MIMO Technique applied to the Greek Theatre of Tyndari

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ABSTRACT

Spatial Multiple Input Multiple Output (MIMO) is an innovative technique developed to provide an appropriate filter array required to virtually reconstruct the perceived sound field at the listener's position, generated by a sound source with arbitrary and time-varying directivity. This is particularly useful when the sound source has a complex directivity pattern (e.g. the human voice or specific musical instruments). To mimic the directivity of a real sound source, a "DodecMIMO" was developed. This prototype loudspeaker is capable of simulating the directivity of any dynamic sound source as well as a standard omnidirectional sound source. Prior to field applications, the sound source was measured in an anechoic chamber to obtain its acoustic characterization. The first on-site application took place in the Greek-Roman theatre of Tyndaris (Sicily, Italy). The measured impulse responses (IRs) were analyzed and compared with previous acoustic studies performed with omnidirectional sound sources. The outcomes were used to compute the acoustic maps for each measuring point by overlapping the panoramic image acquired at each position with the acoustic response recorded by the microphone. This innovative technique is very well suited to create a virtual 3D audio reproduction, technically called auralization, which can faithfully reproduce a complex real sound source.

Keywords: *MIMO technique, auralization, sound map.*

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1. INTRODUCTION

The theatre of Tyndaris (Sicily, Italy) has been the focus of numerous studies: from the study of its reuse as performance space [1], [2] to the simulation and auralization of the ancient structure of the theater [3] or the study of the sound absorption coefficient of the main materials composing the theater [4].

This paper deals with the measurement of the traditional acoustical parameters [5] and the auralization of the ancient Greek-Roman theatre of Tyndari (Sicily, Italy) by using the innovative spatial Multiple Input Multiple Output (MIMO) technique [6]–[8]. The spatial MIMO technique to measure impulse responses employing spherical transducers was first presented by Farina and Chiesi in [7] and a previous version by Farina et al. in [6] working up to the 1st order of spherical harmonics. In practice, both the sound source and the receiver are arrays of transducers. Specifically, the sound source used in this work is composed of 12 loudspeakers organized on a sphere ("DodecMIMO"), in which each loudspeaker can be controlled independently. This makes it possible to simulate any dynamic sound source. The receiver is a spherical microphone array composed of 32 microphones capsules, the "Eigenmike EM32" [9].

For both, sound source and microphone array, are available matrices describing their spatial acoustic behavior.

After the processing of the measurement results, the impulse responses (IRs) were analyzed and compared with previous acoustic studies performed in the same theater with omnidirectional sound sources [2]. Also, the traditional acoustic parameters have been calculated and compared. Then, acoustic maps have been computed through the use of a panoramic 360° camera coupled with the post-processing of the microphone signals.

The paper is organized as follows: after this introduction, the historical background and the architectural organization of the theater are presented in section 2. Section 3 is dedicated to the MIMO theory, while the "DodecMIMO" sound source is described in section 4. Sections 5 and 6 present the measurements and the results. Finally, section 7 is dedicated to the conclusions.

2. FRAMEWORK OF THE CASE STUDY

The theatre of Tyndaris, located on a promontory on the northern coast of Sicily, Italy, has undergone significant changes throughout its history. The original Greek configuration, built in the 4th century BC, had a total capacity of 3000 people and did not have a scenic building (also called skené, the structure at the back of a stage used as backdrop [10]). During the Hellenistic period (323 BC – 30 BC), a scenic building was introduced, providing strong sound reflections thanks to the high reflectivity of the sandstone block it was made of. The reconstruction of the skené represents one of the most significant documents of the architecture of scenic buildings before the Roman imperial age [11]. The Roman configuration (22-21 BC) involved the adaptation of the performing arts space to an arena, resulting in the lowering of the Greek orchestra by 0.9 m and the destruction of the first four rows of steps. The logeion, the high stage used by actors located behind the orchestra and before the skené, was completely destroyed, and its stone blocks were reused for the construction of the podium. Thereafter the city of Tyndaris was abandoned after the conquest by the Arabs in the 9^{th} century AD and the theatre fell into disuse; the scenic building was destroyed by an earthquake and the cavea (the seating section) deformed by landslide. It was brought to light with archaeological excavations during the twentieth century (between 1960 and 1998) and later wooden seats were added to accommodate the public again without damaging the remains of the cavea. Today, the absence of a scenic building and the deterioration of the stone as finish material of the cavea have led to a noticeable change in the acoustics of the theatre. It is currently used for live concerts during summer seasons with a maximum capacity of 900 seats.

3. MIMO THEORY

The technique for environmental acoustic measurements called MIMO has been presented by Farina and Chiesi in their paper [7]. It is a technique that presents a spatial approach to the measurement of acoustics impulse response and involves the use of multichannel sources and receivers, typically spherical arrays, in which the various channels are all independent of each other. The main advantage of this technique is that there is complete spatial control of the sound field generated in the room where the impulse response is measured, being able to control the direction of emission of the test signal. Using the same hardware, this technique enables the creation of omnidirectional sources as well as sources with the directivity of the human voice or of a musical instrument. Also, recording with a microphone array it is possible to trace the sound path between source and receiver, showing where each reflection occurs. In the present case, as mentioned in the previous section, a 12-channel sound source (DodecMIMO) and a 32-channel microphone array (Eigenmike EM32) were used.

As widely discussed in [6], [7], at the end of the measurement for each Source-Receiver pair, after the convolution of the recorded signals with the inverse sine sweep and a proper time windowing, a full MIMO matrix is obtained. In Eqn. (1) the MIMO matrix is shown. This matrix has a size S×M, where S is the number of speakers and M the number of microphones (12 and 32 respectively in the case under study).

$$\|\overset{S\times M}{IR_{MIMO}}[n]\| = \begin{bmatrix} ir_{1,1} & ir_{1,2} & \cdots & ir_{1,m} & \cdots & ir_{1,M} \\ ir_{2,1} & ir_{2,2} & \cdots & ir_{2,m} & \cdots & ir_{2,M} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ ir_{s,1} & ir_{s,2} & \cdots & ir_{s,m} & \cdots & ir_{s,M} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ ir_{S,1} & ir_{S,2} & \cdots & ir_{S,m} & \cdots & ir_{S,M} \end{bmatrix} \quad (1)$$

Thus, applying appropriate beamforming filters for both the source ($\|h_S\|$) and the receiver ($\|h_M\|$), it is possible to obtain a new matrix capable of providing a set of specific directivities for both the source and the receiver. The structure of the $IR_{MIMO\text{-}BF}$ matrix is represented in Eqn. (2).

$$\|\overset{S\times M}{IR_{MIMO-BF}}[n]\| = \|\overset{W\times S}{h_S}[n]\| * \|\overset{S\times M}{IR_{MIMO}}[n]\| * \|\overset{M\times V}{h_M}[n]\| \quad (2)$$

Furthermore, the use of a Plogue Bidule (DAW) [12] and appropriate convolution VST plug-ins allowed the definition of nine High Order Ambisonics (HOA) MIMO IR matrix to be used for the purposes described in section 6.

4. MIMO SOUND SOURCE

For the execution of measurements using the MIMO technique, a special new sound source, named "DodecMIMO" (Fig. 1), was developed in the laboratories of the University of Parma (UNIPR). It is based on a modified version of the dodecahedral sound source Kit 103 produced by Look Line Srl [13]. Unlike the commercial version, in this source each of the 12 loudspeakers that make it up is controlled separately and is connected to a specific amplifier channel.

Figure 1. "DodecMIMO" sound source.

In order to get the acoustic characterization of the sound source, and the beamforming filter matrix $||h_S||$, "DodecMIMO" was mounted on a turntable and measured in the laboratory of UNIPR. The measurement process of the sound source is the same as that already described in [7] section 3. To measure the 12 impulse responses of the loudspeakers that compose the source, it has been mounted on a two-axes rotating table and measured in 362 different azimuth and elevation configurations. Measurements showed a very good response up to 2000 Hz, above that frequency the directivity degrades as depicted in the following figures (Fig. 2, Fig. 3, and Fig. 4). Specifically, in the following figures the frequency response and phase in the direction of maximum directivity, and XY plane and polar patterns are shown. In Fig. 2 the centered octagon layout is shown, while in Fig. 3 and Fig. 4 the W and Y Ambisonics components are shown.

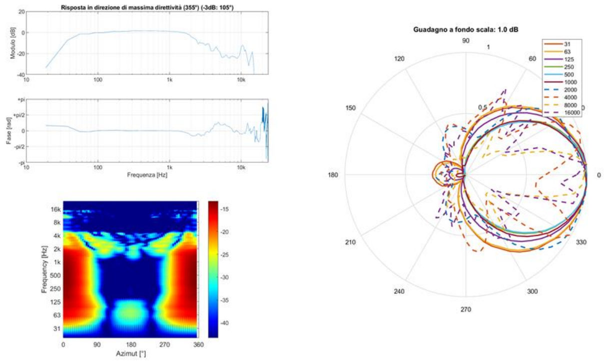

Figure 2. "DodecMIMO" frequency response, XY plane and polar patterns: "Centered octagon".

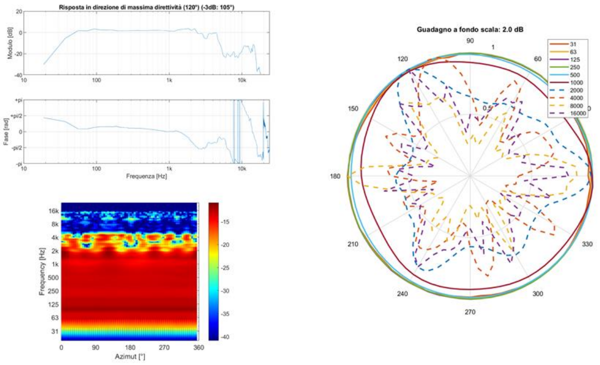

Figure 3. "DodecMIMO" frequency response, XY plane and polar patterns: W Ambisonics component.

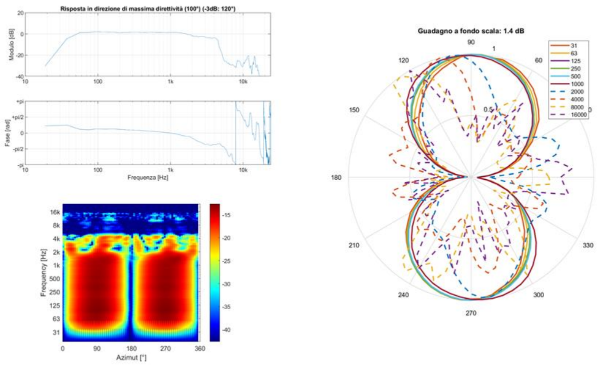

Figure 4. "DodecMIMO" frequency response and directivity patterns: Y Ambisonics component.

5. MEASUREMENTS

5.1 Description

A working group from the Politecnico di Torino had already carried out acoustic measurements in the Tyndari theatre in 2015 [2]. The purpose of this new measurement campaign, conducted in 2022, was twofold. Firstly, to validate the use of the MIMO technique to obtain high order Ambisonics (HOA) MIMO IR matrices, essential to perform an advanced real-time auralization and acoustic reconstruction of the theatre (Past Has Ears project [14], [15]). Secondly, to compare acoustic parameters measured in 2015 using traditional technique, with values obtained using the innovative MIMO one.

5.2 Position

The positions chosen for the measurements were the same as those used in the 2015 measurement campaign. The sound source was placed, at the height of 1.5 m, in two different positions (S1 and S2) in the "orchestra". Furthermore, the receivers were installed, at the height of 1.2 m, in nine different positions (R1÷R9) located in the "cavea" (center and left area). Source and receiver positions are depicted in Fig. 5.
An important aspect of using the MIMO technique is the reference system chosen for both transducers, sound source and microphone array, which must be the same.
In the case under consideration, the X-axis, associated with speaker No. 1 and microphone No. 1 were both pointing towards the skené of the theatre.

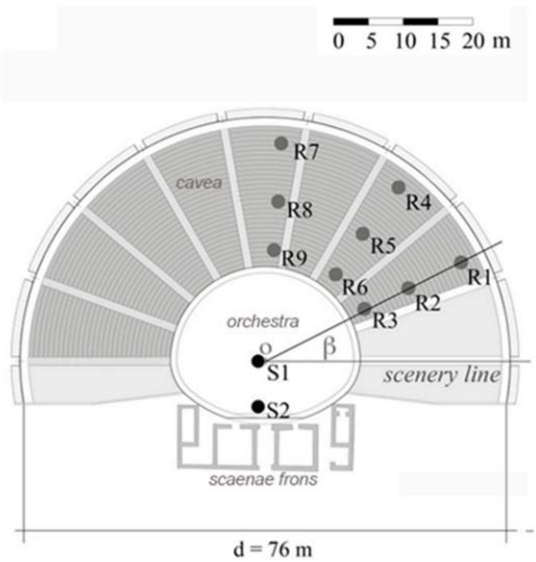

Figure 5. Source and receiver positions during the acoustic measurements.

5.3 Instrumentation setup and chain

The measurements were performed by using the following equipment:

- "DodecMIMO" modified version of dodecahedral sound source "Model Kit103" (12-channels) (by Look Line & E. Armelloni);
- 32-channel spherical microphone array (EM32 Eigenmike®) and EMIB audio interface with MADI interface;
- RME Digiface Dante audio interface with USB, Dante and MADI connectivity;
- 32-channel Class-D audio amplifier with Dante interface (by N. Rocchi – UNIPR);
- 360° camera (Ricoh Theta V);
- Personal Computer.

The RME Digiface Dante, connected to the laptop via USB interface, allowed synchronism between the signals reproduced through the sound source "DodecMIMO" and those acquired with the spherical microphone array EM32.
An important aspect was the use of the digital amplifier with Dante interface, designed and built at the UNIPR laboratories by engineer N. Rocchi during his PhD. During the measurements, only 12 of its 32 channels were used to amplify the signals for "DodecMIMO". In Fig. 6 the measurement chain is shown.
The excitation signal emitted by the sound source was the Exponential Sine Sweep (ESS) [16], [17] having a duration of 20 s in a uniform sound pressure level for the range between 22 Hz and 20 kHz. Measurements, conducted in unoccupied condition and without any scenery, were repeated for each of the Source (S1÷S2) - Receiver (R1÷R9) pairs.

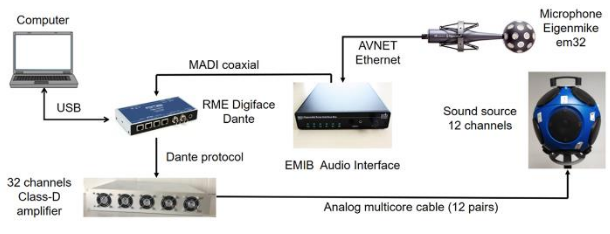

Figure 6. Setting of the measurement chain.

6. RESULTS

6.1 Traditional acoustic parameters

The HOA Ambisonics versions of the IRs were processed and analyzed by Aurora plugins developed for Adobe

Audition software, in according with the specification of international standard ISO 3382 [5], [18].

Figure 7. Example of measurement: sound source in position S1 and receiver in position R3.

In order to obtain correct signals to estimate binaural parameters the pointing direction of the microphone was “artificially” rotated, using a special VST plugin (SceneRotator by IEM [19]), towards the emitting sound sources. Thus, a pair of binaural signals was decoded from the rotated HOA signals using BinauralDecoder plugin by IEM. Tab. 1 reports calculated monaural and binaural parameters in the octave bands 125 Hz - 4000 Hz considered as the average results over all measured Source-Receiver pair.

Graphical versions of the principal monaural parameters are depicted in the following Fig. 8 ÷ Fig. 11 in which averaged values are calculated over all receiver positions with respect to S1, S2 and both sources.

Table 1. Summary table of measured acoustic parameters.

	Freq. [Hz]					
	125	**250**	**500**	**1000**	**2000**	**4000**
C50 [dB]	8.4	12.7	14.3	13.2	10.4	11.9
C80 [dB]	14.7	17.3	20.3	17.7	15.6	16.3
D50 [%]	86.3	94.3	95.8	94.7	91.0	93.2
ts [ms]	34.8	16.5	12.4	11.5	15.1	11.2
EDT [s]	0.4	0.2	0.1	0.2	0.5	0.4
Tuser [s]	0.4	0.5	0.4	0.4	0.5	0.5
T20 [s]	0.5	0.6	0.5	0.6	0.6	0.7
T30 [s]	0.6	0.5	0.5	0.6	0.6	0.7
Jlf	0.1	0.0	0.1	0.1	0.1	0.0
Jlfc	0.2	0.1	0.1	0.1	0.1	0.1
Lj [dB]	-10.2	-7.4	-5.1	-0.9	0.2	-3.7
IACC (Early)	0.98	0.96	0.90	0.78	0.72	0.83
Tau IACC (ms)	0.02	0.01	0.01	-0.03	-0.01	0.00
w IACC (ms)	1.22	0.50	0.30	0.16	0.10	0.06

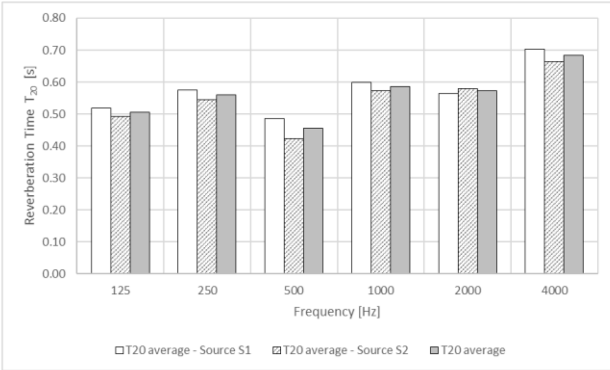

Figure 8. Measured results of Reverberation Time T_{20}.

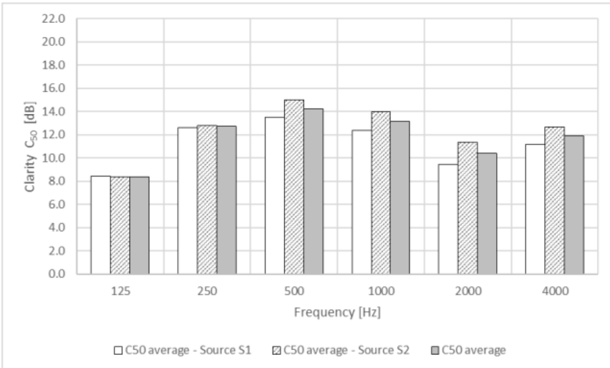

Figure 9. Measured results of Clarity C_{50}.

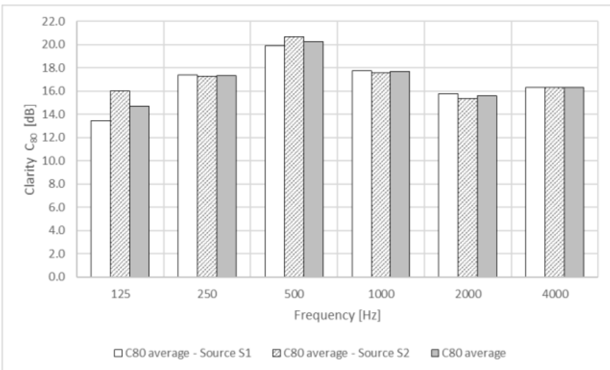

Figure 10. Measured results of Clarity C_{80}.

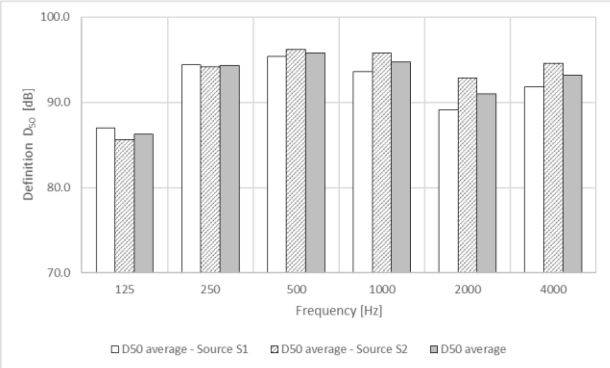

Figure 11. Measured results of Definition D_{50}.

An important comparison can be made with the result obtained in the previous study in 2015. Considering different techniques of measurement (traditional vs MIMO), different theatre configurations (presence of seats and platform in 2015 and their absence in 2022), and, finally, weather differences that certainly influenced the outdoor measurements, a substantial coincidence was obtained between the monaural acoustic parameters measured in the two different campaigns.

The following summary Table 2 shows the comparison of mean values of the parameters T_{20}, C_{50} and C_{80}. Data are referred to the averages of 500 Hz and 1 kHz octave bands. Certainly, the absence of the wooden platform in the performance area affected the reverberation time which appears to be slightly lower than that measured in 2015 in all source-receiver positions. Furthermore, the C_{50} and C_{80} parameters also appear to be slightly different from the previous measurement campaign while remaining comparable.

6.2 Auralization

The auralization of a singer placed in S1 position in the "orchestra" singing by turning her head was carried out using the spatial matrix of the theatre impulse response ($\|IR_{MIMO}\|$), together with beamforming matrices of the "DodecMIMO" ($\|h_S\|$, measured) and of the microphone ($\|h_M\|$, provided by the manufacturer of Eigenmike EM32). In the auralized binaural tracks for various positions in the cavea the effect of the singer's rotation can be appreciated. Binaural audio tracks are available at this link: https://doi.org/10.5281/zenodo.7930580

6.3 Sound maps

The use of the MIMO technique also allows an innovative analysis of the acoustic behavior of the theatre whenever the sound source, having its own directivity, rotates on stage.
In the present case, the 32 signals coming from the spherical microphone array were processed using the Plogue Bidule software and VST plug-ins (SPARTA Suite) developed by AALTO University [20], synthesizing 64 virtual microphones equally distributed on a sphere. Then, using a panoramic image captured by a 360° camera as a background, it was possible to create a dynamic map of the "Level of spatial power density" [dB/sr] of the impulse response of the theatre with different pointing directions of the "DodecMIMO" source.
The software was developed by the start-up company TTRED Srl [21].
This analysis makes it possible to map the energy coming from various directions and thus to identify the contribution of high-energy reflections within the theatre. In the maps, red and warm colors represent the sound waves having more energy and the blue-violet colors characterize poor sound energy.

Table 2. Comparison for mean values of the T_{20}, C_{50}, C_{80} measured with MIMO and traditional technique.

		S1	S1	S1	S1	S2	S2	S2	S2
Acoustical Parameter	Technique	Mean First Row (R3, R6, R9)	Mean Central Row (R2, R5, R8)	Mean Last Row (R1, R4, R7)	Mean Overall	Mean First Row (R3, R6, R9)	Mean Central Row (R2, R5, R8)	Mean Last Row (R1, R4, R7)	Mean Overall
T_{20} [s]	MIMO (2022)	0.50	0.58	0.54	0.54	0.47	0.49	0.50	0.49
	Traditional (2015)	0.54	0.59	0.59	0.57	0.52	0.50	0.50	0.51
C_{50} [dB]	MIMO (2022)	10.9	14.7	13.2	12.9	13.1	13.9	14.9	14.0
	Traditional (2015)	12.1	12.6	12.1	12.3	11.8	13.7	12.8	12.8
C_{80} [dB]	MIMO (2022)	18.6	19.5	18.4	18.8	19.0	18.7	19.2	19.0
	Traditional (2015)	18.0	17.2	17.0	17.4	17.4	18.4	17.6	17.8

The following figures show the sound map of the receiver in position R2. In particular, in Fig. 12 the source is directed towards the skené and therefore the first reflection is very strong and takes place in the time slot 0.03475 - 0.03575 seconds after the direct sound. While in Fig. 13, in the same time slot, there is no reflection because the source is directed towards the cavea. This demonstrates that even if the skené is partially destroyed it produces a strong reflection that can be clearly perceived in the cavea.

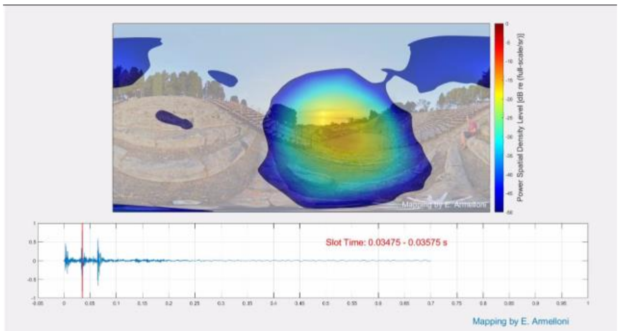

Figure 12. Acoustical map showing the energy of first reflection, source S1 is directed towards the skené.

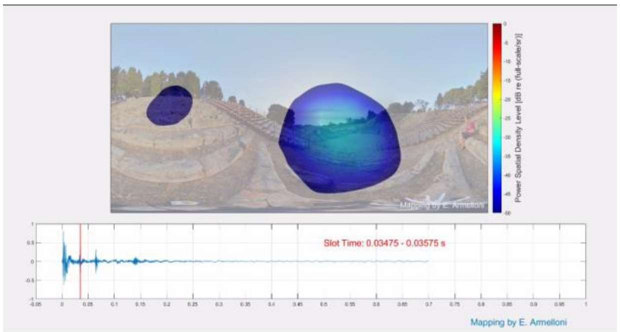

Figure 13. Acoustical map showing the energy of first reflection, source S1 is directed towards the cavea.

7. CONCLUSIONS

This paper presents the application of the MIMO measurement technique to the acoustic characterization of the Greek Theatre of Tyndari (Sicily). In the measurements, conducted in June 2022, the new sound source called DodecMIMO, specially developed at the laboratories of the University of Parma, was used. The measurements were carried out by choosing the Source and Receiver positions already used in the measurements with traditional techniques carried out in 2015 by the Politecnico di Torino.
As far as the acoustic parameters are concerned, the results obtained with the MIMO technique were substantially comparable to those obtained with the traditional technique, despite the fact that the set-up of the theatre was slightly different, as were probably the weather conditions.
Thanks to the MIMO technique, it was possible to perform advanced auralization, in which a good correlation between the singer's actual and perceived pointing position could be appreciated. Binaural audio tracks are available at this link: https://doi.org/10.5281/zenodo.7930580.
In addition, it was also possible to investigate and create sound maps of the acoustic behavior of the theatre (e.g. reflections) as a function of the directivity and pointing direction of the source.

8. ACKNOWLEDGEMENTS

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