sound system. In Ambisonics each channel has information about certain physical properties of the acoustic field, such as pressure or acoustic velocity.

The number of microphones or channels used to characterize the sound field determines the order of the Ambisonics format:

• Zeroth order: offers information about the pressure field at the origin using an omnidirectional microphone.

• First order: adds information about the acoustic velocity at the origin using three bidirectional (figure-of-eight) microphones. The velocity vectors are proportional (up to some equalization) to the gradient of the pressure field along each one of the Cartesian axis.

• Higher orders: adds information about higher order derivatives of the pressure field.

3.1.1 B-Format

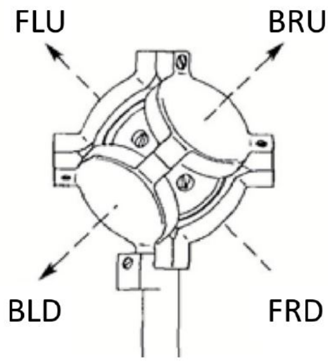
The B-format is the basis for first order Ambisonics, and consists of four channels: W, X, Y, and Z. The W channel represents the pressure component of the signal captured omnidirectionally, while

X, Y, and Z represent the pressure gradients related to the horizontal directions (X and Y) and the vertical direction (Z). B-format signals can be obtained using three bidirectional microphones and one omnidirectional, which must occupy the same spacial point.

3.1.2 A-Format

The A-format is obtained by recording with a Soundfield microphone, Figure 1a, that consists of four cardioid or subcardioid capsules with identical responses. Each one of them correspond to four of eight vertexes of a cube, which represents the head of a listener. This cube's faces are parallel to the cartesian reference system and are labeled the following: Up-Down, Front-Back and Left-Right. Each vertex of the imaginary cube is defined by the intersection of three faces, and so, for example, a microphone pointing to Front, Left, Up will be labelled FLU. Figure 1b shows all capsules orientation in a Soundfield microphone.

(a) Soundfield microphone (ST-250).



(b) A-format capsule orientation.

In order to process A-Format information it is necessary to convert it to B-Format, which is simply done by performing matrix arithmetic with the signals coming from the capsules using the Equations 1, 2, 3 and 4:

$$W = h_w \,.\, (FLU + FRD + BLD + BRU), \tag{1}$$

$$X = h_{xyz} \,.\, (FLU + FRD - BLD - BRU), \tag{2}$$

$$Y = h_{xyz} \,.\, (FLU - FRD + BLD - BRU), \tag{3}$$

$$Z = h_{xyz} \,.\, (FLU - FRD - BLD + BRU), \tag{4}$$

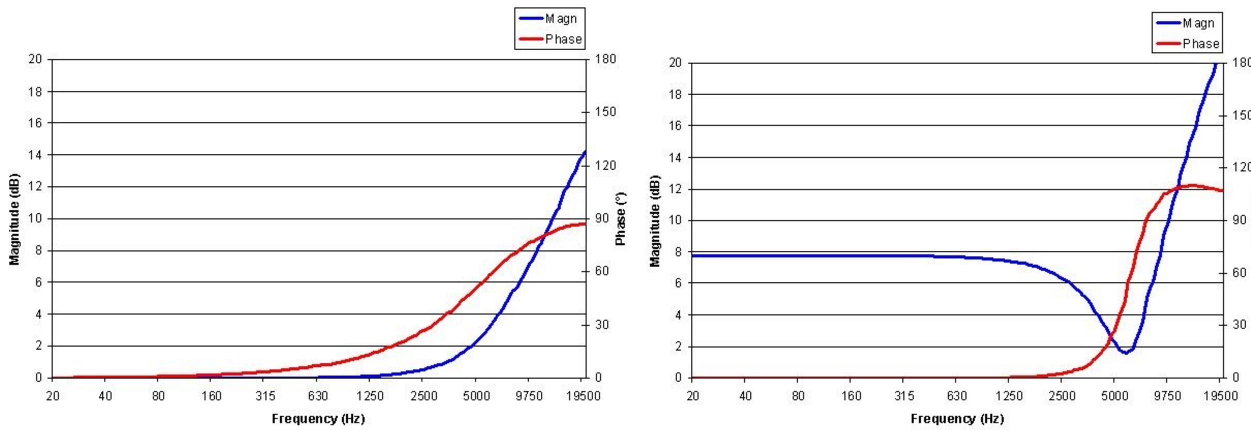
where h_w and h_{xyz} are the impulse response of filters explained in the next section.

3.1.3 Non-coincident capsules compensation filters

The fact that all the capsules of a Soundfield microphone are not in the same point in space presents a problem, specially in high frequencies. Craven and Gerson developed filters to compensate their position, and they are presented in Equations 5 and 6. This filters have such a response as shown in Figures 2a and 2b.

$$H_w(\omega) = \frac{1 + \frac{j\omega r}{c} - \frac{1}{3}\left(\frac{\omega r}{c}\right)^2}{1 + \frac{1}{3}\frac{j\omega r}{c}} \tag{5}$$

$$H_{xyz}(\omega) = \sqrt{6}\,\frac{1 + \frac{1}{3}j\omega r - \frac{1}{3}\left(\frac{\omega r}{c}\right)^2}{1 + \frac{1}{3}\frac{j\omega r}{c}} \tag{6}$$



(a) Magnitude and phase of H_w filter.

(b) Magnitude and phase of H_{xyz} filter.

Figure 2: Non-coincident capsules compensation filters.

3.2 Acoustic Intensity

The spatial analysis of the 3D impulse responses is made from the calculation of the intensity vectors. Those are divided in three spatial components, that are obtained by doing the element-to-element product of the pressure vector W (omnidirectional channel) and the corresponding pressure gradient vector X, Y or Z, as shown in Equations 7, 8 and 9. The modulus of the sound intensity vector is calculated by Equation 10.

$$I_x = W.X \tag{7}$$

$$I_y = W.Y \tag{8}$$

$$I_z = W.Z \tag{9}$$

$$|I| = \sqrt{I_x^2 + I_y^2 + I_z^2} \tag{10}$$

Then, the three spatial components and modulus are used to obtain the azimuth ϕ (horizontal) and elevation θ (vertical) angles, using Equations 11 and 12.

$$\phi = arctan\left(\frac{I_y}{I_x}\right) \tag{11}$$

$$\theta = arccos\left(\frac{I_z}{|I|}\right) \tag{12}$$

4. Methodology

4.1 Software Development

SUGIRA [1] is developed integrating Python, HTML and Javascript programming languages. In order to be an easy to maintain, open-source software with a high quality code, the following technical stack was selected:

- python = 3.9 as the programming language for signal processing [6]
- html for implementation of plots in the GUI

[1]Code is freely available at: `https://github.com/TomiMezz/SUGIRA.git`.

- javascript for implementation of plots in the GUI.
- pyqt5 = 5.15.10 for GUI development [12]
- numpy = 1.26.4 for matrix algebraic operations [8]
- soundfile = 0.12.1 for reading audio files [10]
- scipy = 1.12.0 for filtering [9]
- plotly = 5.19.0 for plotting [11]
- kaleido = 0.2.1 complementing plotly [17]
- poetry = 1.8.2 for dependency management [7]
- pytest = 8.1.1 for debugging [14]
- pylint = 3.1.0 as a static code analyser [13]
- black = 24.2.0 as a uncompromising code formatter. [15]
- pyinstaller = 6.8.0 to package the application. [16]

4.2 Signal Processing

Following all the introduced concepts in the theoretical framework section, the signal processing is detailed next. In order to begin the obtaining of the hedgehog plot the software must start with B-Format Ambisonic signals, so the first block consists in the conversion of the input signals to B-Format. The loaded signals can be A-Format impulses responses or A-Format recordings of Log-Sine Sweep (with its corresponding Inverse Filter); both recorded with a Soundfield microphone. Considering the first case (A-Format LSS + IF), the four impulse responses are calculated. Then, the non-coincident capsules filters are applied and, finally, the conversion to B-Format is performed. This process is shown in Figure 3 as a block diagram.

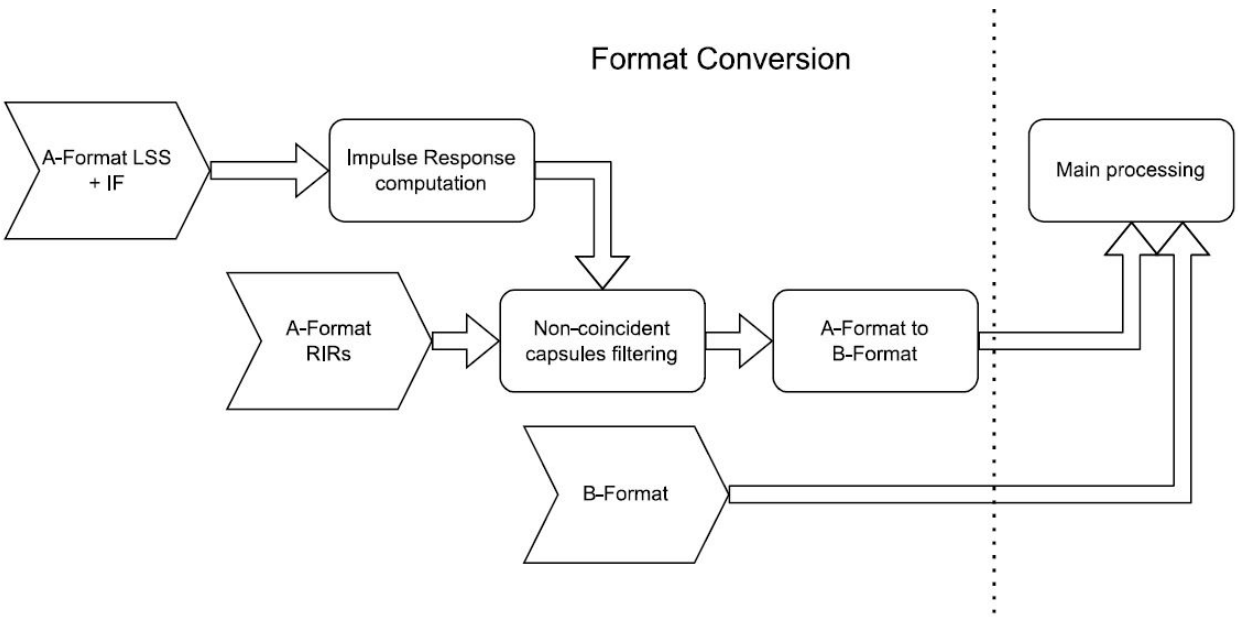


Figure 3: Block diagram of the format conversion.

With all B-Format impulse responses, the calculation of the intensity vectors is computed, as mentioned from Equation 7 to 10. Then, there is an optional low pass filter block to be applied by the user if desired. This LPF intends to be a smoothing tool that some authors recommend in order to avoid analysing the low coherence frequency band of the signals, high frequencies, due to the relation between the size of the capsules and the wavelength. This block was implemented as an optional tool taking into account that signals generated from a simulation could be analyzed by SUGIRA, so in those cases there is exactly one listening point. The filter has a cut-off frequency of $5\ kHz$ [5].

The next step consists in cropping the signal to the analysis length that the user wants, followed by the windowing of the intensity vectors. The time window is another parameter to be chosen by the user, and it has a severe impact in the representation of each one of the graphed vectors. In other words, the amount of samples contained in a same window affect the frequency resolution and its minimum frequency analysis. A long analysis time length may also contain information from more than one reflection, which leads to constructive and destructive interference. Then, the integration of the intensities is performed.

All this process outputs the intensity magnitude, azimuth and elevation of the 3D impulse response. The reflection detection algorithm comes into play at this point. While several methods can be used, the one selected is an already implemented analysis of the surrounding samples at local maxima, available as a function in Scipy. This way, several local maxima are discarded, and only greater ones are kept. This is applied to the intensity magnitudes, azimuths and elevations vectors.

The last block of this process is the application of the threshold, which is another input parameter that affects the amount of spines that are shown in the hedgehog plot.

4.3 Hedgehog Plot

The main display of SUGIRA is a hedgehog plot, using Plotly, that corresponds to the 3D impulse response on the Main Window. It consists on a scatter plot complemented with graph objects for customization. Also, a Plan View is displayed in the software, to position the hedgehog plot in its corresponding measurement point over a loaded image.

When processing the loaded signals, two files are generated. The first one called *sugira.html* (HyperText Markup Language) is the one displayed in the Main Window, and it is embedded to the GUI. The second one is called *sugira_plan_view.json* (JavaScript Object Notation) and it only contains the hedgehog plot, without any additional information. The reason for doing this is that this kind of file allows the hedgehog plot to be inserted, modify its size and position, over the plan image. Then, a file called *sugira_plan_view.html* is created, embedded into the GUI, and displayed in the Plan View section. This allows the signal processing to be performed once, despite being two windows showing hedgehog plots.

There is several information transmitted by this type of plots. The longest spike corresponds to $0\ dB$ and represents the direct sound. Every spike length represents the magnitude of each reflection, and its color shows the arrival time, both relative to the direct sound. However, SUGIRA can toggle the color scale to represent time or magnitude, in case the user chooses to do so.

4.4 Graphical User Interface (GUI)

PyQt5 framework is used for developing SUGIRA's GUI. It consists of a complete set of Python bindings for Qt v5, which is a cross-platform set of C++ libraries that implement high-level APIs to access many aspects of modern desktop and mobile systems [12].

4.4.1 Main Window

Figure 4 shows the Main Window of SUGIRA.

On the left down corner of the Main Window the user has 4 buttons:

- Process: begins the computation of the hedgehog plot.
- Load Signals: displays a new small window, where the user may select a tab corresponding to the format of the signals to be analyzed. Figures 5 and 6 show every tab of this window.
- Export: generates a text file with *W channel* and hedgehog plot data.
- Clean: discards the hedgehog plot and the loaded plan in the Plan View.

Above this buttons, three checkbox are shown:

- Low Pass Filter: allows the user to turn on the $5\ kHz$ cutoff frequency low pass filter.

- W channel energy: changes the omnidirectional channel amplitude to energy.
- Time colorscale: changes the hedgehog colorscale to represent amplitude in dB instead of time.

Then, three customizable parameters are displayed:
- Integration Window: shows a combo-box which contains five different window sizes ($1\ ms$, $3\ ms$, $5\ ms$, $7\ ms$, $10\ ms$).
- Analysis Length: sets the time of the impulse response that will be analyzed, discarding the information after that time.
- Threshold: sets the minimum level in dB necessary for the spikes to be considered as relevant reflections. Those below this threshold are interpreted as noise, and are not displayed in the hedgehog plot.

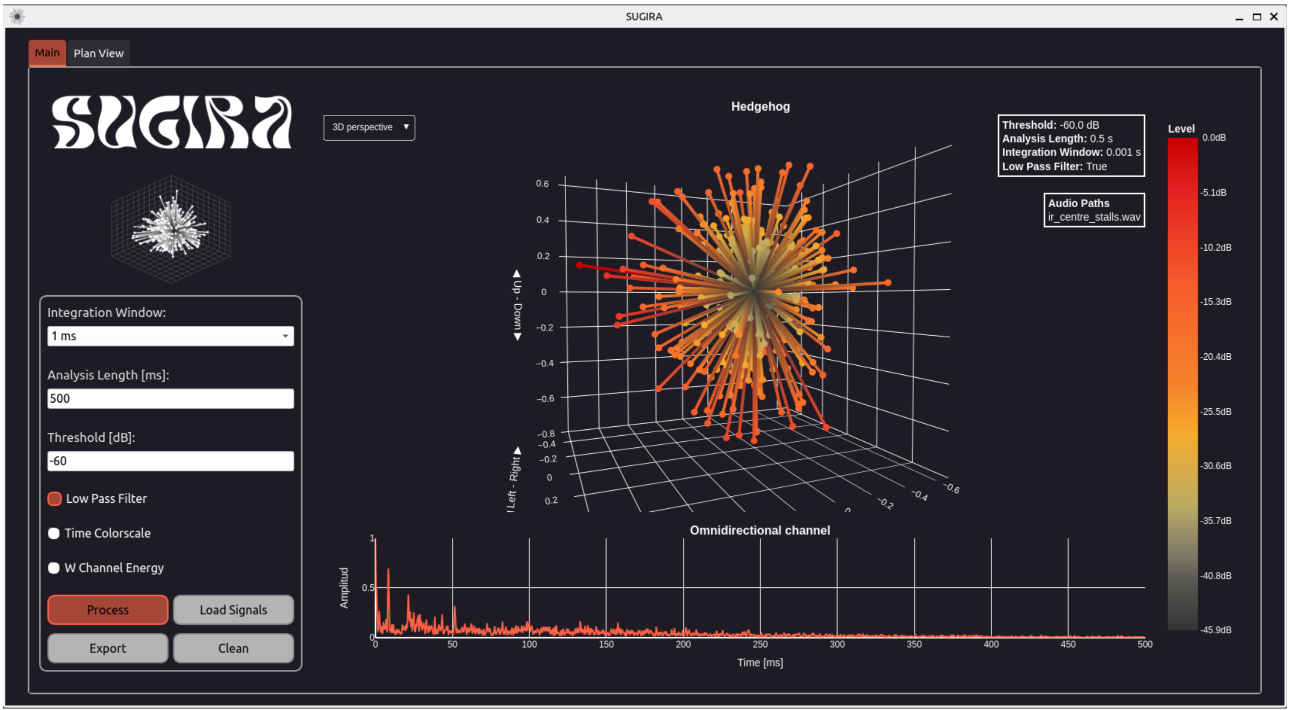
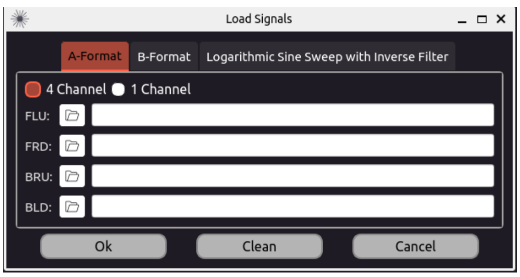
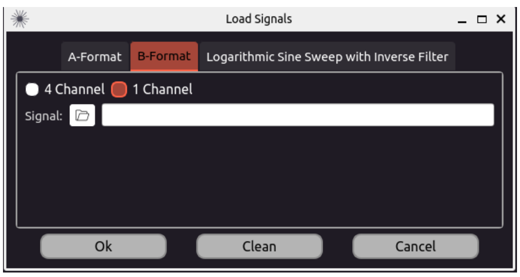


Figure 4: Main window of SUGIRA.



(a) A-Format, 4 Channels.



(b) B-Format, 1 Channel.

Figure 5: Load signals view.

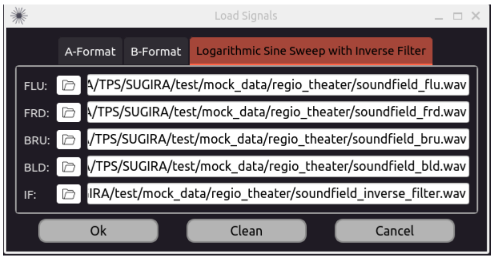


Figure 6: A-Format with IF, 5 Channels.

The Main Window also includes three predetermined views for the hedgehog plot, corresponding to the XY, XZ and YZ planes. Additionally, it allows the user to check information related to each reflection, such as its Azimuth, Elevation, arrival time [ms], and energy relative to the point of origin. This is shown in Figure 7. Furthermore, Figure 8 shows the W channel plot options, these are ampltiude or energy.

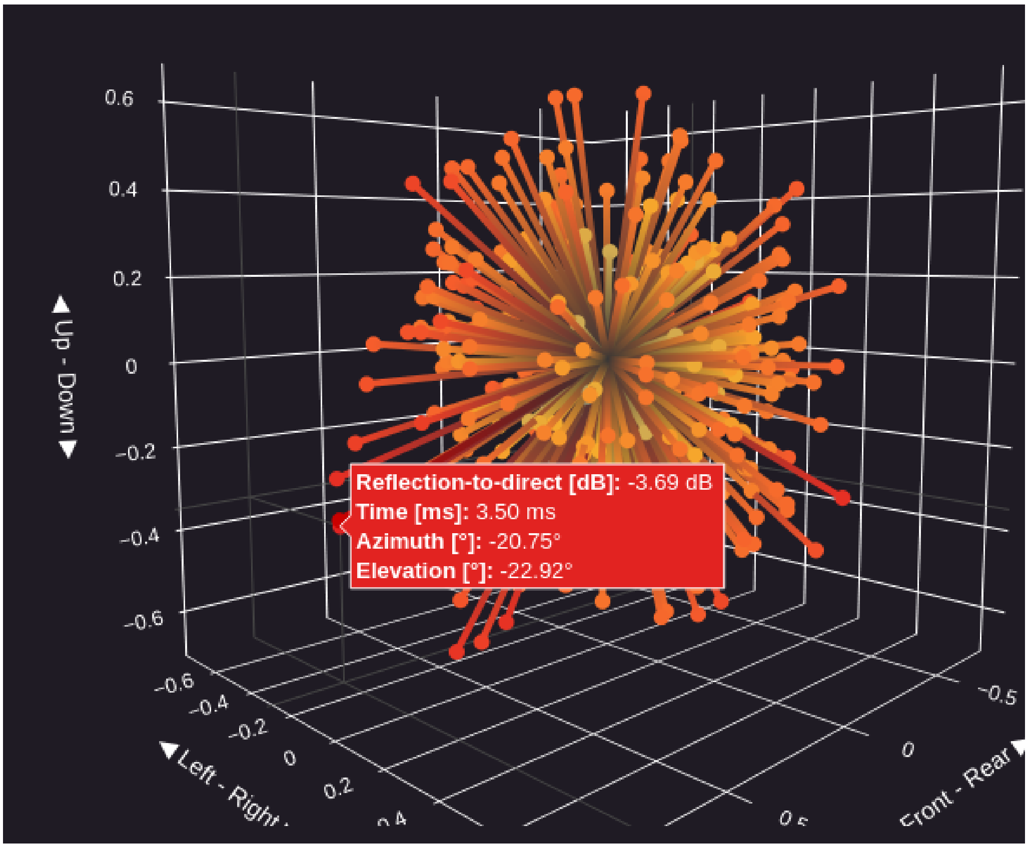


Figure 7: Plan View of SUGIRA.

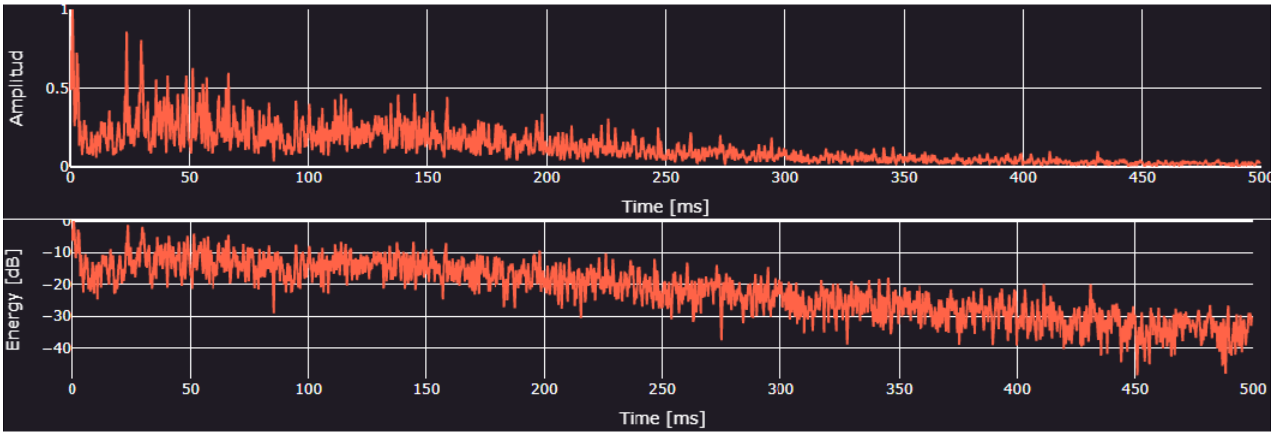


Figure 8: Amplitude and energy of W channel plot.

4.4.2 Plan View

Figure 9 shows the Plan View of SUGIRA.

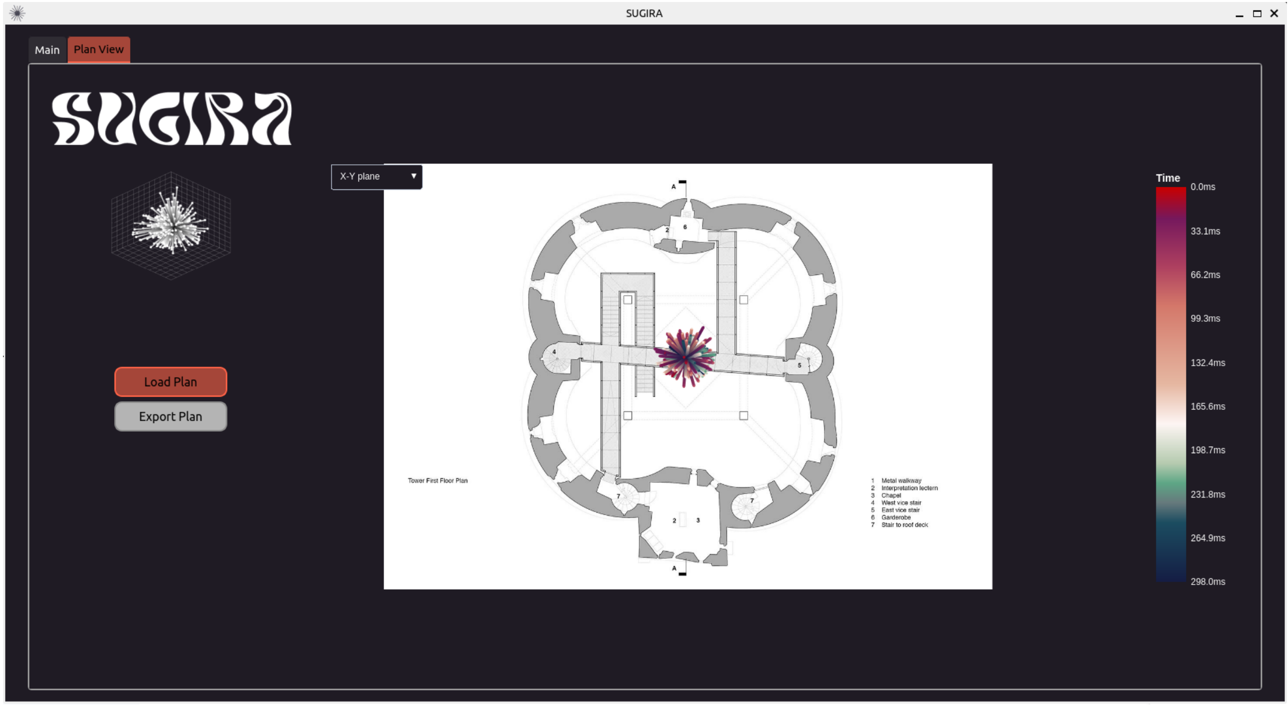


Figure 9: Plan View of SUGIRA.

On the left side of the Plan View the user can see 2 buttons:

- Load Plan: opens the File Browser where the user may select an image to load and display.
- Export Plan: exports an image of the Plan View, with its corresponding color bar.

This part of the software allows the hedgehog plot to be placed anywhere over the loaded image. If the plan has the sound source and the corresponding recording point marked, then the user can adjust the hedgehog to be oriented with the direct sound spike pointing to the sound source. This is useful to get an analysis of the reflections while looking at the boundaries or surfaces shown in the image. It is worth mentioning that the hedgehog is not fixed to the XY plan view, but it can be rotated as well as in the Main Window. In case the user loads a side view plan, the hedgehog can be rotated to the YZ plan, for example.

5. Results & Analysis

When analyzing the results, it is essential to verify them against a reference to determine the software's accuracy. In this case, two validation methods are used. First, a direct comparison between the results obtained by SUGIRA and an internationally validated software is conducted to see if the generated 3D graph matches expectations. Secondly, a visual inspection of the intensity and angles reported by the hedgehog graph is performed in various real venues and microphone positions.

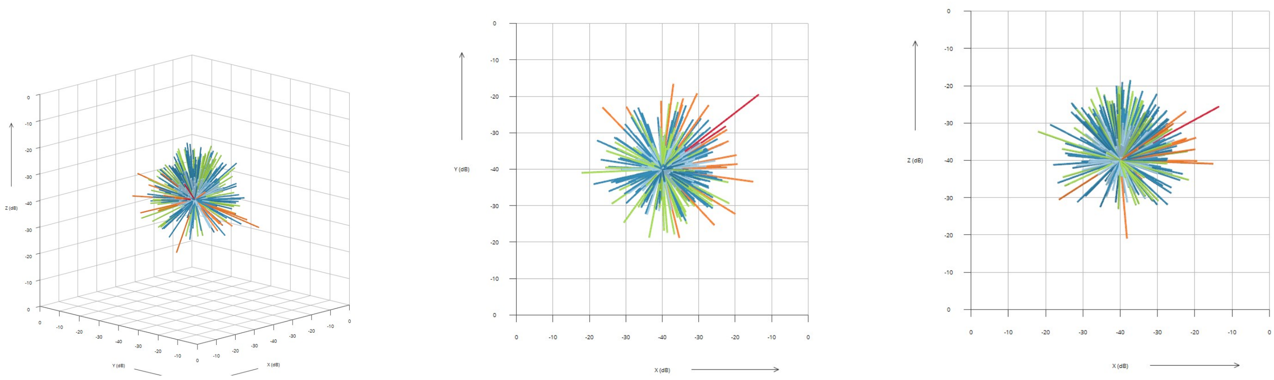
Initially, the Central Hall auditorium of the University of York [18] is analyzed. Subsequently, Clifford's Tower in York is tested using data from the OpenAir database [19], and a measurement conducted by the authors in the Teatro San José in Buenos Aires is also analyzed.

The combination of these two methods allows for a thorough assessment of the software's capabilities, ensuring that it can reliably replicate real-world acoustic scenarios.

5.1 IRIS Validation

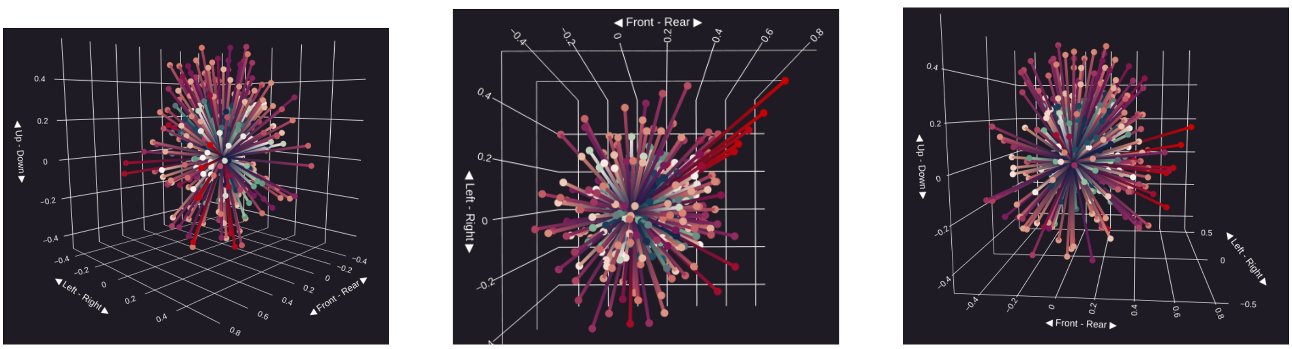
The demo version of IRIS software was used to process a real measurement (B-format) and produce a hedgehog plot. The settings were: $1\ ms$ time window, $-50\ dB$ threshold, and *align direct sound (xy) to x-axis* disabled, which keeps the global coordinates of the measurement. Figure 10 shows three different perspectives of the results.

Then, the same B-format signals were loaded and processed in SUGIRA, with the same settings. Figure 11 shows the obtained results, aligned in the same perspective as the IRIS results. Also, in Figure 24 and 25, placed in the Appendix, the comparison with another measurement point can be seen.



(a) 3D Perspective (b) XY View (c) XZ View

Figure 10: IRIS Results



(a) 3D Perspective (b) XY View (c) XZ View

Figure 11: SUGIRA Results

After inspecting both Figures, one can notice that IRIS' and SUGIRA's hedgehog plots resemble a similarity. Both the relative spike length and color scale look alike, as well as the density of the hedgehog due to the time window and threshold parameters. Focusing on the direct sound spike, one can tell that the orientation of the plot in general is the same too.

5.2 Central Hall, University of York

The Central Hall measurements available online were used for validating the software. The application of a 3D impulse response analysis may be of interest in venues like this one, in order to detect undesired reflections, for example. The measurements were performed with a Soundfield microphone, and loaded to SUGIRA in B-Format. Figure 12 shows several hedgehog plots placed in their corresponding measurement points, using the Plan View window.

The sound source is indicated by the green dot, so the direct sound of the plots must be aimed to the center of the scenery before performing an analysis. Plotly allows the user to rotate and resize the hedgehog in order to adjust its position in the inserted plan.

Considering the measurement point to the right of the stage, the displayed results in the plan view present strong reflections from the front wall. Figure 26c, from the Appendix, shows a brick wall in that area, which reinforces the obtained results by the software, since that surface can be considered sound reflective.

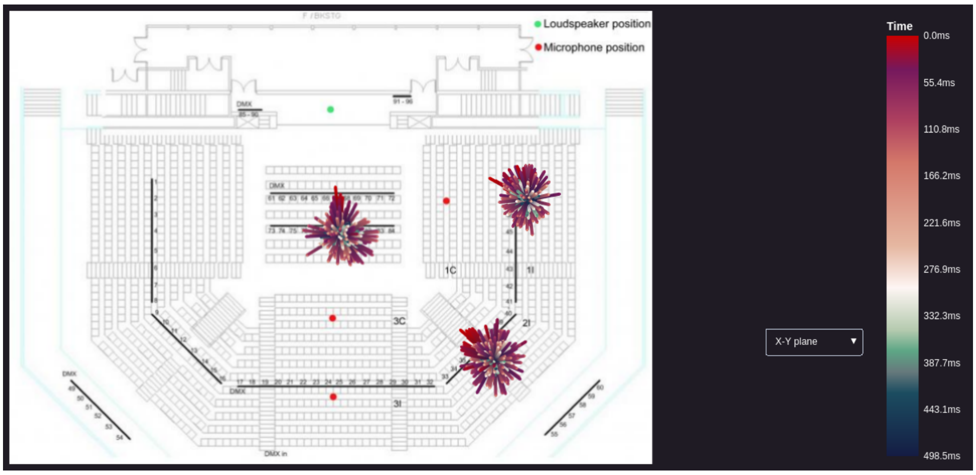


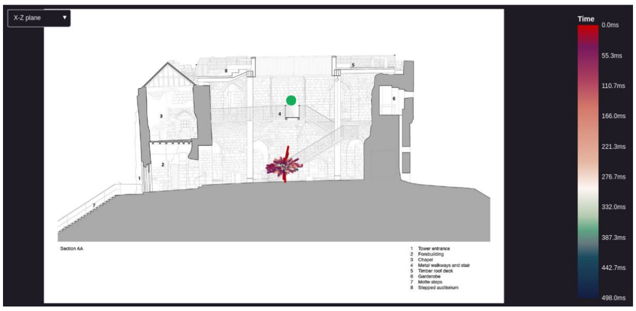
Figure 12: Three hedgehog plots placed in the corresponding measurement points in Central Hall (Plan View).

5.3 Clifford's Tower, York

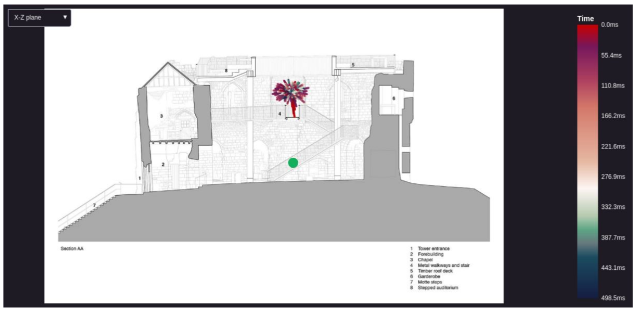
Clifford's Tower measurements available online were used for validating the software, which were taken into account because they enable SUGIRA to be tested in an acoustic environment that is far from being a concert hall. This signals were loaded in B-format too, and the recordings were made with a Zoom H3-VR Ambisonic Handy Recorder. Figure 13 shows the Plan View of SUGIRA, but this time with a side view image loaded.

Figure 13a presents the hedgehog plot, in which the direct sound spike points upwards where the loudspeaker was located. A photograph of this measurement is shown in Figure 27d (Appendix). Figure 13b shows the side view in SUGIRA of another measurement that inverts loudspeaker and microphone position compared to the previous one. Figure 27c (Appendix) is a photograph of this other measurement. In both cases, the bridge provokes some kind of acoustic shadow, that could be the reason for the direct sound spike's elevation to differ from zero.

Another tests are performed and showed in Figure 28 (Appendix), where the hedgehog plot was placed over a 3D model image of the Clifford's Tower internal structure.



(a) Hedgehog placed on Clifford's Tower side view.



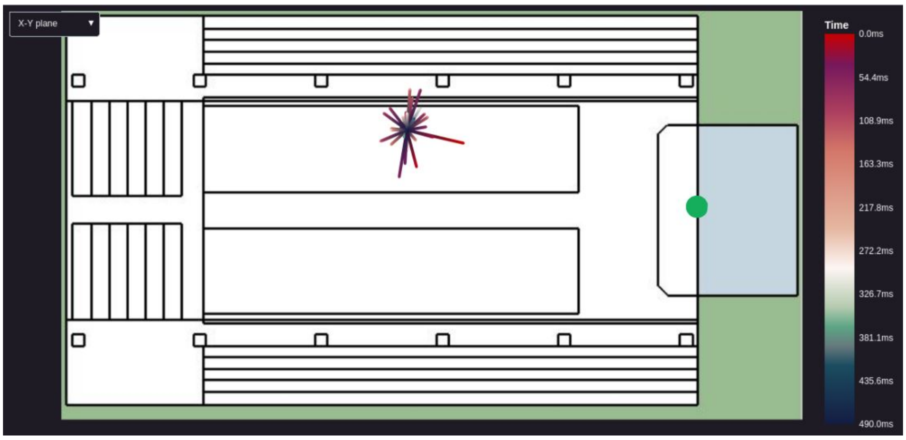
(b) Hedgehog placed on Clifford's Tower side view.

Figure 13: Side view of Clifford's Tower.

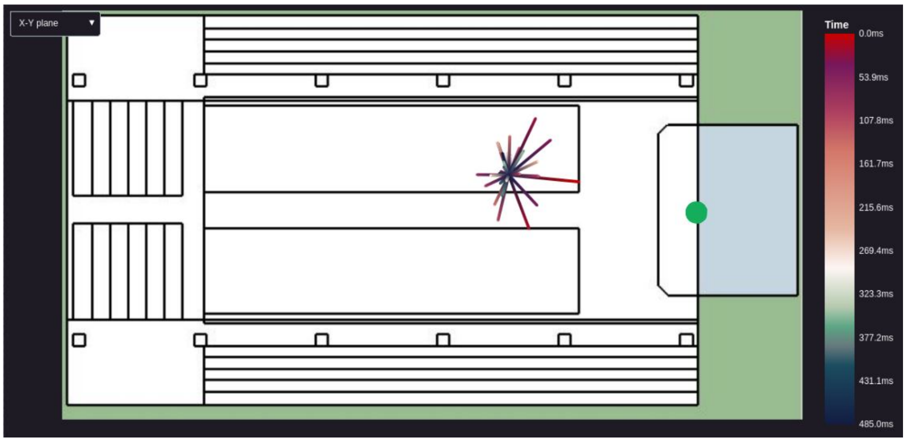
5.4 San José Theatre, Buenos Aires

Finally, recordings done by the authors of this work, using a Soundfield SPS200, were processed in SUGIRA. This time, the used input format is LogSineSweep + Inverse Filter, and the results where presented in the Plan View of the San José Theatre. Figure 14 presents the plain view of this venue, with a green dot indicating the omnidirectional source used.

With these measurements results, SUGIRA is performing the proper conversion from A-format recordings to B-format, and then the corresponding hedgehog plots, indicating the sound source and early reflections in the measuring point.



(a) Hedgehog plot placed in the corresponding measurement point in San José Theater (Plan View).



(b) Hedgehog plot placed in the corresponding measurement point in San José Theater (Plan View).

Figure 14: Plan view of San José Theatre, Buenos Aires.

6. Conclusions

A solid software foundation has been established, meeting the set requirements and some of the highest standards for open-source, highly sustainable software development, with a minimalist, user-friendly interface. Currently, it is one of the few software applications capable of fully interacting not only with the isolated three-dimensional response but also with different planes, allowing for quick result verification and export in both .HTML and .TXT formats with recorded information for each output parameter. Furthermore, it supports measurements in both A and B formats, adhering to current standards for acoustic analysis.

SUGIRA allows for a better understanding of sound propagation in an enclosure, especially in the early field, by identifying the arrival coordinates in space, time, and intensity of both direct sound and successive reflections within a specific analysis period. Knowing the arrival times of reflections provides insight into the acoustic texture of the space. The level difference between direct sound and reflections indicates how well these reflections are managed. One critical parameter in impulse response analysis is the integration time, as some reflections may be lost in averaging depending on it. Another key point for validation concerns both the correlation between the obtained results and a controlled simulation, and the conditions of real measurements. For future works, it is proposed to establish regulations or standards for microphone orientation, achieving a form of spatial calibration that ensures better analysis.

7. References

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19. Clifford's Tower, York, Open Air Library, Online: `https://www.openair.hosted.york.ac.uk/?page_id=1413`

8. Questions

¿How can a 3D impulse response analysis be related to the spatial perception of the acoustic field? In other words, ¿what parameters can be modified, and what is their value, in order to represent the human listening from an ambisonic recording?

9. Apendix

9.1 Different Views.

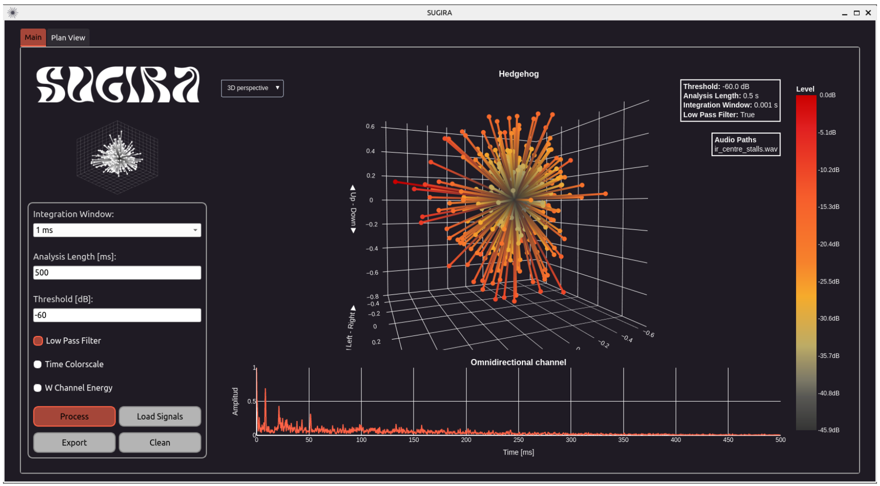


Figure 15: Intensity Colorscale and W Channel Amplitude.

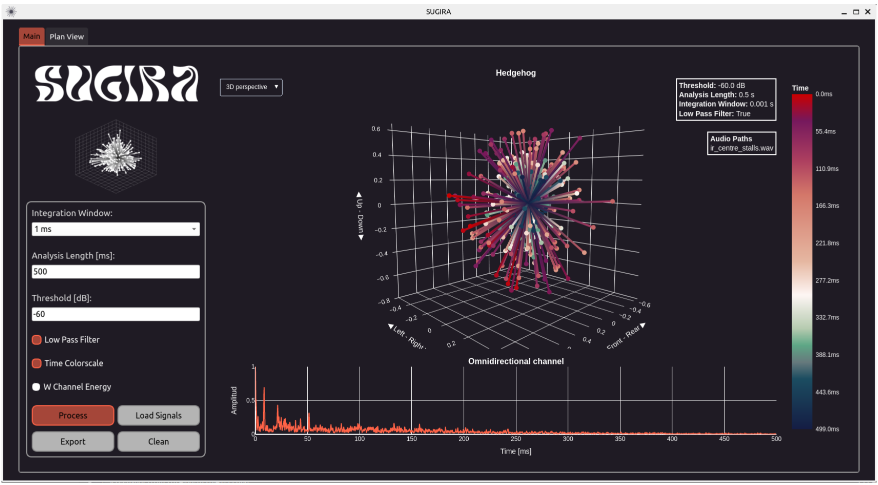


Figure 16: Time Colorscale and W Channel Amplitude.

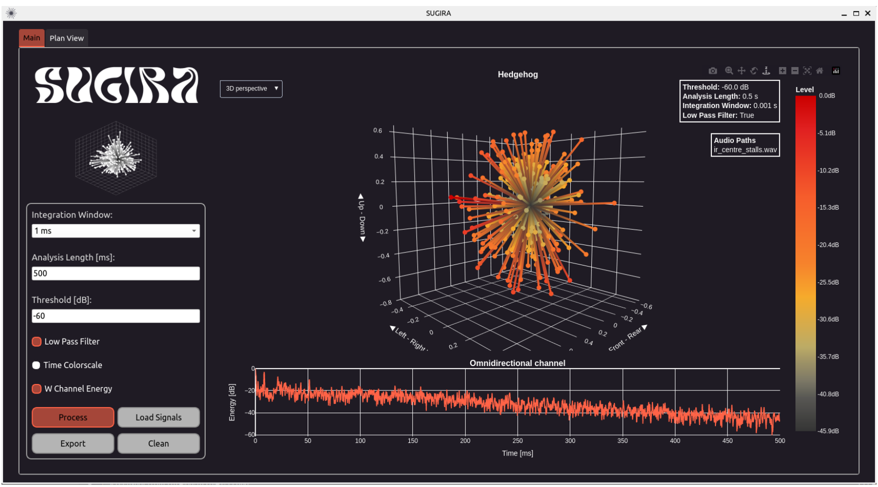


Figure 17: Intensity Colorscale and W Channel Energy.

9.2 Different Integration Time.

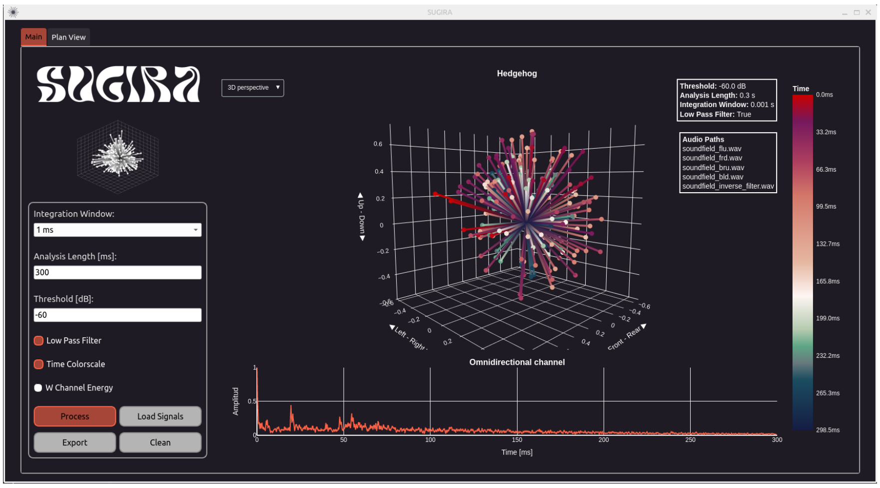


Figure 18: Integration Time = 1 ms. Analysis Length = 300 ms.

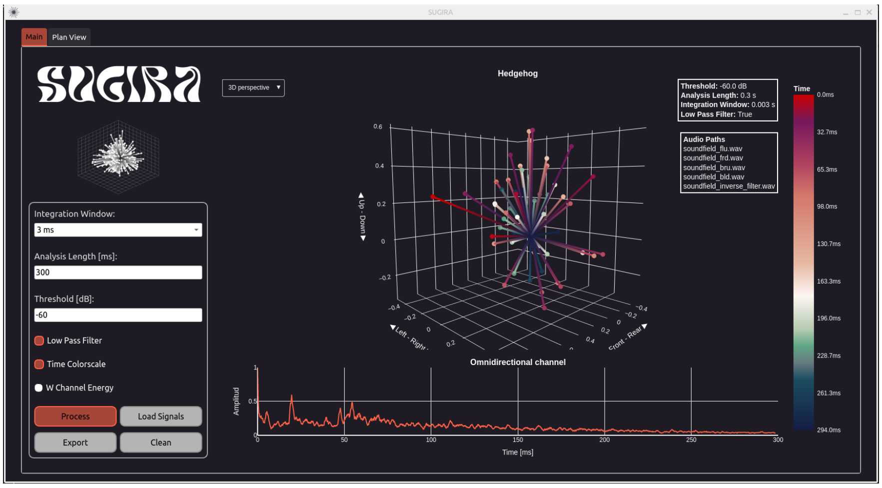


Figure 19: Integration Time = 3 ms. Analysis Length = 300 ms.

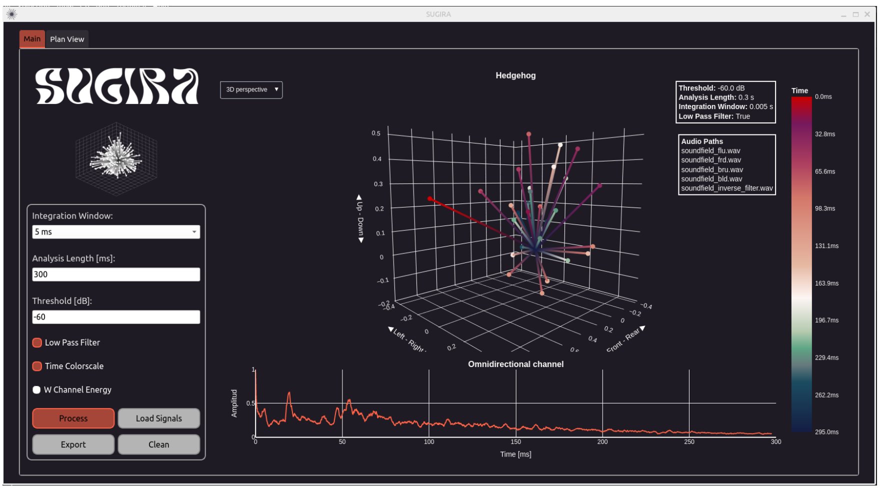


Figure 20: Integration Time = 5 ms. Analysis Length = 300 ms.

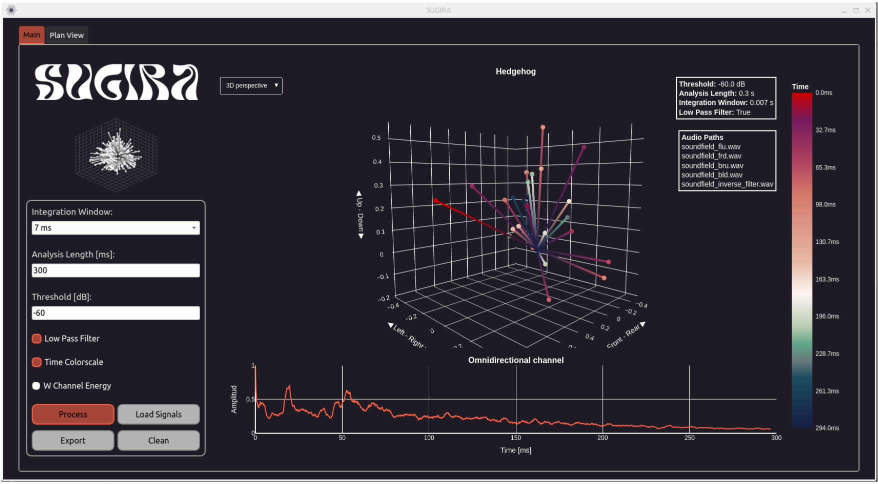


Figure 21: Integration Time = 7 ms. Analysis Length = 300 ms.

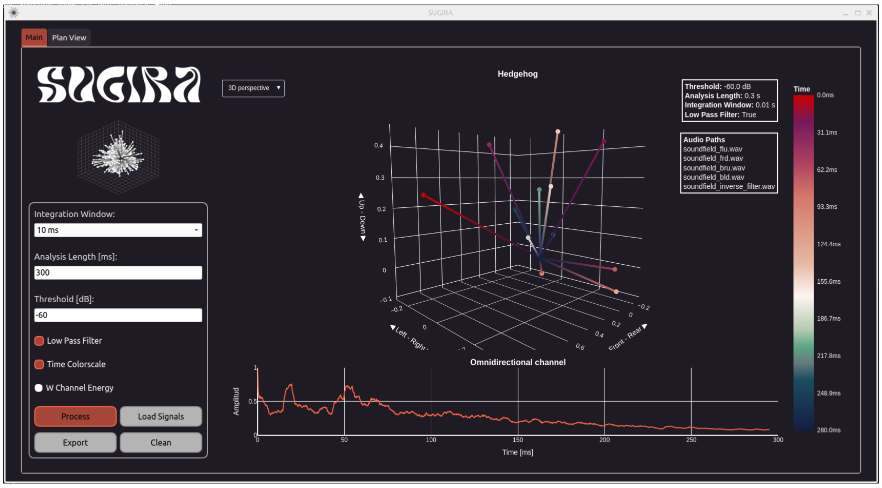


Figure 22: Integration Time = 10 ms. Analysis Length = 300 ms.

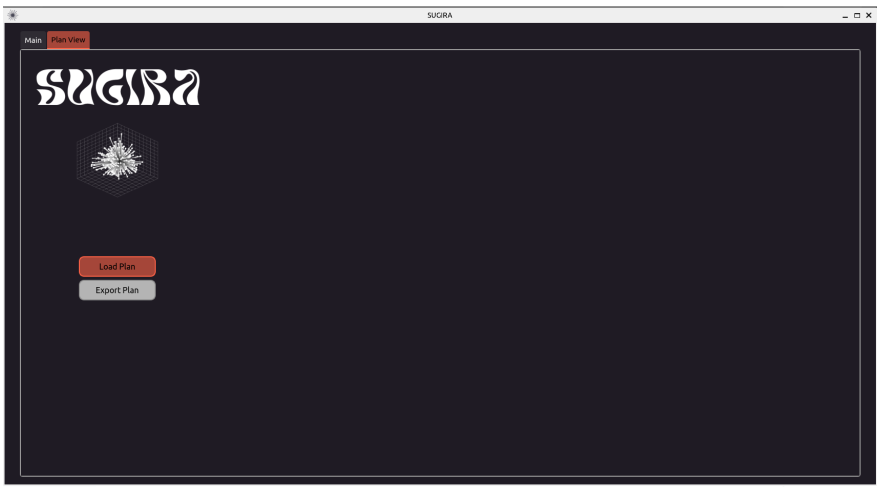
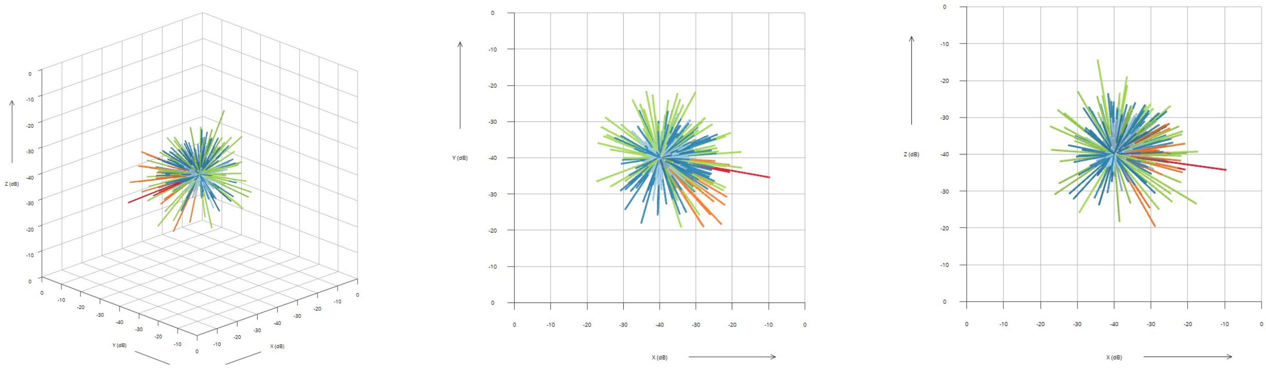


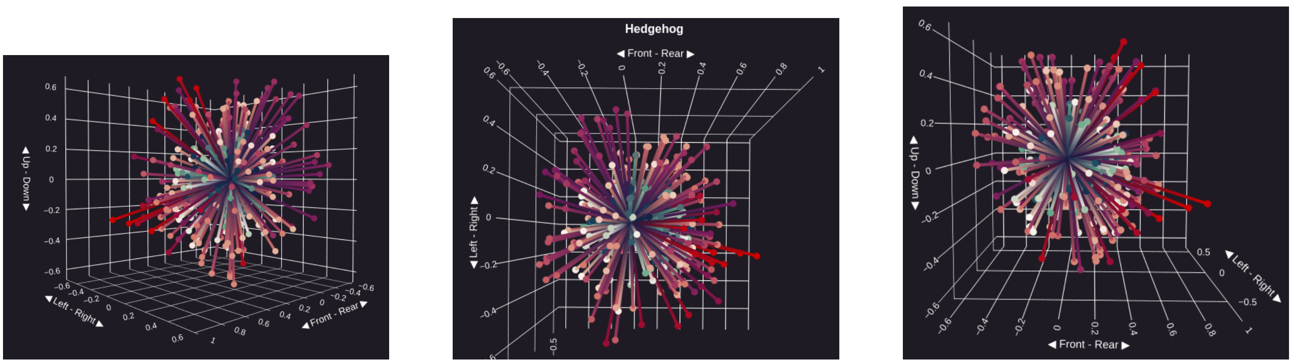
Figure 23: Integration Time = 1 ms. Analysis Length = 300 ms.

9.3 IRIS - SUGIRA Comparison



(a) 3D Perspective (b) XY View (c) XZ View

Figure 24: IRIS Results

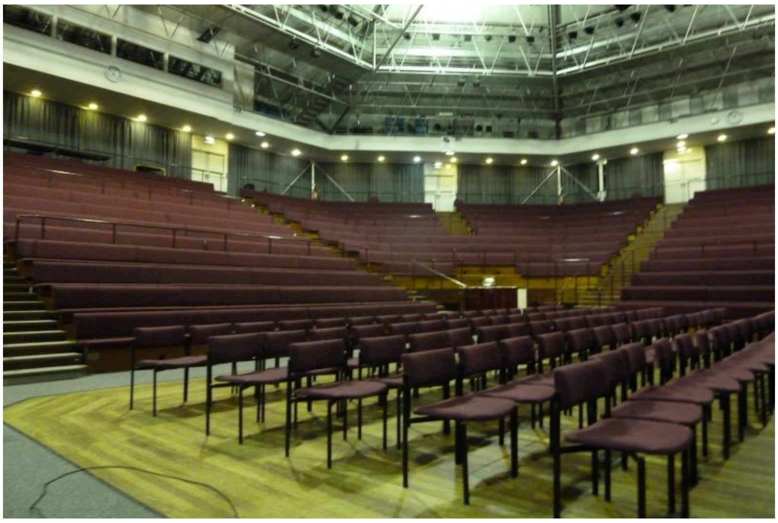


(a) 3D Perspective (b) XY View (c) XZ View

Figure 25: SUGIRA Results

9.4 Central Hall, University of York

(a) Scenery, front and left audience area of the Central Hall.



(b) Back and left audience area of the Central Hall.

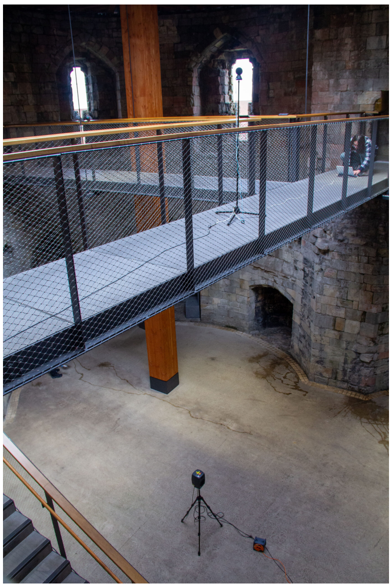
(c) Front and right audience area of the Central Hall, view from the back.

Figure 26: Photographs of the ambisonic measurements in Central Hall, University of York.

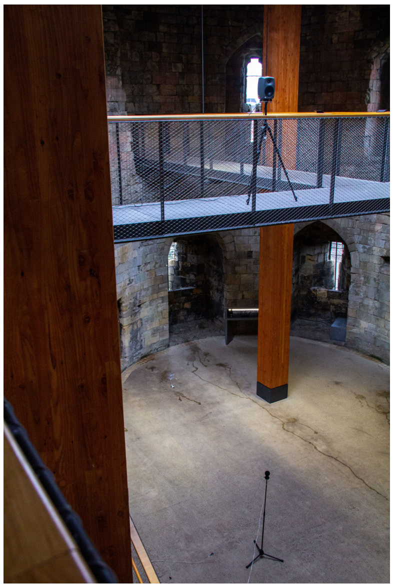
9.5 Clifford’s Tower, York

(a) 1st measurement.

(b) 2nd measurement.



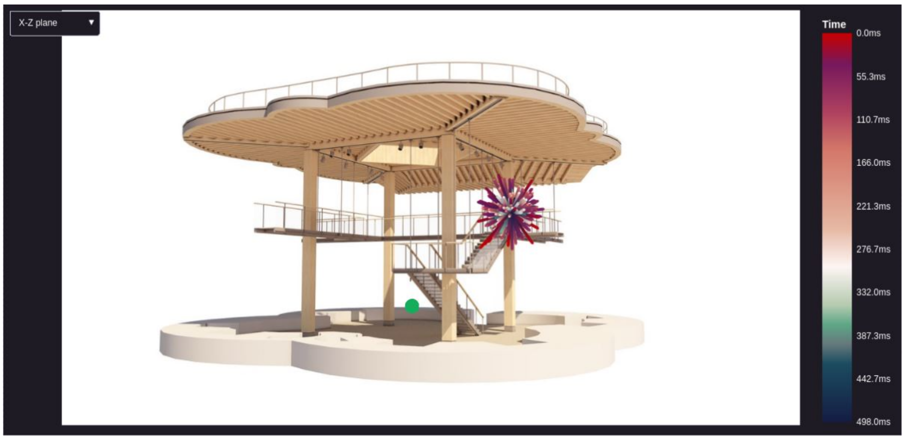
(c) 3rd measurement.



(d) 4th measurement.

Figure 27: Photographs of the ambisonic measurements in Clifford’s Tower, York.

(a) 3D model with hedgehog placed.



(b) 3D model with hedgehog placed.

Figure 28: 3D model of Clifford's Tower interior structure.

9.6 San José Theatre, Buenos Aires

(a) Front view of the audience area.

(b) View from the left balcony.

(c) Audience area.

Figure 29: Photographs of San José Theatre.