ReS, RESONANT STRING SHELL, DEVELOPMENT AND DESIGN OF AN ACOUSTIC SHELL FOR OUTDOOR CHAMBER MUSIC CONCERTS.

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1 INTRODUCTION

ReS (Resonant String Shell) is a sustainable hand-built temporary acoustic shell, developed since 2011 and built during the architectural workshop at Villa Pennisi in Musica in Acireale, Sicily, every year since 2012.
It is the product of a research program started at the Department of Architecture (DiARC) of the University of Naples Federico II, Italy, which involves a team of Italian experts in architectural design, product design, computational analysis and acoustics, together with the invaluable help from the soloists of the *Orchestra dell'Accademia Nazionale di Santa Cecilia* in Rome.
The design concept aims to provide a portable structure by reducing the on-site construction problems and the skills required by the builders, together with maximizing the acoustic performance for the audience and the musicians. The shell is built using only wood, mostly recycled.
The acoustic shell is developed by the ReS Team, which is composed by:

- Serafino Di Rosario, Acoustics, Buro Happold Engineering
- Sergio Pone, Associate Professor, Department of Architecture, University of Naples “Federico II”
- Sofia Colabella, Contract Professor, Department of Architecture, University of Naples “Federico II“ Italy
- Bianca Parenti, Architect, Department of Architecture, University of Naples “Federico II" Italy
- Davide Ercolano, Student of Architecture
- Daniele Lancia, Architect
- Eduardo Pignatelli, Architect
- Gabriele Mirra, Architect

ReS Team has been presented with the Peter Lord Award 2015 by the Institute of Acoustics.

This paper describes the research process, which spans over 4 years now, and presents the final results in form of acoustic simulations performed by acoustic modelling software and real world measurements of a real scale prototype during the annual Summer School VPM: Villa Pennisi in Musica.
ReS 4.1, made in 2015, represent the acoustic upgrade to the design of the fixed panels shell made for their final thesis by E. Pignatelli, G. Mirra and G. Carlucci of the ReS team.

2 RES, DEVELOPMENT OF THE DESIGN

ReS is entirely made of low-cost and recycled materials assembled through simple construction methods conceived, at the same time, according to an accurate and complex design process.
The original concept for ReS was developed from the silhouette of old fashioned gramophones, able to amplify and project the sound uniformly to the audience.
The acoustic shell is conceived starting from two different systems: structure and panelling - a wooden spatial structure supporting the inside surfaces, which have the important task of reflecting the sound toward the audience. With the realization of the 2015 festival at Villa Pennisi, we have reached the fourth prototype construction.
The structure of the first three prototypes has been made out of four timber portals composed of lattice beams, decreasing in height and length from proscenium to backdrop. These polygonal portals are connected through a secondary triangular structure to achieve static indeterminacy and offering additional rigidity to the supporting elements. The inside panelling is hanged to the structure and its shape is defined from the panels' tilt studied to offer the most comfortable listening experience up to the last seat of the open-air audience. This continuous surface is made of chipboard, a cost-effective material, able to reflect the sound across a wide frequency range, thanks to their weight (20 kg/m^2).

The first prototype, “ReS 1.0” built in 2012, had three strips of rectangular panels suspended to the structure and a simple back wall realized with the same panels. An external strip of cantilevered panels (called eyelashes) was fixed to the exterior portal to improve the acoustic response in the last rows of the audience. ReS 1.0 - 3.4m depth, 7m wide, 3,8m high at the proscenium and 2m high at the back wall - had a good overall acoustic performance and a loss in low frequency range due to the large openings between the panels, due to construction issues.

The second experimental structure, “ReS 2.0”, retains the same shape and number of elements, but it is larger than the previous one - 4m high at the proscenium, 2.2m at the back wall - furthermore, its panelling set is made out of trapezoidal chipboards, directly connected to the structure through bolted joints instead of ropes. ReS 2.0 had a better performance in low and mid-high frequency ranges: the tight connection between the panels eliminated any hole in the shell (thus reducing the previous loss in low frequency), whereas an array of small panels improved the mid-high-frequencies response in the farthest rows of the audience and the mutual listening between the musicians. Together with this global improvement to the propagation of sound up to the farthest rows, there was, however, a loss in the “character” of sound; furthermore, the musicians felt that the low-frequency response under the shell was too loud, masking the other frequencies.

The third prototype (“ReS 3.0”, 2014) presented a growth of the structure, where the wheelbase of the portals was increased by around 250 mm, to gain a larger depth of the stage - 4,2m - and the Cilia's new dimensions, increased to reach a final length of 900mm; in order to recover the "character" of sound, lost in the previous version, the panels were suspended by ropes, as in the first prototype. A new device was added on the scene's bottom. The deeper scene performs a higher sound pressure on the audience's area, furthermore an easier way to set the angle of the Cilia and the angle of the Array panels, allows the optimization of the shell’s performances, according to the number and the position of the musicians. Finally, to achieve a better diffusion of the sound, a QRD (Quadratic Residue Diffuser) diffuser was added on the back wall.

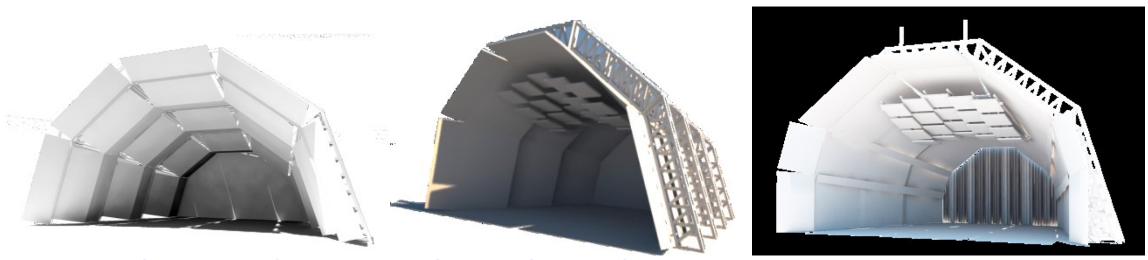

Figure 1: ReS design (left to right): ReS1.0, ReS2.0, ReS3.0

3 RES - ACOUSTICS CONCEPT

The request of design originally came from the Villa Pennisi in Musica festival and Classical music masterclass, where the musician were in need of an architectural element that can provide them with the same acoustic condition as when they rehearse in their room or play in auditoriums designed for chamber music. The design aims to reproduce these conditions in the best possible way considering the lack of a room volume that can provide reverberation.

Three fundamental purposes have been investigated to better perform open-air concerts with ReS:

1. To generate a uniform sound field to the musicians, improving the ensemble and reducing any frequency-cancelation event or comb-filtering;
2. To increase the sound loudness and clarity on the audience;
3. To enhance spatial perception and apparent source width.

ReS takes advantage of several acoustic prediction systems, which belong to different subject areas, mainly Acoustics and Computational Design.
We refer to the totality of the shell as “acoustic machine” and to each element that composes it as “acoustic subsystem” indicating the different parts of the shell that have different acoustic functions.
The acoustic machine results from the aggregation of four main acoustic subsystems, designed to work together:

- The main shell – composed by the bigger outer panels;
- The array – that realizes the second series of panels;
- The eyelashes – the closest row of panels to audience;
- The bottom of the scene - which enclose the deep end of the shell;

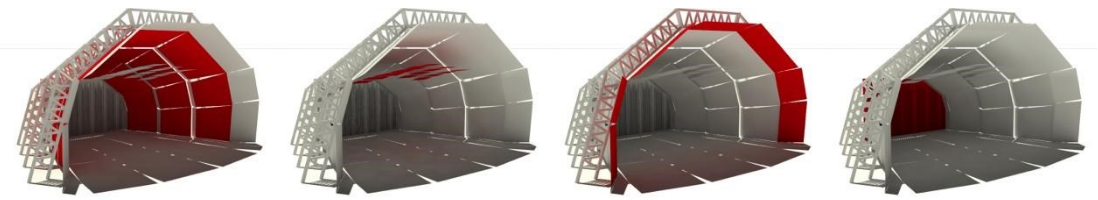

Figure 2: Acoustic subsystems (left to right): Main shell, Array, Eyelashes, Bottom of the scene

The design process starts with the Computational design analysis, in which each acoustic subsystem is subjected to a digital dynamic shape improvement procedure, which leads to an optimal way to use the subsystem itself.
The whole algorithm has been developed in the Grasshopper™ environment with the help of external plug-ins for the acoustic simulation and form optimization.

The purpose of the main shell is to provide an enclosure that would capture the acoustic energy of the musical instruments, which would be lost otherwise due to the variable directivity of each of them in each frequency band, and project this to the audience and back into the stage.
By increasing the amount of the early reflections, it improves the audience’s listening experience, through the increase of the perceived loudness and the control of the sound dispersions in a large frequency range, together with creating a basic support for the musicians to improve their mutual listening.
On the other hand, there is a much higher boost of the SPL inside the shell and a consequently non-uniform sound field, which is the result of the strong symmetrical reflections that are to be controlled by the optimization of the panels’ inclination.

The shape of the shell, which has been determined according to the architectural concept, is submitted to a restricted form-improvement process, defined by three elements that correspond to the variables and constants of the algorithm:

a. The emitters – the sources of the acoustic simulation; variable;
b. The reflective panels – the room of the acoustic simulations; variable;
c. The target surface – the audience area to be mapped; constant.

A standard string sextet (2 violin, 2 viola, 2 cello) configuration defines the emitter models, in which every source is intended as omnidirectional.

All panels (Main shell, Array and Eyelashes) are suspended from the main supporting structure by the use of sailing ropes.

21 reflective panels that are hinged on their front edge to the structure compose the acoustic room. This condition allows the panels to perform a rotation around the fixed edge, which will be the rotational axis. The angles of rotation are the only parameters in the modelling stage and represent our calculation optimization variables. This will configure a complex shell in which each element performs an independent rotation with the only constrain of a symmetric structure, to ensure a symmetric acoustic response and a simpler installation in the construction phase.

A similar shape development has been used for the array system, composed by several smaller elements, arranged inside the main shell, right beneath its top. They are organized in a matrix of panels whose variables are their density, the array overall dimensions and the distance between the panels.
The array system improves:

1. The mid-high frequencies early reflections toward the audience;
2. The musicians' mutual listening and the ensemble;
3. The clarity of the sound perception, by reducing the time of arrival of the high-frequencies reflections versus the time of arrival of low-frequency reflection.

The array is also used to provide variable acoustics condition by changing its shape and inclination according to the type of ensemble and its instruments composition (String Trio, String Quartet, Quartet with Oboe, String Sextet, String Octet, 12 elements Orchestra).

The shaping behavior is studied through the same process used for the main panels system of the shell, but the study of each system, in terms of Computational Design, is independent and follows similar but parallel processes. The input system, indeed, differs from the previous one, as several emitters' set-ups are considered: i.e. string and oboe quartet, string sextet, string octet, orchestra of 12 elements. The panel array is effectively used to provide the optimal acoustic response for each stage configuration by allowing a flexible use of the acoustic shell in a festival condition.

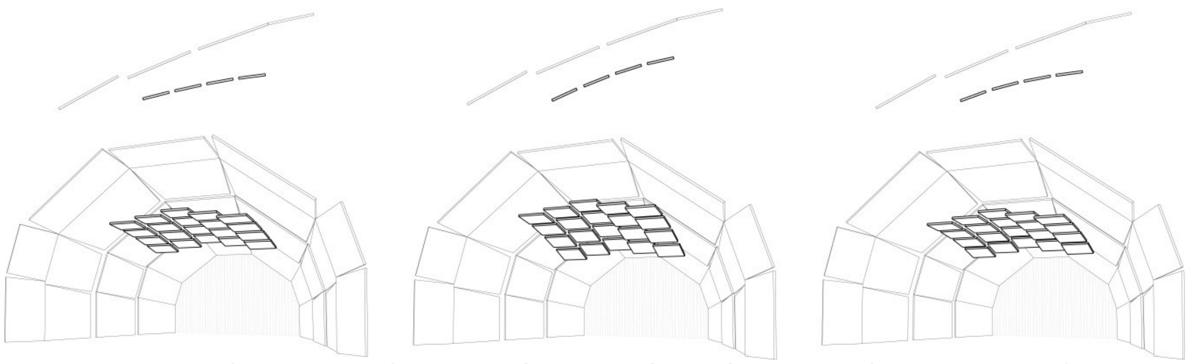

Figure 3: Array configurations (left to right): Orchestra, String Quartet and String sextet configurations of the array shape.

The eyelashes help to improve early reflections to the last row of the audience area and their inclination can also be modified to accommodate different ensembles configuration.
Each panel is fixed to the structure only on one side, which provides the rotational axis, and it is then suspended by the use of sailing ropes to the other.

The bottom of the scene is comprised mainly of a 1D QRD diffuser that creates a nice diffuse field under the shell and helps reducing the strong reflection from the big bottom panel.
The panel has the following performance:

- Scatter Frequency: 300 Hz
- Diffuse Frequency: 600 Hz
- HF cutoff: 2150 Hz
- Minimum distance to efficient response: 1.7 m

The design of the diffuser has been influenced by the typical frequency range of instruments that typically form the chamber music ensembles, by the requirement of reducing low-mid frequency reflection form the bottom panel and by the architectural and construction complexity constraints.

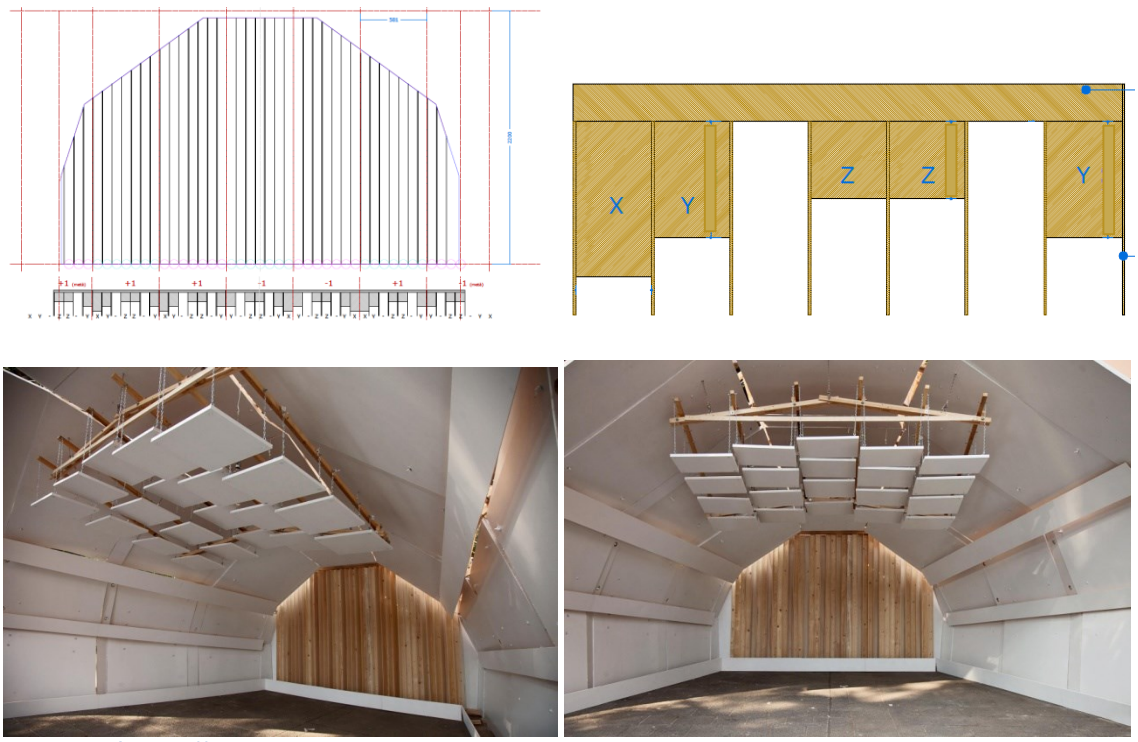

Figure 4: QRD diffuser details and pictures

The acoustic performance is measured by two main objectives: the overall sound level and its distribution on the audience.

It is important to mention that the algorithm works only in the geometrical acoustics domain, performing a geometrical optimisation of the panel shapes and inclination, while a more accurate analysis with a specialist acoustic software (CATT Acoustics) is performed to take into account instruments' directivity, frequency response, scattering and diffraction around the small elements comprising the panel system.

3.1 ReS4.1 – The newest outcome of the research program

The change in the environmental and acoustical conditions requires an upgrade of the previous ReS. New features include a wood platform required because of the grass surface covering the stage area.
The design method has evolved from a form improvement design practice to a more complex form finding process, in which the domain of the shape variations is greatly increased.
To fill such a pronounced gap, a computational morphogenetic process is involved in the definition of the innovative design method. To find the shape with the best acoustical performance, a large number of solutions is tested. Each shape analysis is performed through a customized Image Source algorithm, in which the calculation is extended until the 2nd order of reflections. The details of the whole method are not to be presented in this paper, because of its involvement in the HANGAI prize competition 2016.

The results of the design method are a group of 21 planar surfaces arranged to form a continuous concave shape, to best reflect the sound energy. It covers an area of 27,6m^2 and envelops a volume of 89,5m^3, rather than the 21,1m^2 and the 52,7m^3 of the previous ReS version.
In order to guarantee the flexibility of the system, an Array made by 25 elements arranged in a 5x5 matrix is designed and optimized for different musical set-ups.

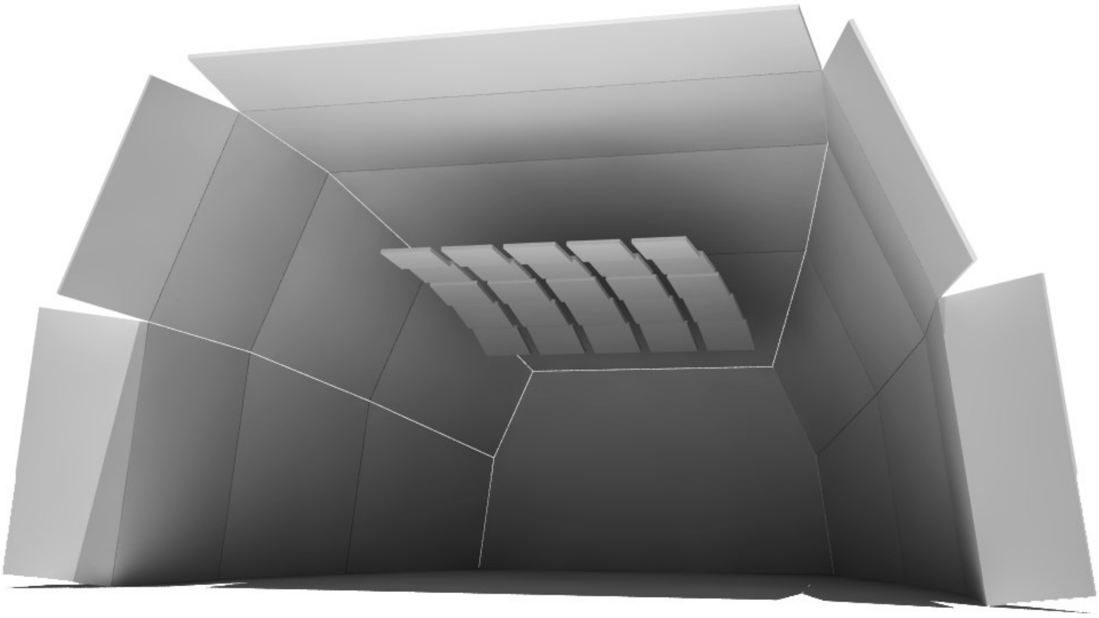

Figure 5: ReS 4.1 architectural rendering

The following Figure 6 to Figure 8 show the acoustic modelling results (in terms of SPL, C_{80} and ST_{early}) for a string sextet configuration considering respectively the case without any acoustic shell (Empty); Main shell only; Main shell and eyelashes; Main shell, eyelashes and array together.
All models present the QRD diffuser on the back panel.
Audience area is 21.7m long and 24m wide with a distance of 3m from the center of the first structural arch.

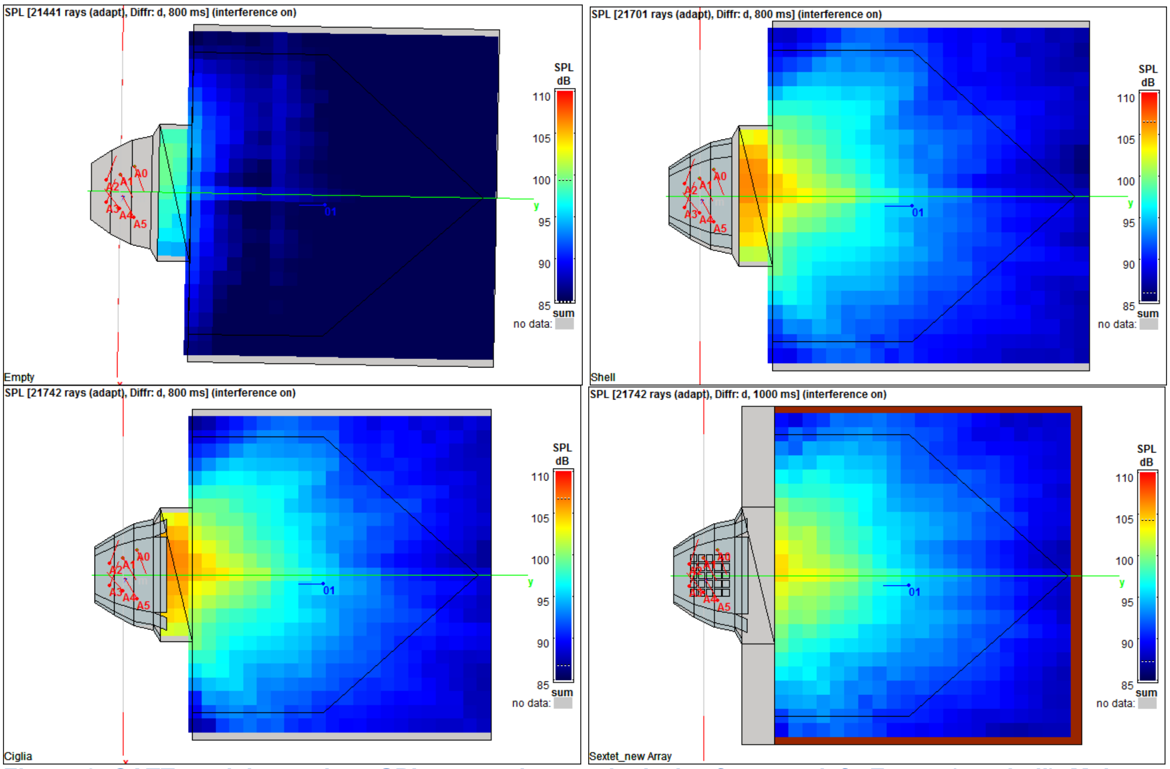

Figure 6: CATT models results – SPL comparison – clockwise from top left: Empty (no shell), Main Shell, Main Shell + Eyelashes, Main Shell + Eyelashes + Array

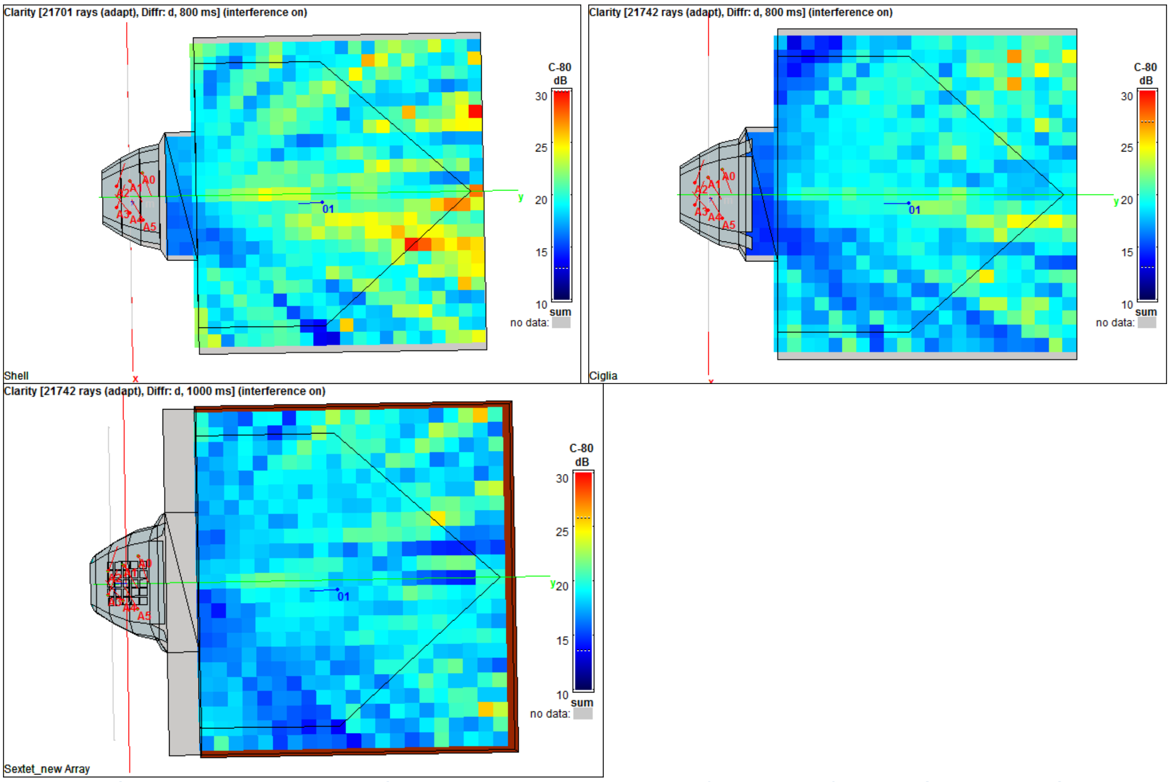

Figure 7: CATT models results – C_{80} comparison – clockwise from top left: Main Shell, Main Shell + Eyelashes, Main Shell + Eyelashes + Array

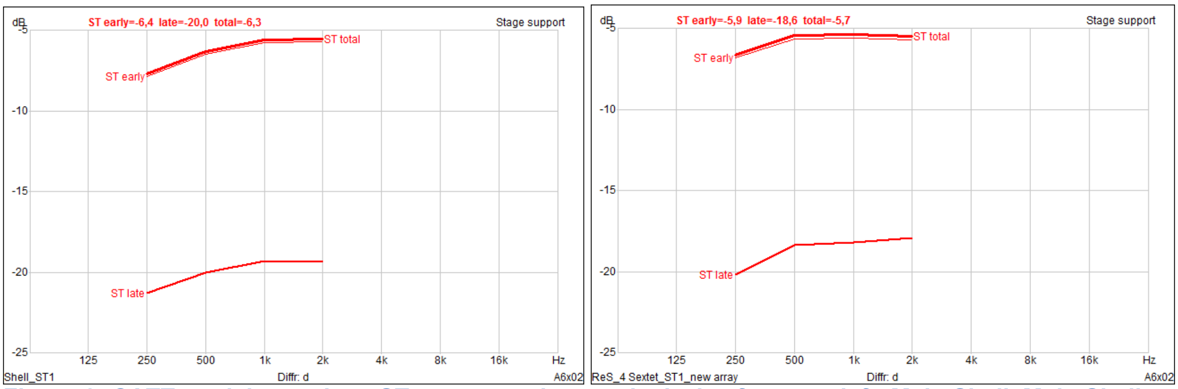

Figure 8: CATT models results – ST_{early} comparison – clockwise from top left: Main Shell, Main Shell + Eyelashes + Array

From the figures above we can assess:

- The effect of the shell compared to the empty case, increases the max level on the listeners area by about 7 dB but mostly distributes the sound evenly, increasing the level at the far end of the audience to more than 10 dB;
- The inclusion of the eyelashes pushes the sound even further and increases the level at the far end by about 2 dB;
- The inclusion of the Array reduces the sound to the sides by concentrating the energy more towards the center of the audience with the result of increasing even more the level at the far end.

From Figure 8 it can be seen that C_{80} values seem to be reduced in the case of the inclusion of the Array, even if much better distributed in comparison of the case with only eyelashes. The results in the case of the main shell only shows a very high value of the C_{80} which is actually not perfectly representative of the subjective experience during the concerts, we assume that this is due to the fact that the shell optimise the very first reflections to the audience while the inclusion of the others elements show a more complex reflections pattern and introduce more energy after 80ms.

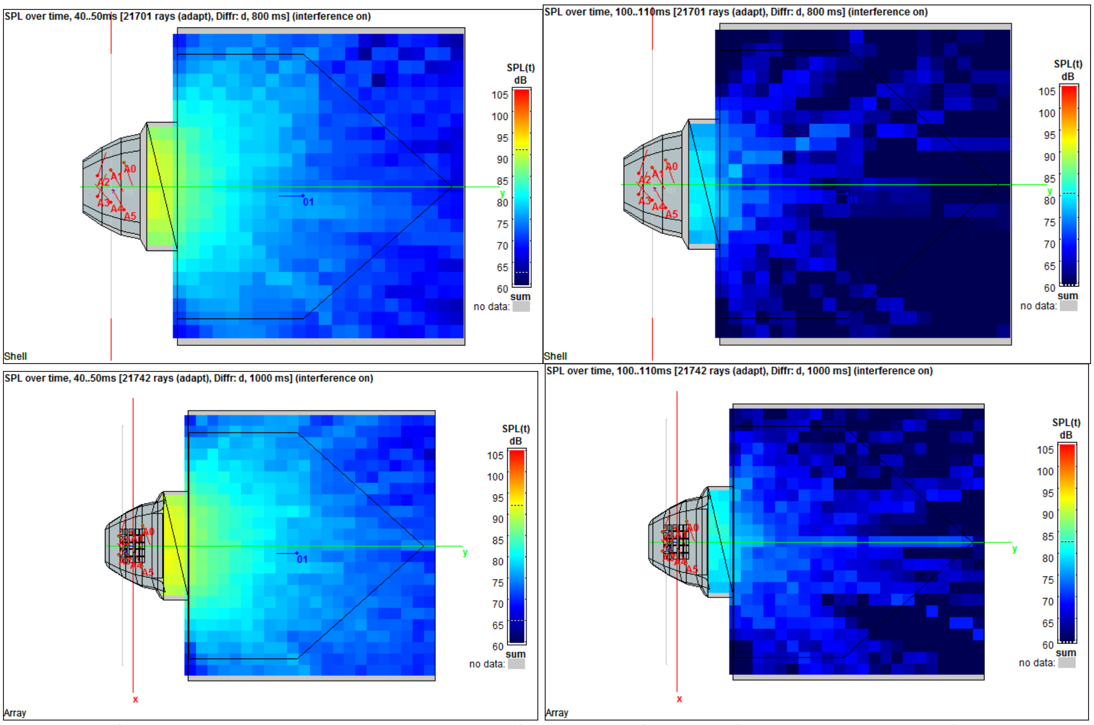

Figure 9: SPL over time analysis - clockwise from top left: Main Shell (40ms), Main Shell (100ms), with Array (40ms), with Array (100ms)

Figure 9 shows that the amount of energy after 100ms in the case of the shell with all elements including the Array is increased by about 5dB at the centre of the audience area, hence we deduct that this is the possible reason of the reduction of C_{80} values.

Ultimately Figure 8 shows that in the case of the Array, there is an increase of about 1 dB in the ST_{early} parameter.

3.2 WOOA – Wandering Orchestra Open Air

As discussed previously, the development of ReS is also part of an architectural workshop and classical music festival where the students are asked to help in the construction of the structure. The outcomes of this workshop are many and some of the students has now become active part of the team (also authors of this paper) by helping the research development, while others have started to develop their skills in the topic and have produced interesting studies.
This section shows the initial study for an acoustic shell for a small orchestra (42 elements) and the development of the algorithm to find the optimized shape of the panels.

The work has been presented by N. Timpanaro in his thesis "WOOA. Wandering Orchestra Open Air. Progetto di una scena acustica per spettacoli musicali all'aperto" on the 21st of July 2015 at the Dipartimento di Ingegneria Civile e Architettura, Università degli Studi di Catania.
ReS team has provided technical support to the research.

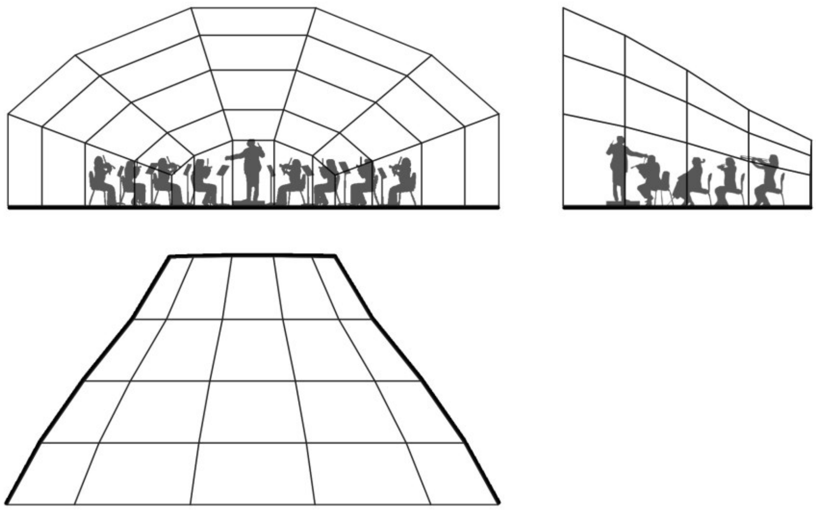

Figure 10: WOOA architectural sketches

The entire design of the acoustic scene for orchestra is built in Grasshopper, creating a visual algorithm that takes explicit reference from ReS

In order to describe the propagation of sound, the image source method, limited to the first reflection, was used with the 42 members of the orchestra represented by 7 omni sources.

The optimization is divided in two phases with two main targets: projecting the sound away from the scene and obtaining a distribution as uniform as possible. Thus the process of form finding was based on two groups of parameters, referring to longitudinal and transverse development of the scene. The algorithm only takes into account the first reflection from each panel.

Audience area is considered 53m x 60m at about 3 m from the proscenium.

During the first phase, the longitudinal development is manipulated changing the scale factor for each of the arches, and the algorithm has to calculate the average distance run by the rays. Fitting the maximum value of that average, the solution represent the family of shapes that maximize sound pressure to the bottom of the audience. The family of possible shapes moves inside the range of dimensions that allows the arrangement of 42 musicians. The orchestra's morphological and acoustics characteristics represent the key of morphogenesis, guiding the rules definition in the first step of algorithm.

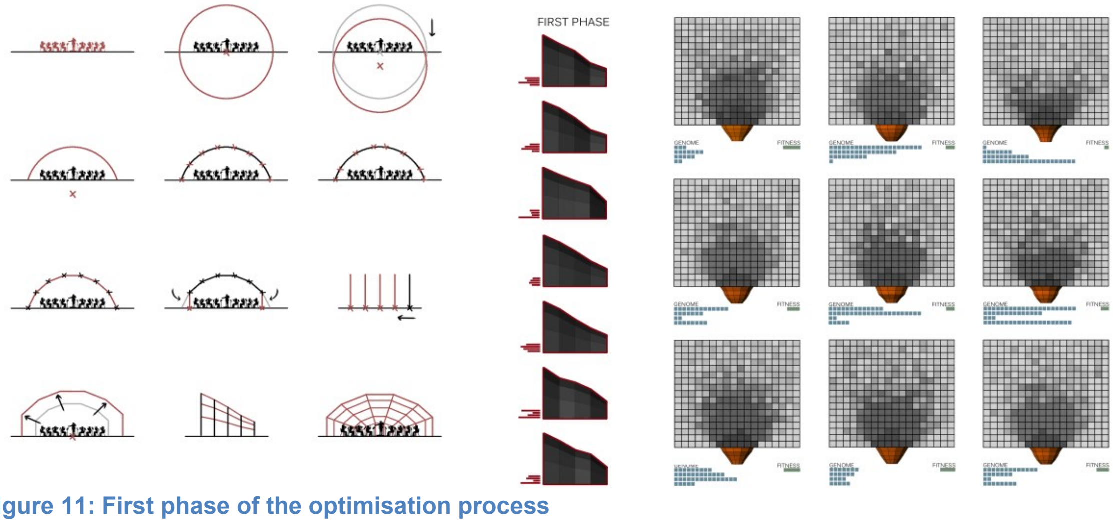

Figure 11: First phase of the optimisation process

The ensemble will be enclosed by the scene generated by a sequence of arches, aimed also at improving the mutual listening for the musicians.
Starting from that group of shapes, the second phase manipulate the transverse development to achieve the uniformity of distribution. The receiving surface is subdivided in small squares representing all receivers: the fitness function tries to minimize the number of square not reached by any ray.

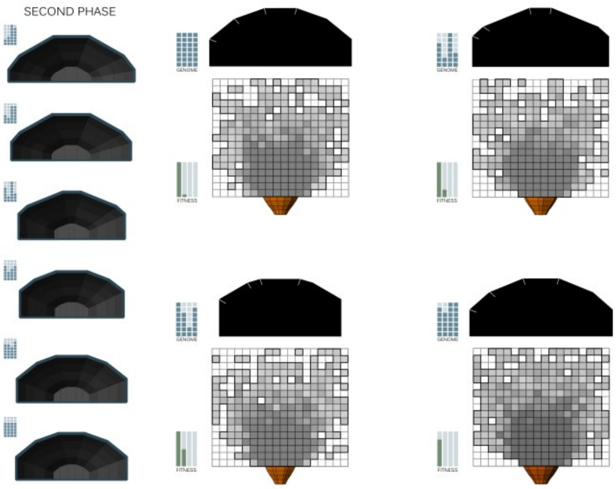

Figure 12: Second phase of the optimisation process

CATT-Acoustics simulation show the efficiency of algorithm. Comparing three different conditions, one without acoustic scene, one intermediate solution and the final choice taken from the best results of the algorithm, the efficiency of the scene like the algorithm of morphogenesis is quiet obvious.

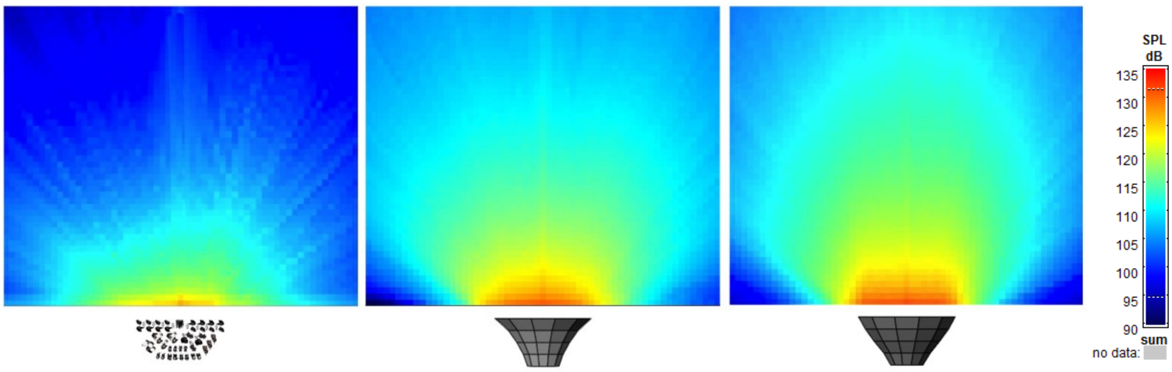

Figure 13: Acoustic modelling results (left to right): Empty case, Intermediate optimisation, final result

Additional research is in progress in order to extend the algorithm to higher order reflections and to improve the supporting structure in order to optimise construction times and costs.

4 ACOUSTIC MEASUREMENTS

As described in the previous paragraphs, ReS has been built since 2012 and has gone through different iterations and shape optimization that were mainly influenced by its construction and architectural complexities being resolved over time, and by the location (first three years in the Villa's courtyard, Villa's garden in 2015).

In this section we present measurements results from latest version of the shell (ReS 4.1) made in 2015; also a measurement with the same source has been performed in 2014 without the presence of the acoustic shell (Empty condition) in the Villa's courtyard and it is presented for comparison.

Our approach is based on the comparison between the results we obtained from the same measurements in empty conditions, without the structure been built, and the one in the "as-built" conditions.
Acoustic parameters analysed are:

- SPL [dB]: sound pressure level at the receiver location, calculated relative to free field measurement of the source level at 10 m;
- C80 [dB]: Clarity, level balance between early energy and late energy (arriving after 80 ms from the direct sound;
- *STearly* [dB]: Stage support, a measure of the mutual hearing and ensemble performance on stage, this parameter is currently under discussion in the scientific community about its real quality in describing the mentioned subjective measures on stage;
- Impulse responses evaluation: identifying the beneficial support provided by the acoustic shell to the audience in terms of additional early reflections (where applicable)

ST_{early} parameter has not been measured in empty conditions.
One aspect of the ST_{early} parameter to note is that its optimal range is based on large Orchestras while our specific case is for smaller ensembles, which prefer an higher presence of strong early reflections hence we expect an higher value of the ST_{early} parameter (we propose up to -4 dB).

Every measurement has been performed with a dodecahedron loudspeaker whose acoustic performance is in accordance with EN ISO 140-4 and has been kindly provided by Aesse- Ambiente S.r.l., based in Rome.

10s Logarithmic Sweep sine signal with 1s silence has been used as excitation signal and only 1 measurement per point has been considered due to the length of the signal used.

The loudspeaker emission level has been measured with a Type-A Sound Level Meter in almost free-field (measurements have been performed in the villa's garden without buildings or obstacles nearby and source and receiver at 4m from the floor) and the recording and reproduction chain calibrated.

The loudspeaker's SPL at 1m during measurements, after calibration and equalization is:

Dodecahedron measurements @1m - SPL [dB]											
	31.5	*63*	*125*	*250*	*500*	*1k*	*2k*	*4k*	*8k*	*16k*	L_{Aeq} *[dB]*
	--	--	83.9	83.9	83.9	83.9	83.9	83.9	83.9	83.9	90.2

Table 1: Dodecahedron SPL @ 1m - measured

The microphone used for the measurements is a DBX RTA measurement microphone.

Figure 14 show locations of source and receivers for ReS 4.1.

It is important to mention that the measurements in the Empty case have been performed in the Villa's courtyard where the main building (5 stories) sits on the left of the audience and the floor is made of stone.

Reflections from the building on the right side of the audience, the stone floor and the presence of the enclosed entrance, basically a long reverberant corridor in correspondence of the 2m measurement point, provide an increase in SPL by additional reflected energy reaching the microphone. This is reflected in the non-linear SPL decrease with doubling the distance that can be noted especially in the measurements without the shell (Empty case) and in the comparison between the levels at 2m and 4m from the source (Figure 15).

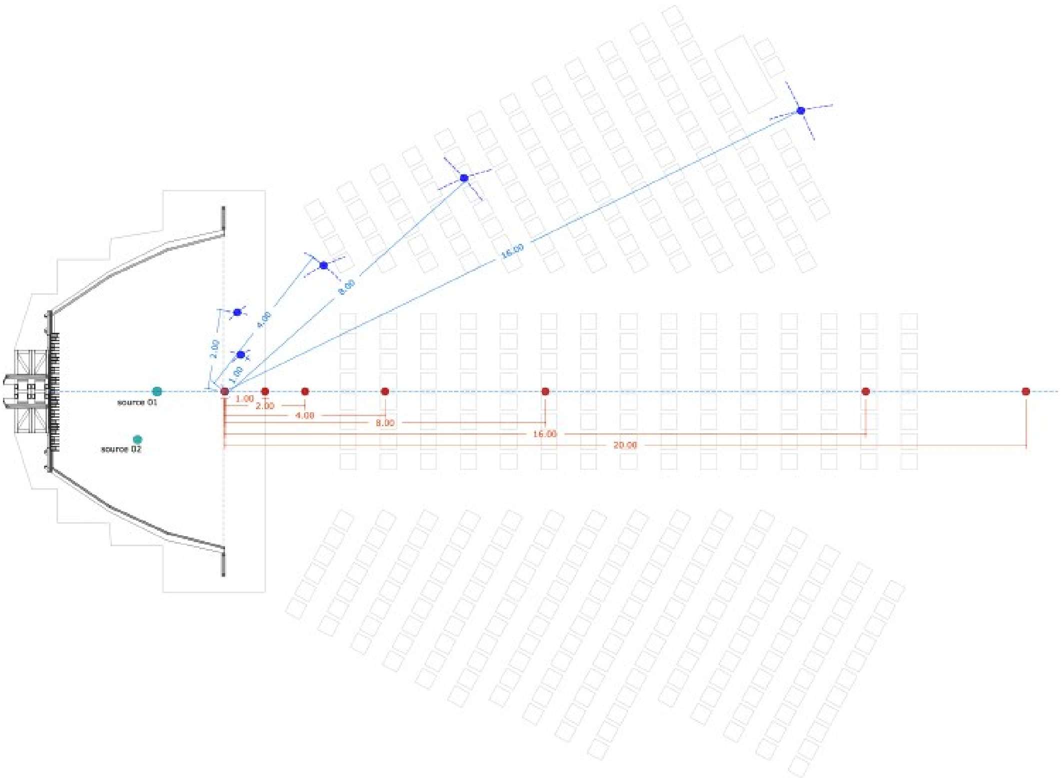

Figure 14: Source and receivers plan – ReS 4.1

Measurements for ReS 4.1 have been made in the Villa's garden without any obstacles apart from trees and plants, which provides the closest possible condition to an open-air concert.

The differences with the empty condition measurements only represent a qualitative comparison as the sound propagation conditions are different due to the lack of additional reflections in the Villa's garden by elements that are not part of the acoustic shell.

It is important to note that 2015 has been the first year ReS has been tested in a proper open-air condition and the results are quite reassuring that the design is providing a good support to the audience and the musician by making possible the listening of acoustic music that otherwise would be impossible.

Also, as the measurements have been performed by an omni-directional source, they do not clearly represent the real acoustic performance of the shell for real musical instruments, as they have a more directional and complex directivity, hence the increase in the SPL and C80 value would be in reality higher if measured with source with the same characteristics of musical instruments in comparison to the empty case.

Additional note is also given by the indeterminacy of the temperature and humidity for two different years and orientation of the acoustic source especially for the measurements in close proximity.

4.1 Empty (no shell)

Figure 15 and Figure 16 below show results of the measurements in the case of the absence of the acoustic shell.

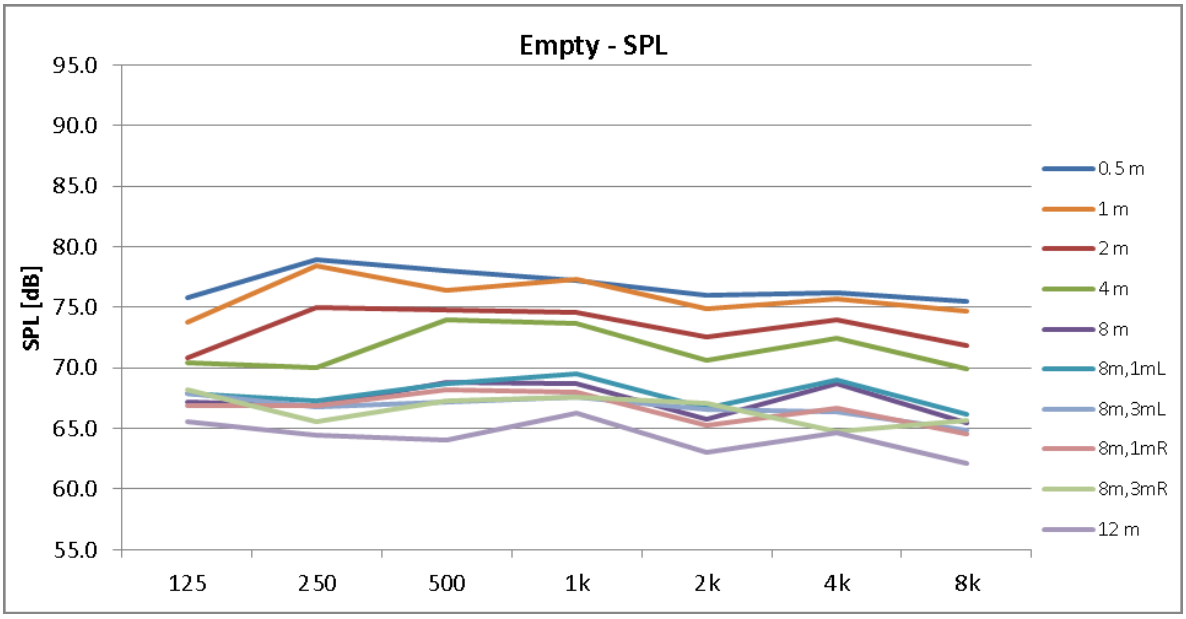

Figure 15: Measured SPL – Empty case

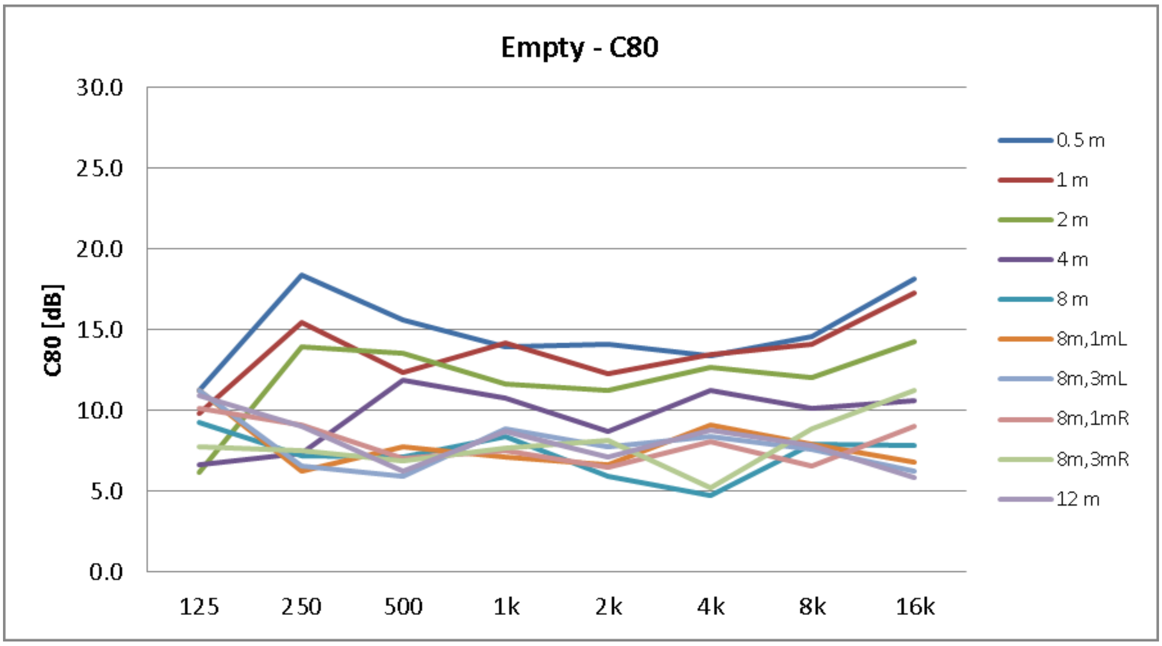

Figure 16: Measured C_{80} – Empty case

4.2 ReS 4.1 (2015)

The move to a larger area (garden) with no obstacles (apart from plants and trees) leads to the possibility of increasing the shell size and improving its acoustic performance to larger audience area of about 600 people.

Measurements have been performed with two different source positions and at various distances in the central area of the audience and on the right side as shown in Figure 14.

Figure 17 and Figure 18 below show the results for the central area of the audience and for the source in the middle of the shell (soloist).

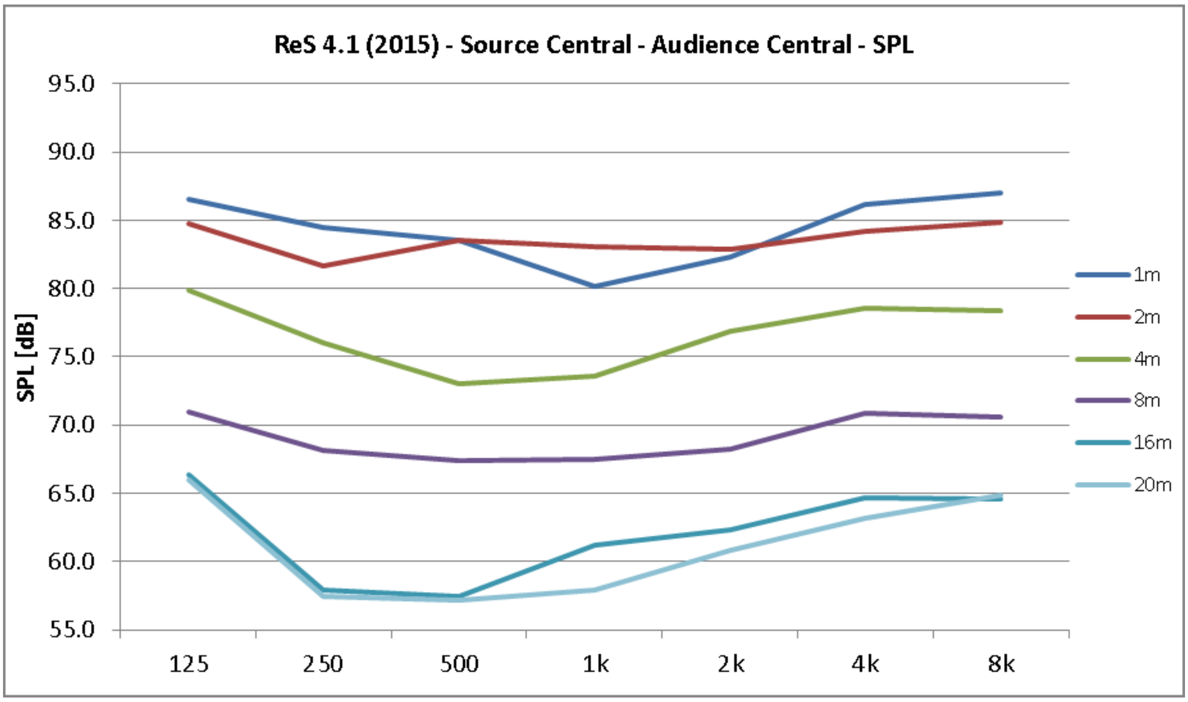

Figure 17: Measured SPL – SRC central, Rec central – ReS 4.1

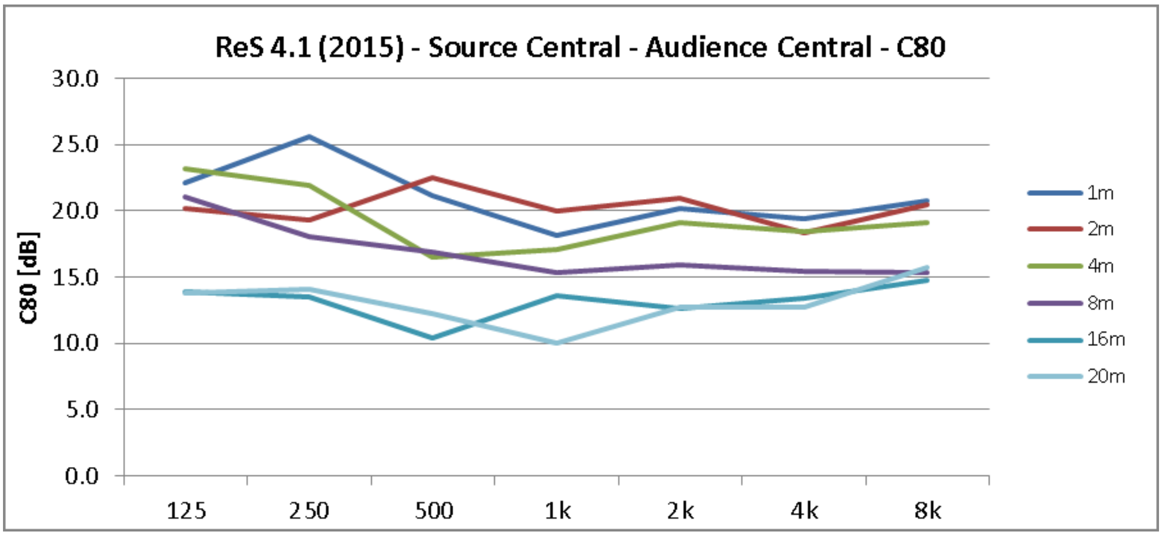

Figure 18: Measured C80 – SRC central, Rec central – ReS 4.1

Figure 19 and Figure 20 below show the results for the right side area of the audience and for the source in the middle of the shell (soloist).

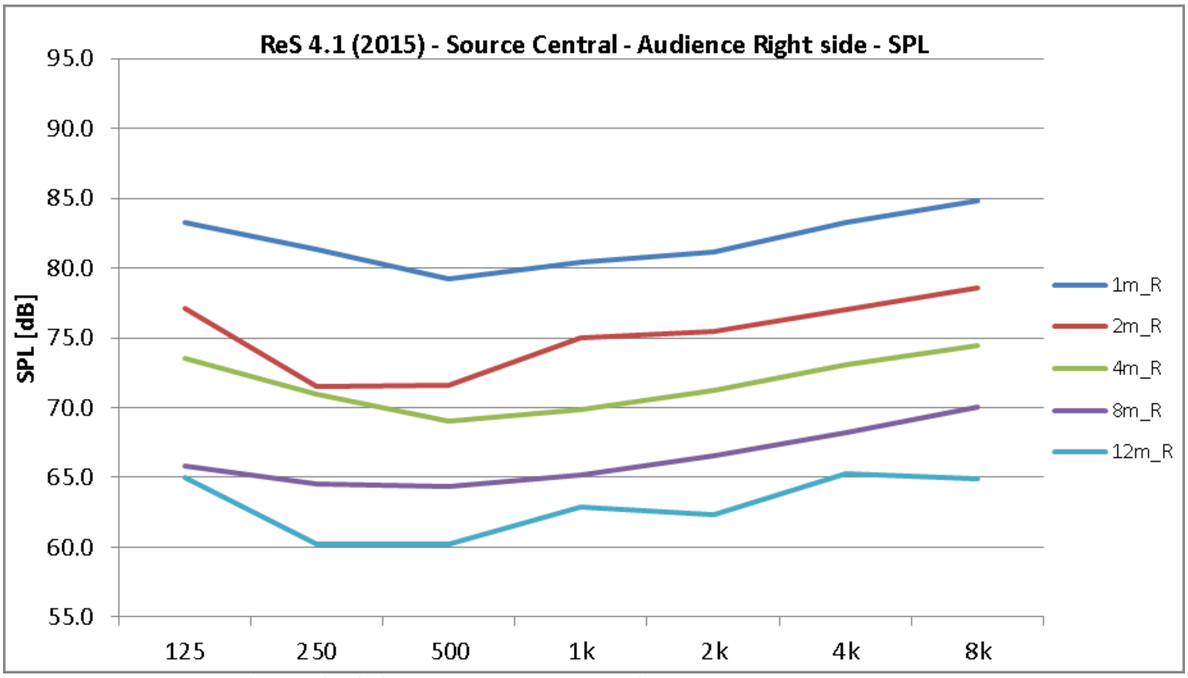

Figure 19: Measured SPL – SRC Central, Rec right – ReS 4.1

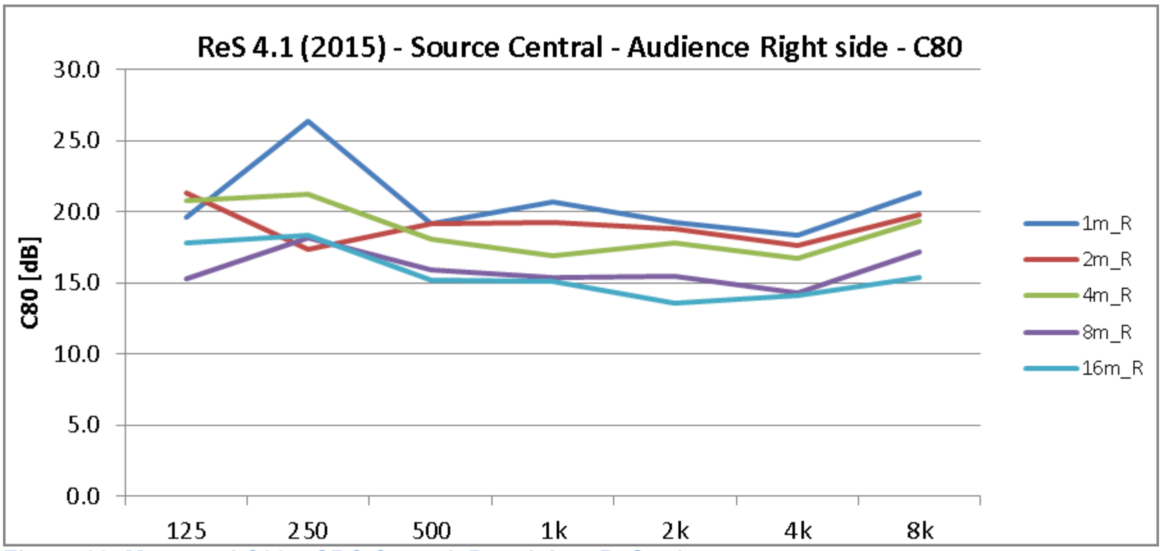

Figure 20: Measured C80 – SRC Central, Rec right – ReS 4.1

Figure 21 and Figure 22 below show the results for the central area of the audience and for the source on the right side in correspondence of middle of the shell (second violin sextet configuration).

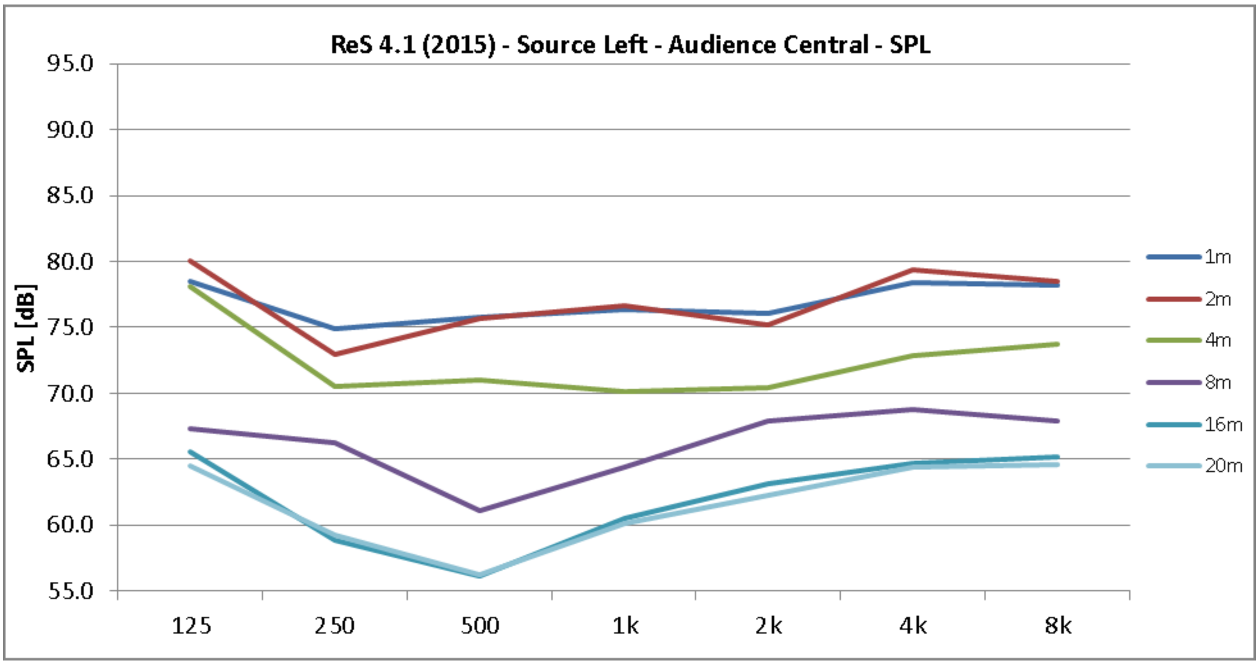

Figure 21: Measured SPL – SRC left, Rec central – ReS 4.1

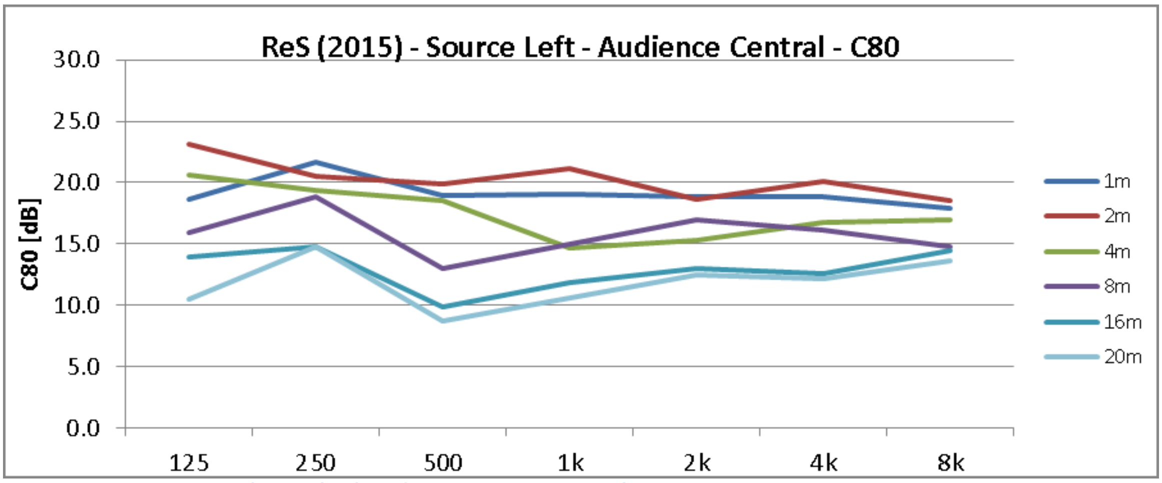

Figure 22: Measured C80 – SRC Left, Rec central – ReS 4.1

Figure 23 and Figure 24 below show the results for the right area of the audience and for the source on the right side in correspondence of middle of the shell (second violin sextet configuration).

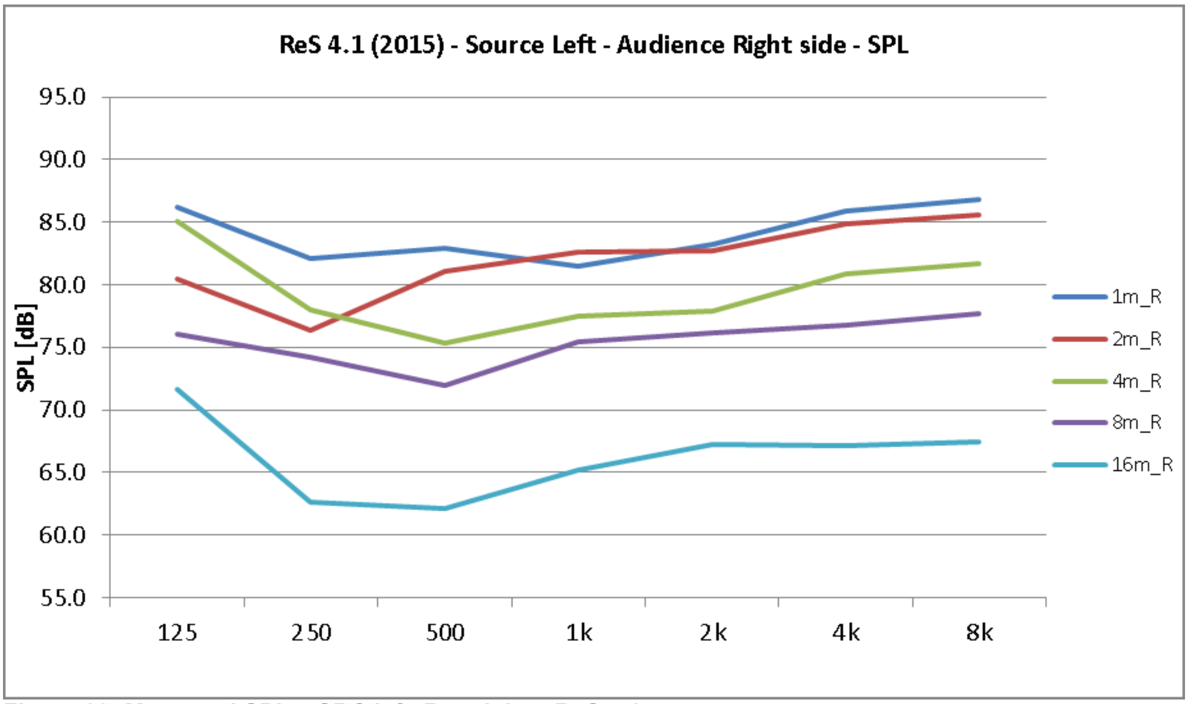

Figure 23: Measured SPL – SRC left, Rec right – ReS 4.1

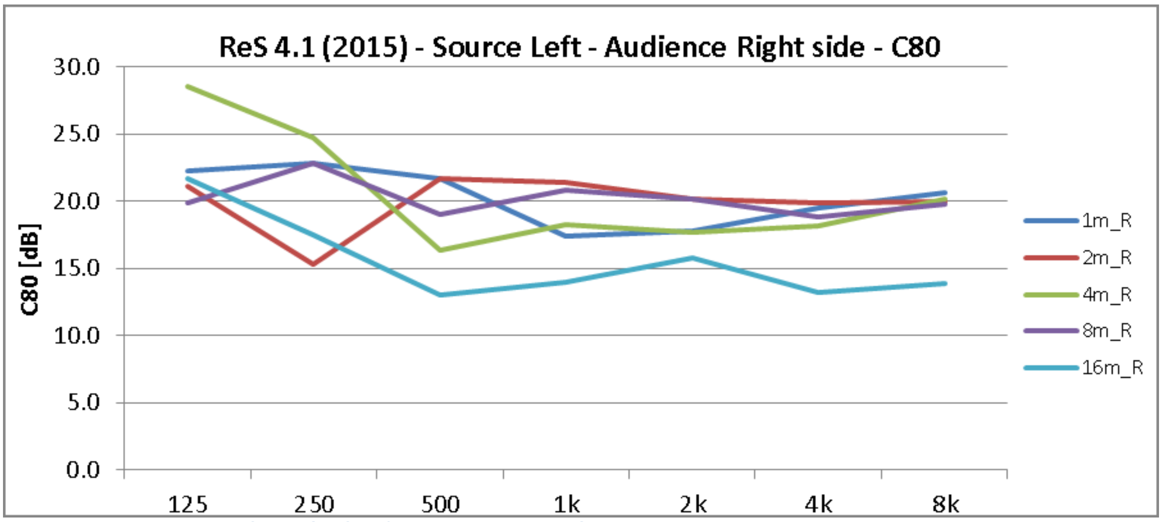

Figure 24: Measured C_{80} – SRC left, Rec right – ReS 4.1

From the results shown we can assess:

- In the case of source in the middle of the shell, the reduction of sound energy by doubling the distance is more uniform and kept to a maximum of about 20dB between the loudest point and the quietest, the reduction of C_{80} also confirm the same results;
- In the case of source on the left side of the shell, the distribution of sound energy by doubling the distance is less uniform but is still kept to a maximum of 20dB and C_{80} also reflects this results;
- It is evident that in the empty case, additional reflections from the building are the reason why the level at the far end of the audience is about 5 dB higher than the case with the

shell; unfortunately in 2015 it was not possible to perform an empty case measurements due to timing constraints with the construction.

From Figure 25 below it can be seen that the density of reflections is much larger than the empty case.

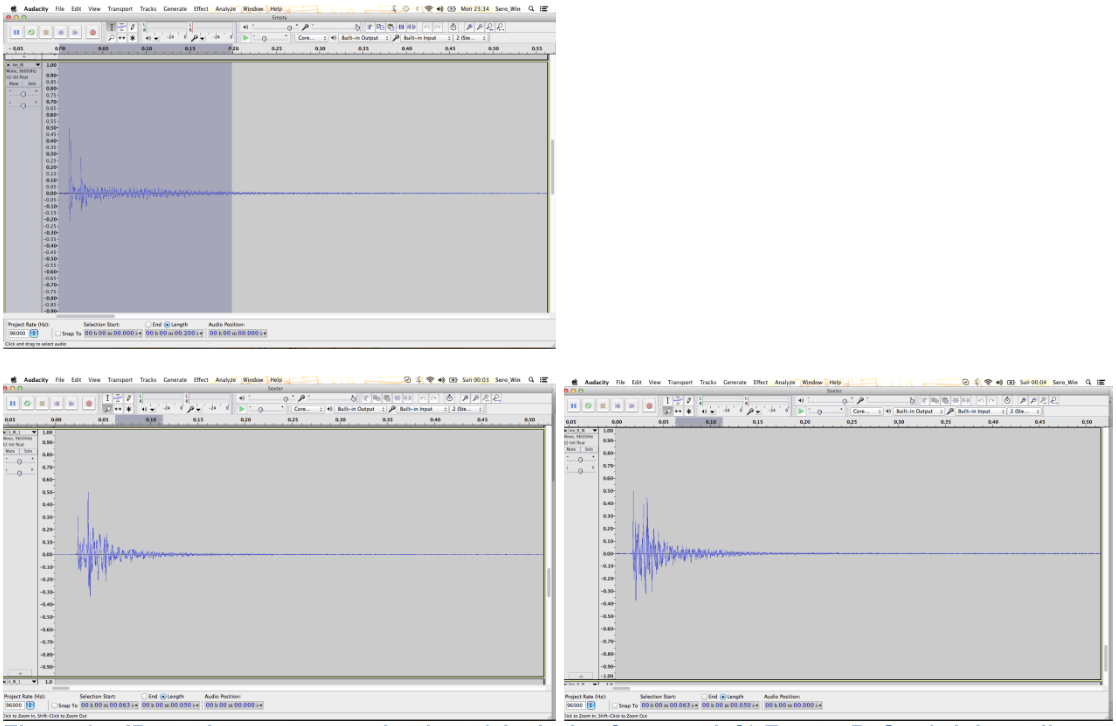

Figure 25: IR results at 4m central point – (clockwise from top left) Empty, ReS 4.1 right audience, ReS 4.1 central audience

Table 2 below shows results for ST_{early} that are also compliant with the target, while reduction of the value compared to the case of ReS 3.0 is expected given the substantial increase in the internal volume of the shell.

ReS 4.1 (2015) - ST_{early}[dB]											
Central Loudspeaker											
	31.5	*63*	*125*	*250*	*500*	*1k*	*2k*	*4k*	*8k*	*16k*	*Average* 250-2000 Hz
ST1_R	-11.6	-22.1	-12.8	-12.1	-12.4	-11.4	-9.4	-4.5	-14.5	-15.4	-11.3
ST2_R	-10.5	-21.9	-13.0	-11.9	-12.6	-11.2	-9.4	-5.5	-14.8	-15.6	-11.3
ST1_L	-10.8	-21.0	-10.3	-14.9	-11.3	-10.4	-10.4	-8.7	-12.0	-15.2	-11.7
ST2_L	-10.5	-20.5	-10.0	-15.3	-11.2	-10.1	-10.3	-8.9	-11.9	-15.3	-11.7

Table 2: Measured ST_{early} – ReS 4.1

5 CONCLUSIONS AND FURTHER DEVELOPMENT

This paper shows the design and development of an acoustic shell for outdoor chamber music concerts and its performance both in terms of acoustic modelling and measurements results.

The benefit of the design is clearly demonstrated by comparisons between measurements made in empty stage conditions and with the shell installed; also Orchestra ensemble parameter ST_{early} is demonstrated to comply with expected target as shown in literature.
Results of SPL and C_{80}, demonstrate that the acoustic machine is able to project sound up to 20m from the proscenium with a general increase of about 6dB in the SPL, compared to the empty stage condition. Moreover, it allows a more uniform and frequency-balanced response across the whole audience.

Further development is required to provide a more uniform coverage of the audience area and additional elements to increase ensemble; also an application for larger orchestras is under study through the help of scale modelling measurements and assessment.

6 ACKNOWLEDGEMENT

We thank David Romano for his ability to bring out the best of each participating to VPM, and *Teda legno Srl* for the supplies and their support.
This paper is dedicated to the memory of ***Ian Thompson***, previous head of the Acoustics group of Buro Happold Engineers, who has been an early advocate of the project and has been an invaluable guide in finding the right path during the early stages of the design.

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