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CAPTUREING HISTORICAL BUILDINGS SPACE SOUND SIGNATURE USING BEAMFORMING

Mojtaba NAVVAB[1], Fabio BISEGNA[2], Gunnar HEILMANN[3] and Magdalena BÖCK[3]
[1]**University of Michigan,** College of Architecture and Urban Planning, Arch Bldg.,
2000 Bonisteel Blvd., Ann Arbor MI 48109, E-mail:moji@umich.edu
[2] **SAPIENZA**, the University of Roma, Rome. Italy
[3]**Gfai** Tech GmbH, Berlin, Germany

ABSTRACT

Historical buildings and ancienet theaters are used for live performances for a variety of venues, and there is a demand for detail information relating to sound field within these remarkable historical architectural buildings. The objective method used to examine these types of spaces for their room acoustic characteristics is onsite sound measurement using beamforming at their current status. Computer simulation incorporating the past archeological records for their architectural details that relate to material and surface characteristics are also used for parametric design studies. The objectives of this study are to demonstrate the ability to visualize sound fields and to capture a sound signature that significantly represents the room acoustics characteristics of all architectural elements toward their historical preservation. The results are used to represent these acoustic conditions for the general public to experience using virtual environment.

Key words: Reverberation, Absorption, Reflection, Diffusion, Beamforming, Visualization,

1.0 INTRODUCTION

There is a strong demand from the public for access to the outdoor archaeological sites during daytime and even more during night time, both for archaeological visits and for the organization of several types of cultural events, ranging from sport shows, to symposia and concerts. Most archaeological sites cannot be considered sustainable for their cultural heritage that has not yet been reached. The building officials and historical societies that manage the use and operation of these ancient architecture buildings or theatres have outlined a series of guidelines for their use by the public that includes the role of acoustics and lighting techniques in the modern use of these ancient places. The acoustic properties of ancient performance spaces have been studied for accurate reconstruction from possible alternatives of material and design evolution by many investigators. Parametric studies and examinations of computer simulation methodology for ancient buildings provide new indexes to examine the contribution of each design component. Measured and simulated results show that scattering and diffraction from seats and architectural elements, which are important in outdoor theatres, impact the sound quality and condition. The specific changes in material characteristic have increased the reverberation and enhanced the sound levels. Computer simulations using a range of boundary absorption and scattering coefficients play a very important role in supporting the choice of the best or most acceptable choice of material for their reconstruction, or sustainable design approach among different possible alternatives being practiced by superintendents and the facility managers of these historical sites. This study presents application of a newly developed technique in beamforming as a close numerical examination to provide evidence for the relevant acoustical aspects of historical buildings. This paper describes a new approach in measuring the contribution of sound reflected component in frequency and time domain for evaluation of the existing room acoustic condition of selected historical buildings. Data were measured using Acoustic Camera spherical array, 120 channel data recorders, and utilizing various acoustic software for data reduction, computer modelling, simulation and analysis. As part of the new historical preservation effort, and given the historical records on the use of materials with their unique surface characteristic, the frequency domain and spectral analysis are used as input to the computer modelling, simulation of the space. Newly developed room acoustic indicators provide a new approach in estimating the impact of the direct and reflected sound contribution to the sound level available within the current space. The results show a new research approach in room acoustics evaluation utilizing current standards and techniques.

2.0 METHODOLOGY

Architecturally speaking, not all ancient theaters are designed equally since the space geometry for each period varies given the required acoustic performance. The desired sound level is not loud enough because the human vocal cords are not strong enough, and or the listeners are not close enough to the source/speaker. The discipline of architectural acoustic requires designers to estimate the reverberation time as one of the indexes for room acoustic studies. Acoustic performance evaluation of these selected buildings show that the reverberation time varies for low, mid and high frequencies. Reverberation time is defined as the time in seconds that it takes for the sound to drop off to a set point such as 20, 30 or 60dBA below the starting sound, and it is shown as RT20, 30 and 60 or T_{20}, T_{30}, and T_{60}, . Most reported measured RT is T_{60} for 500Hz or the average of 500 HZ and 1000 HZ. Measured data for 250 Hz and lower are not reliable, and calculated results at an early stage of the design are good enough to 125 Hz only, given the feedback from acoustic society members and published data **[1-4].**

It is possible to simulate the building geometry and its surface characteristics (e.g. material and or surface properties). Simulation capabilities of EASE software **[5-6]** and computer drawings were used to input the geometrical data along with surface characteristic such as, absorption coefficient, scattering coefficient, source, and receivers (seats) within the EASEaura module. Room impulse response on a probe and binaural impulse response measurement with the Head Related Transfer functions (HRTF) are used to create the file that contains the Auralization of simulated spaces as is or designed. The objective of this study is to visualize the noise/sound/acoustic performance of the space for validation of their use based on historical records using computer simulation. It is hoped to produce a protocol for future onsite data collection to capture a sound signature that significantly represents the room acoustics characteristics of a selected building. Sound pressure level measurements were made at each site. See **Figures 1-5**. The sound meter was positioned at a given location to capture the impact of the wall or any architectural element surface characteristics given the current structure conditions of the space. The contributions from direct and reflected sound components using impulse (large scale balloon and or sweepers as a source were determined along with the maximum equivalent A-weighted sound pressure level (SPL) for various locations within the space. Additionally, a Head Related Transfer Function was utilized along with the use of acoustic camera in order to determine which portions or direction of the viewing areas of by the speaker or the sources of sound were contributing to the majority of the sound pressure level reaching a particular measured location. The results based on measurements and simulations indicate that large wall surfaces close to the audience seating areas or speaker are able to most effectively project the generated sound onto the field and side walls. The differences between total and direct sound pressure levels as a function of frequencies indicate the contributions of the reflected and or diffuse sound due to the wall surface characteristics and their current geometry. This estimation contributes to parametric studies of various materials within the space, and their impact on sound condition in these historical spaces.

2.1 Application of the Acoustic Camera

The Acoustic Camera was used to measure from both center and side filed positions within the each building to capture the total sound presseure level, while making a good attempt to capture reflected compontes if any. The system produces images of sound sources or “localizes” sound sources using the Beam forming technique. Delay-and-sum Beam forming, is one of the oldest and simplest array signal processing algorithms…“as far back as 1880. The acoustic images consist of color contours indicating where the most significant noise sources are located. Detailed review of this technique are described in references **[7-10].** The system consists of a microphone array with camera, data recorder, and Noise Image software running on a laptop PC. **Figure 1** shows the typical system components used by the Acoustics Camera and the actual setting for measurements within the coliseum. Despite its extreme simplicity, the delay-and-sum method in the time domain is quite robust and powerful and has shown its practical usability in an extraordinary wide range of acoustic localization and troubleshooting applications for years now **[7].**

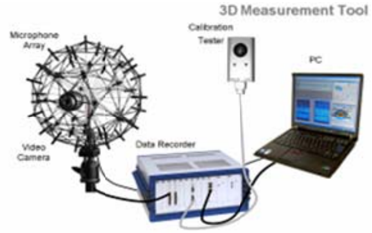


Figure 1. Acoustic Camera actual set up.

Figure 2. *Rome Coliseum.*

Figure 3. *Ostia Antica*, *Theatre*.

Figure 4. *Adriana Villa,* Maritime Theatres and Hall of Philosophers*.*

Figure 5. Taormina Theater

The net result from the system is a sound image superimposed onto a 3-D CAD model for specific application. Data can be analyzed for specific time periods and frequency ranges allowing results to be correlated with standard architectural acoustic measures. The measured results were used to simulate the sound source in EASE and other ray tracing acoustic programs **[5-6].** The 120 small microphones recorded the impulse noise using large scale balloon and sweepers using computer generated signal for 8 seconds and live noise by crowd of tourist participation in making noise simultaneously at a given signal. The software allows the user to pinpoint exactly how much sound individual people and musical instruments make in a large open space like roman coliseum. Other factors such as the duration of the yells from the crowd, and the length of time it takes the balloon burst or the sweepers signals to reach "full loudness", the point at which the sound intensity level remains steady had to be evaluated for peak measurements, and their spectral characteristics.

2.2 Application of HRTF

Head Related Transfer Function (HRTF) describes how a given sound wave input is filtered by the diffraction and reflection properties of the body, before the sound reaches the eardrum. Hearing with both ears is defined as binaural hearing. It provides the ability in hearing the sound naturally and accurately. The sound that is received from both ears localizes the direction and true spatial perception of sounds. The geometrical parameters of the human body have a major impact on binaural hearing. The application and the analysis of the specifically collected room acoustic measurements by the Acoustic Camera allows examination of this concept and the creation of a possible new room acoustic index that captures space's sound signature.

3.0 RESULTS and ANALYSIS

The following sections describe the sources of measured data and the different observations based on their correlation to the theoretical models as well as their time or frequency dependencies for calculation of different room acoustic indices. The results are explained and shown in the form of plotted graphs and or utilizing some 3D visualization capability within selected capability of the Noise Image program.

Sound of impulse using balloon and in some cases crowd noise conditions within these selected historically known theaters are measured and simulated. The results through some well-known room acoustic indices show the impact of space geometry, architectural surface characteristic (absorption, reflection, diffusion) and specific building elements in size within the space. It is important to resolve or to determine the contribution of each architectural components from the room acoustic design point of view at the early stage of historical design studies or its investigation and not after the measurements are completed or without relying on only computer simulation. There is a need for an index to show and demonstrate the relative acoustic contribution of each surface and architectural elements in a given space for designers and practitioners that are interested in integrating their design concept or correlating with their historical records on a given project site for room acoustics.

Coliseum and Ostia Theater were selected for their capacity seating area of the spectators. Specific measurements and simulation were made for their room acoustic performance. As part of the acoustic analysis the sound conditions inside this space, the peak impulse measurements were captured similar to crowd noise at the Coliseum. Measured data using acoustic camera then were converted from pressure units to relative sound intensity level distribution and presented equal to the HRTF distribution as described in section 2.1.

The results for crowd noise (Coliseum) and impulse measurement in Ostia are plotted for two slices of time. Two locations within the Adriana Villa namely; Maritime Theatres and Hall of Philosophers were measured and results are shown in **Figures 6-16**. The peak noise levels are clearly identified in purple colors in 3D architectural representations. The sound intensity from the surrounding crowd noise and low levels from sky and not much contribution is shown from below in Coliseum data, however, much contribution from the ground and dome structure within the Hall of philosopher in villa Adriana is shown. It is also possible to identify specific sound intensity distribution and its directionality at a given point. See Web links 16-19 for general historical information on all site under studies by the authors.

During the time allocated for our studies, the sound in coliseum was measured to predict what impact the planned renovations / restoration would have in making the coliseum to have its original looks and materials. The measured results were used as an input in computer simulation modelling for various parametric studies. Acoustic Camera data was post processed to produce Acoustic Photos files for each set of measurements and sound or background condition byond our control such aa air or ground traffic noise conditions and measurement position. The methodology and calculation procedures were applied each sound source and intensity was simulated using the Acoustic Camera data recorded data as an input. The sound recording was generated taking the background into account by using sound from prior to the start until after the sound reverberation had stopped. An Acoustic Photo file was generated for as many locations and time intervals required for these computer simulations. These simulations uses 3D acoustic views and the dynamics of the sound rays within the space during the steady state behavior, this visualization of the sound field as it interacts with the interior surfaces of the space allows the calculation of time histories for specific points of interest in the space. This data can then be used to correlate the coliseum acoustic model for acoustic metrics in a space based methodology. The 3D acoustic models including the spectral characteristic of the tourist yelling noise are shown for selected zones in **Figure 6.** Tourist participation was almost entirely controlled by the announcement made during the measurements and the public willingness and effort. If all individuals or 50,000 original occupancy execrators during ancient times had yelled at the same intensity, the measurement would have increased to 101 dBA, Leq. Within the centre of the coliseum, which is a significant sound increase? Digital recording of the data measured within the centre using acoustic camera using sweeper as source is shown in **Figure 7.** In addition, the spectators' peak noise as time series data measured over the length of a time at various locations within the space.

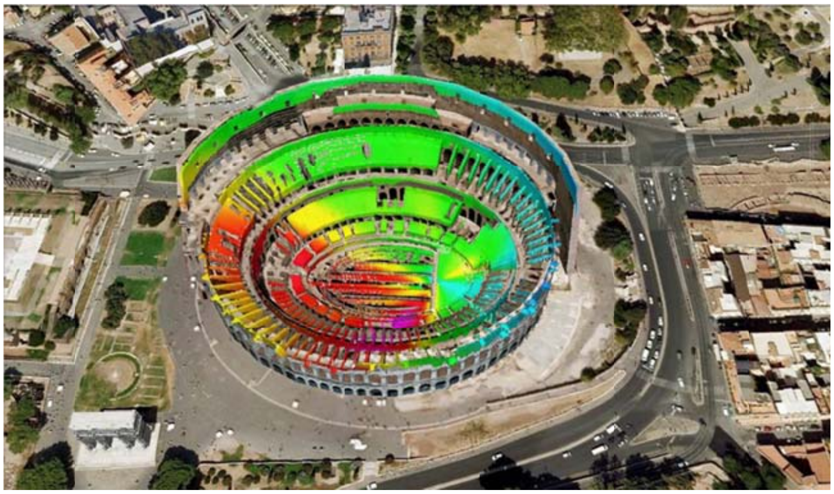


Figure 6 *Measured crowd noise propagated within the Roman Coliseum, representation of the utilization of beamforming techniques within real and virtual environment,* ***Red*** *= high and* ***Blue*** *= low sound pressure levels in dBA.*

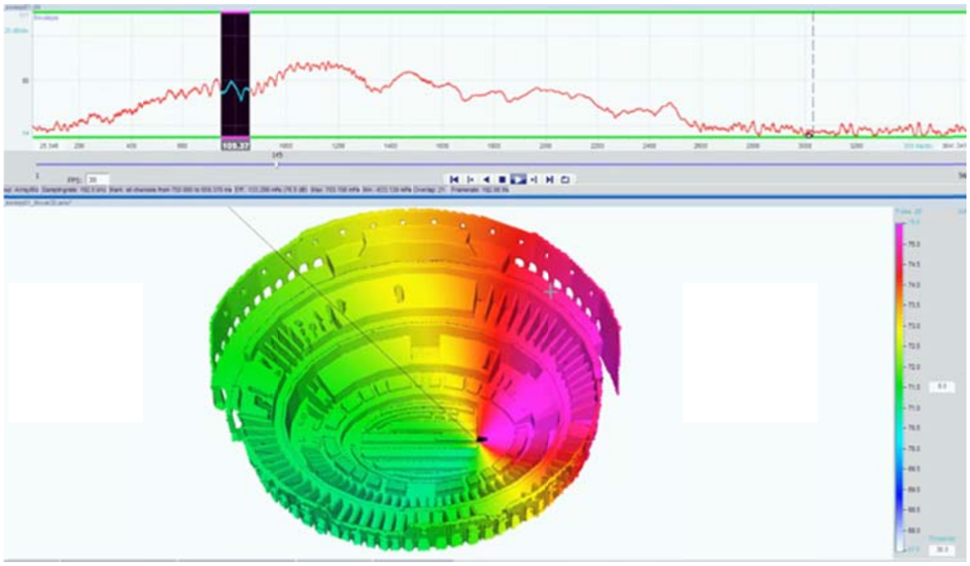


Figure 7: *A time series measured data in the coliseum for a sound generated by Sweeper.*

Figure 8: *Surface characteristics within the current condition of the coliseum*

Sabine's equation for reverberation provides a good index for the sound behavior in a fairly reverberant space with a uniform distribution of absorptive materials **[1-4]**. This is due the Sabine's assumption that the sound decays continuously and smoothly, a scenario that requires a homogenous and diffuse sound field without major variation within the space surface properties. The calculated RTs in **Figure 9** are based on measured data using Sabine's concept and show the impact of open and partially closed roof top based on the historical records. The results show the open roof top has obviously lower RT at lower frequencies. This procedure provided an opportunity to examine variant in material properties and their impact on the acoustic characteristic of the space based on historical.

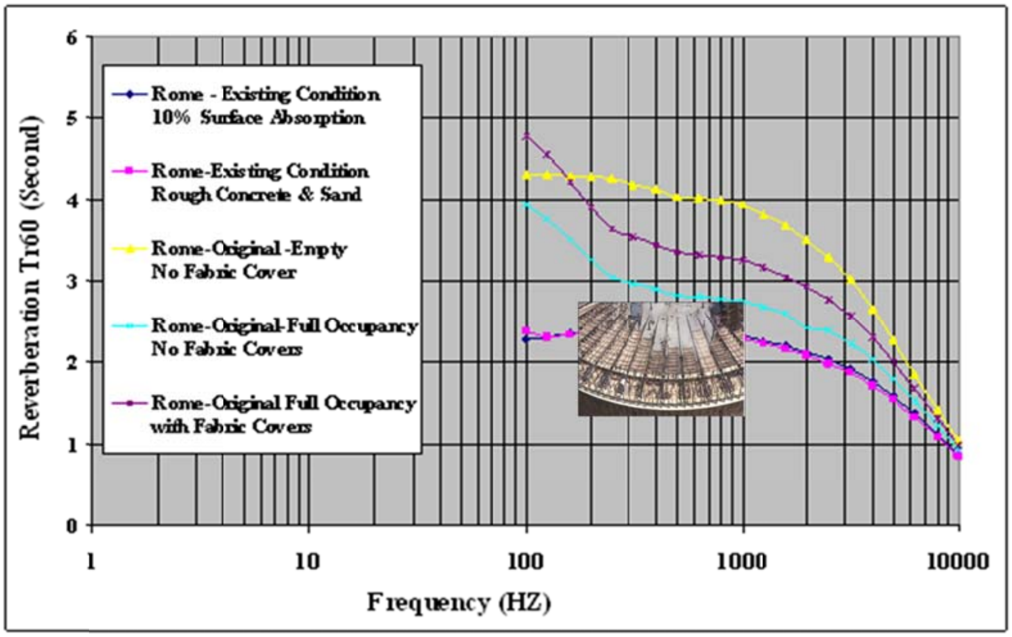


Figure 9: *RTs 60 dBA based on simulation for existing Coliseum and its original conditions with and without the spectators with their roof top cover full open and closed.*

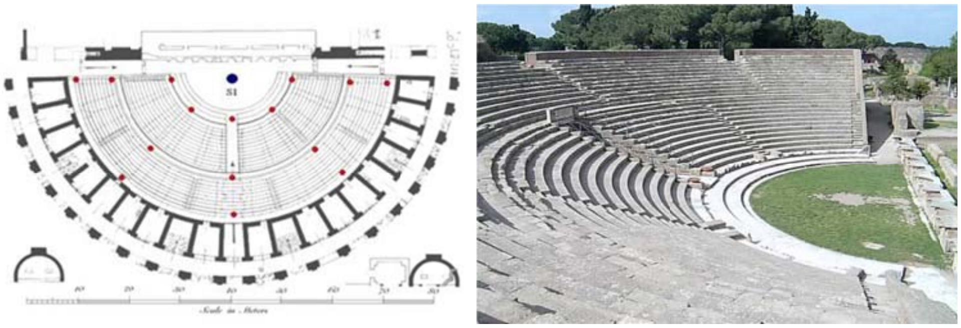


Figura 10. Ostia Antica.

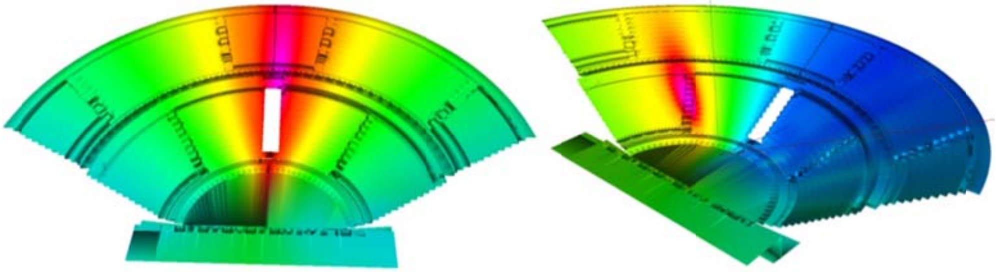


Figure 11. Details of the measurement points and the positions of the source.

Figure 12. Details of the archiutectural elements within *Adriana Villa,* Maritime Theatres*.*

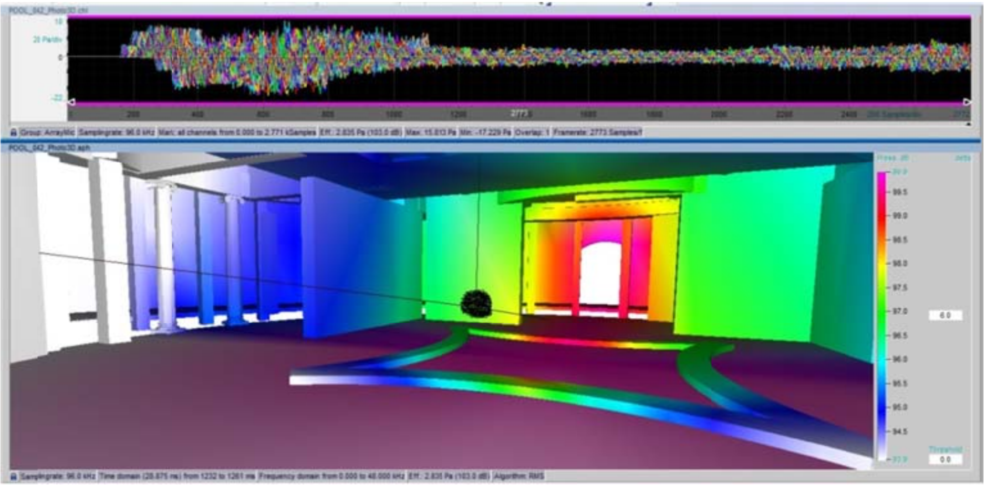


Figure 13. Measured sound distribution within *Adriana Villa,* Maritime Theatres..

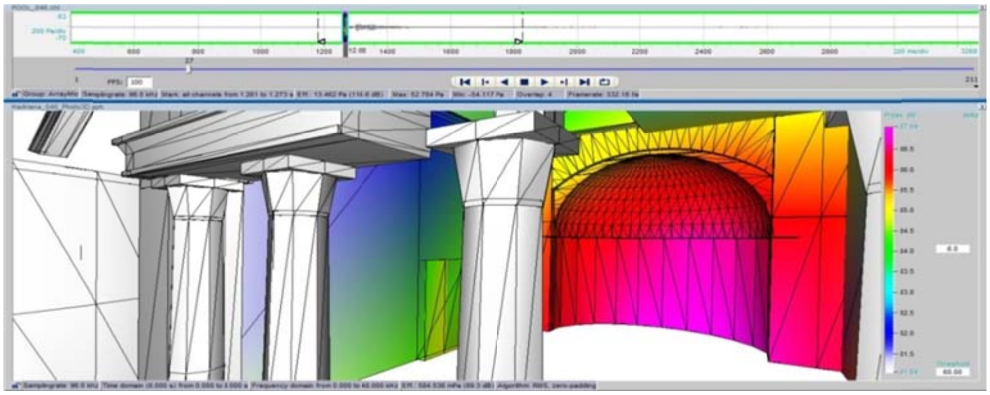


Figure 14. Measured sound distribution within *Adriana Villa,* Hall of Philosophers.

The results presented in **Figures 10 – 16** shows the sound intensity distribution based on the reflected and absorption of the archiutectural elements within Adriana Villa, Maritime Theatre, Hall of Philosophers and the Taormina Theater. These measurements were based on the impulse geneted by bursting larg scale ballons at selected locations to examin teh refeleted compomenets. These results were use to selected the approprate material peroperties to matchj the historical records similrat o the procedure used for Colosium.

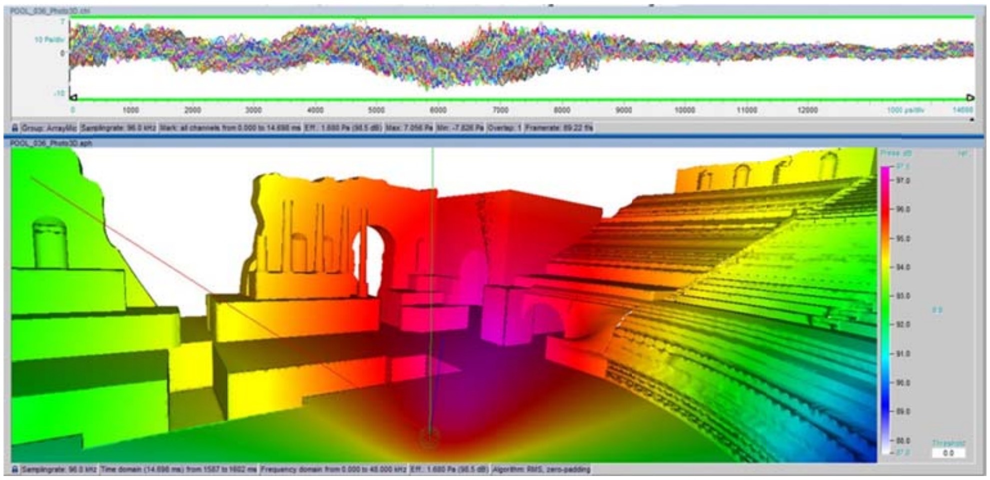


Figure 15. Measured sound distribution within *Taormina Theater*

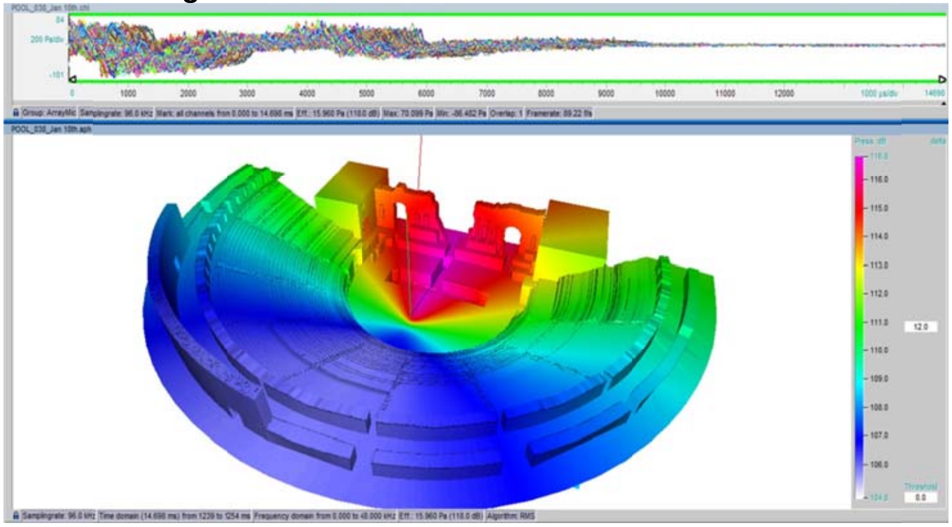
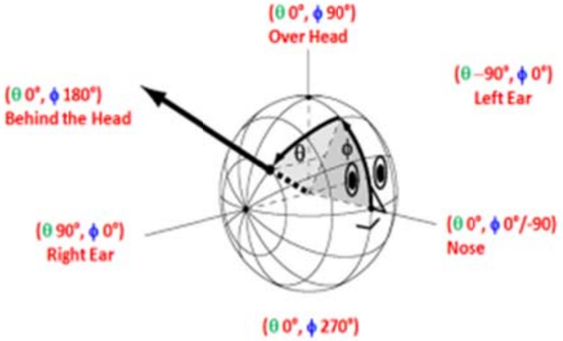


Figure 16. Measured sound distribution within *Taormina Theater*

4.0 CAPTURING SPACE'S SOUND SIGNATURE This section describes the process in obtaining the similar data to HRTF and its conversion to Spatial Frequency Response Surfaces (SFRS) through the format used by MATLAB data files of compensated Head-Related Impulse Response (HRIR) measurements. The HRTF varies with range as well as with azimuth and elevation [11-13]. To better understand its far-range behavior; an algorithm was then developed for computing the variation in sound pressure received at the location by an acoustic camera from all the surfaces of the space as a function of direction and range to the sound source. The impulse response generated from the large size balloon, clapper, yachting cannon or yelling crowd were measured experimentally. The impulse response P is a function of azimuth, elevation and time. In the data files, P is sampled in space and time. The values of azimuth, elevation and time are specified by discrete indices, Naz, Nel and Nt, and P (Naz, Nel, Nt) is a 37 x 73 x 8000 ms (8 seconds limit of fast recording time and needed time for T_{60} reverberations); as a 3-dimensional array. Thus, HRIR values are given for 73 different azimuths, 37 different elevations, and at least 8000 ms instants in time. The azimuth angle 0 and the elevation angle 0 are measured in a head-centered interaural-polar coordinate system **(Figures 17a)**. The azimuth is the angle between a vector to the sound source and the midsaggital or vertical median plane, and varies from -90° to +90°. The elevation is the angle from the horizontal plane to the projection of the source into the midsaggital plane, and varies from -90° to +270°. The following are the coordinates in which the data is reported to a conversion matrix for plotting by Mat Lab. (0°, 0°) corresponds to a point directly ahead, (0°, 90°) corresponds to a point directly overhead , (0°, 180°) corresponds to a point directly behind, (0°, 270°) corresponds to a point directly below, and (90°, 0°) corresponds to a point directly to the right, (-90°, 0°) corresponds to a point directly to the left. This set of data was converted through a matrix and plotted in a 3D form as shown in **Figure 5a** and **5b**. The maximum, minimum and mean plotted data are in color dots.



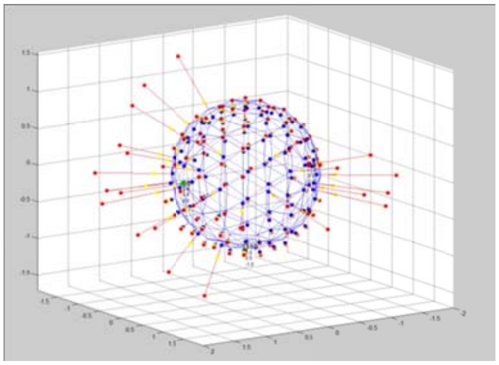


Figure 17a. Schematic view of the inter-aural-polar coordinate system
Figure 17b. Measured data plotted by MATLAB toward creation of HRTF.

The acoustic camera microphone positions were converted to altitude and azimuth and positions uniformly. This angular increment divides the full circle into equal parts in altitude and azimuth, and are used in MATLAB, the elevation angle corresponding to $N_{elevation}$ is the N^{th} element of the P vector elevations = -90 +90 The temporal sampling frequency is fs = 96 kHz. The schematic view of the concept is illustrated in **Figure 18**.

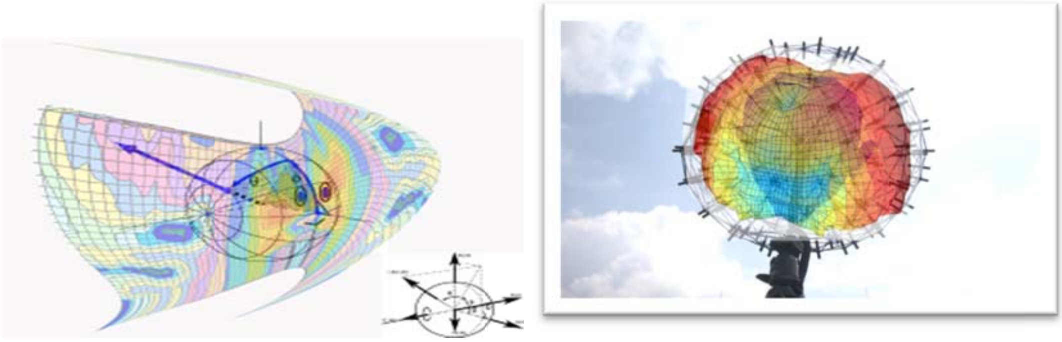


Figure 18. Schematic view of the concept for showing the HRTF as an acoustic signature.

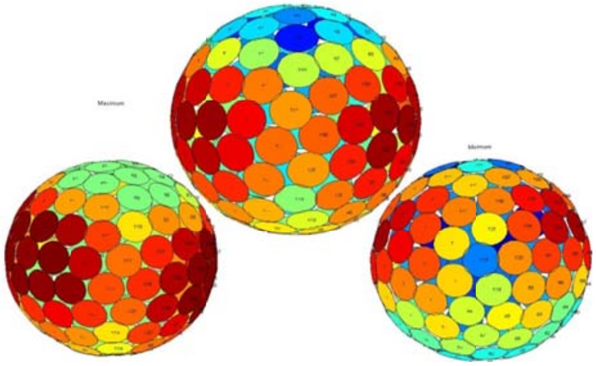


Figure 19. Schematic view of the concept for showing the HRTF Sound intensity for each Mic in the array

Impulse or Crowd Noise Level Leq (dBA re 20μPa)

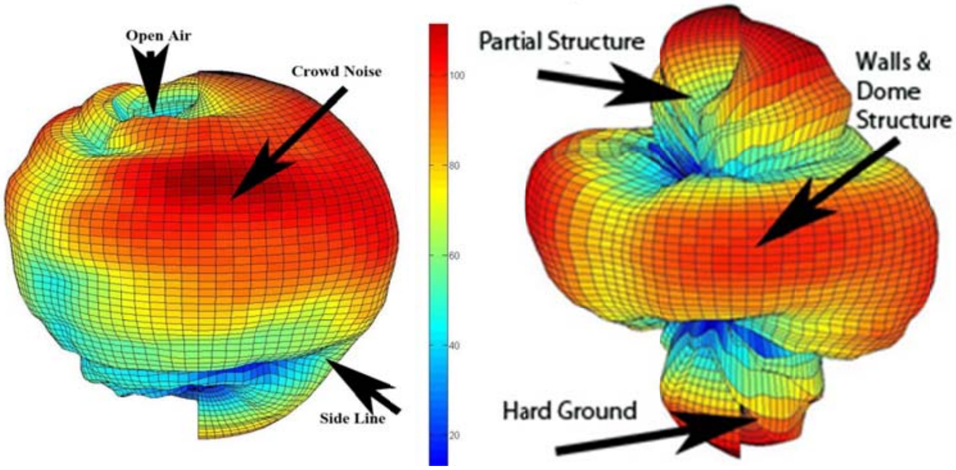


Figure 20 Measured acoustic signature of the Coliseum (Left) and Villa Adrian (Right) based on the HRTF.

Max, Min and Average of the sound intensity levels measured by each Mic in the array are preseneted in the same coordinate within the Acoustic Camera 120 array and translated to the coordinates used for application of HRTF. The results are presented for each mic in **Figure 19** and the interpolated results through a smooth function for total viewing are presented in **Figure 20** (left) which shows the measured acoustic signature of the Coliseum in units of normalized (dBA) including the incoming sound from the crowd and reflected sound from the sky upper level seating/standing areas. There is not much contribution from the surface of the Coliseum soft sand on the arena's ground or lower level cavity where animals were used to be kept given the historical record; however, the Villa Adriana data **Figure 20** (right) shows the sound from the walls and ground hard floor and partial dome structure within the space and the reflection from the partial walls surroundings the sides of the Villa by the Hall of Philosophers are contributing to the total reflections. There are many other possibilities to isolate or highlight the data in terms of source directivity for its reflected components from various architectural elements or crowd noise. This could be clearly demonstrated using the time series data as well as filtering for specific spectral band of frequencies. The authors hope to publish more in depth data analysis in the future from the larger set of examples of surface reflections with high dynamic range of data collection. **Figure 21** shows the proposed general and detail research paths given available methodologies. As; A) How to capture a space sound signature that significantly represents the characteristics of all architectural elements with their contributions to the room acoustics toward their historical preservation. B) How to visualize the audible impact of these elements, and represent these acoustic conditions within a virtual environment for the general public to experience **[14-15].**

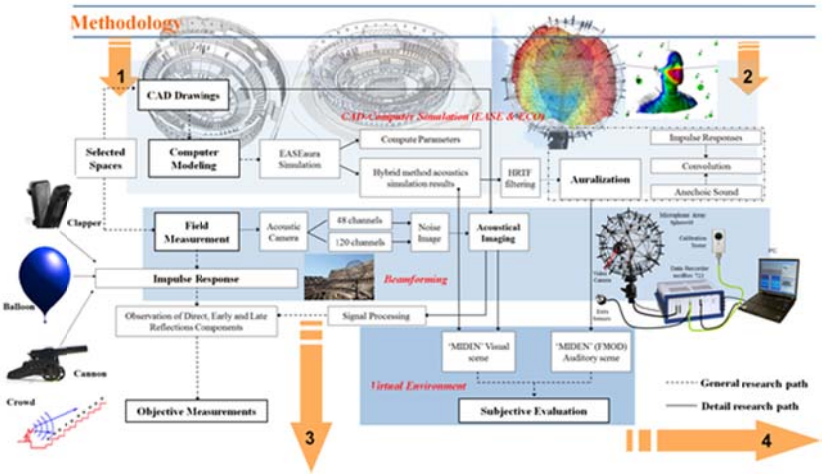


Figure 21. *General and detail research paths given available methodologies.*

5. CONCLUSION

For the historical building, ancient theatres and or arenas, the reverberation time is one method of determining acceptable room acoustic conditions. The Coliseum, Ostia and Taormina theatres sound conditions with open-air as compared to partially enclosed spaces in Villa Adriana are difficult to understand without the contribution of each surface and their directionality. Reducing the unwanted sound, the echoes and reverberation requires designers to shape and or treat building surfaces. Hard, smooth objects reflect sound similar to light. Change of surface angles and absorption characteristic within computer simulation allow observing the sound behaviour as to its reflection and direction.

The proposed method in measuring the incoming sound from all directions allows matching the HRTF format and to capture a space unique room acoustic characteristics as its sound signature that significantly represents the characteristics of all architectural elements and the amount of their contributions to the space. This room acoustics signature contributes toward better understanding of specific contribution from each architectural elements, thus their reproduction for their unique room acoustic condition though aurulization. It is important for designers and cultural heritage reserchers to visualize the estimated audible impact of these elements at a given time to study historical record more carefully. This capability and its application in a virtual environment for the general public to experience the sound as close to a real condition as possible are under investigation. Although these outdoor thears are not the same as a concert hall, the required architectural elements in size and geometry to solve the sound reflections in the low frequency range and utilizing the diffused sound simultanouly remain a major challenge in architectural acoustic design, and moreover present a unique demand in recording such effects or the total impact of low frequency sound energy.

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