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MEASUREMENT OF ROOM ACOUSTIC PARAMETERS WITH AN OMNIDIRECTIONAL PARAMETRIC LOUDSPEAKER IN AN CONVERTED CHAPEL FOR CHORAL MUSIC PERFORMANCE

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ABSTRACT

An omnidirectional parametric loudspeaker (OPL) is a sound source made of hundreds of ultrasonic transducers arranged in a spherical configuration. Each transducer emits ultrasonic waves and, due to the nonlinear effects of air, these waves generate audible sound within the ultrasonic beam. Compared to a dodecahedron loudspeaker, the OPL offers improved omnidirectionality, although it operates at lower sound pressure levels (SPLs). Exponential sine sweeps have shown to be very effective with this new type of loudspeaker, which opens the door to using it in some acoustic tests. This paper explores the performance of the OPL in measuring room acoustic parameters, such as reverberation time, early decay time, definition and clarity. The case study selected is the Pere Pruna Civic Center in Barcelona. Originally built as a single-nave chapel in the early 20th century, the building was restored and converted for civic use in the late 20th century. It is currently used mainly for choral music, with a capacity for about 80 people. Acoustic measurements were conducted according to ISO 3382-1 using the OPL and a commercial dodecahedron loudspeaker. The results show that the OPL performs well in mid and high frequencies, although it requires higher SPLs at low frequencies.

Keywords: *parametric acoustic array, omnidirectional parametric loudspeaker, room acoustic parameters, church acoustics.*

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1. INTRODUCTION

An omnidirectional parametric loudspeaker (OPL) is a novel omnidirectional sound source with hundreds of ultrasonic transducers placed in a spherical configuration. Unlike conventional loudspeakers, the OPL generates audible sound through the nonlinear interaction of ultrasonic waves in the air, a phenomenon known as the parametric acoustic array (PAA) [1]. Parametric Acoustic Loudspeakers (PALs) have traditionally been employed to create highly focused audible sound beams [2–7]. In contrast, the OPL achieves an omnidirectional sound field due to the spherical distribution of its transducers. Compared to a conventional dodecahedral loudspeaker, the OPL maintains omnidirectionality over a wider frequency range thanks to its high transducer density — 750 in the prototype described in [8]. This feature is particularly beneficial at high frequencies, where standard dodecahedral loudspeakers tend to lose their omnidirectionality as their drivers become increasingly directional [9]. However, a key limitation of the OPL is its lower sound pressure levels, which may constrain its applicability in room acoustics.

Recent studies have shown that exponential sine sweeps (ESS) can significantly improve OPL performance by concentrating energy at specific frequencies, thus helping to trigger the nonlinear effect in the air needed to generate the audible field [9, 10]. The OPL has been successfully applied to measure reverberation time and the sound absorption coefficient of material samples in a reverberation chamber [11], showing promising results even at low frequencies. However, its potential for measuring room acoustic parameters in real-world spaces remains still unexplored.

The goal of this study is to evaluate the feasibility of the OPL to perform room acoustics measurements, focusing on key parameters such as reverberation time, early decay time, central time, definition, and clarity. As a case study, acoustical measurements are conducted at the Pere Pruna Civic Center in Barcelona, a public facility in the district of Sarrià-Sant Gervasi. The center is housed in the former Chapel of the Mothers of Reparation, which retains the decorative artwork of the painter Pere Pruna. Originally built as a chapel in the early 20th century and later repurposed for civic and musical events, this venue provides an ideal setting for assessing the OPL's performance due to its moderate volume and high reverberation time. Measurements were conducted in accordance with ISO 3382-1 [12], and the results were compared to those obtained using a standard dodecahedral loudspeaker.

The paper is structured as follows. Section 2 presents the methodology followed in this work, introducing first the Pere Pruna Civic Center and then describing the measurement campaign. The results of the room acoustic parameters measured with the OPL are shown in Section 3 and compared with those obtained with a commercial dodechaedron loudspeaker. The conclusions close the article in Section 4.

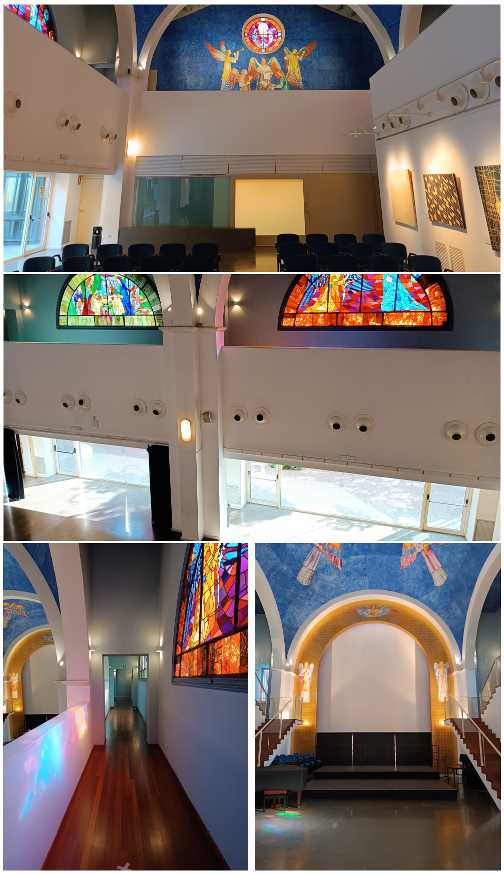

Figure 1. Images of Pere Pruna Civic Center.

2. METHODOLOGY

2.1 Pere Pruna civic center

The Pere Pruna Civic Center (see Figure 1) is a public facility located in the Sarrià-Sant Gervasi district of Barcelona, Spain. Originally built in 1928, it served as a chapel for the Mares Reparadores convent, which had been established in 1904. Designed by architect Enric Sagnier, the chapel underwent restoration under his supervision following the Spanish Civil War. Its architectural layout features a single nave with vaulted segments and a semicircular apse. Notable elements include its stained glass windows and the frescoes painted by Pere Pruna between 1952 and 1954. In 1970, the convent was sold and subsequently demolished, though the chapel remained and was transferred to the ownership of the City Council. After being closed for an extended period, it was renovated in 1998 and integrated into the city's civic center network, now bearing the name Pere Pruna.

Today, the building serves as a cultural facility that hosts music performances, art exhibitions, and community activities. Throughout the rehabilitation process, significant interventions were concentrated on the lower floor, such as the installation of light brick walls for contemporary art displays, a modest stage for performances and conferences, and an intermediate floor connecting the side aisles, which allows visitors to traverse the entire space. However, utmost care was taken to preserve the original layout of the church, including its external facade and the frescoed chapels.

The Pere Pruna Hall is designed as a typical rectangular shoebox space. Its large central nave hosts the audience seating, while the music stage is positioned to one side. The design includes architectural pillars and open spaces that form two smaller side aisles on an intermediate level, which is accessible by staircases near

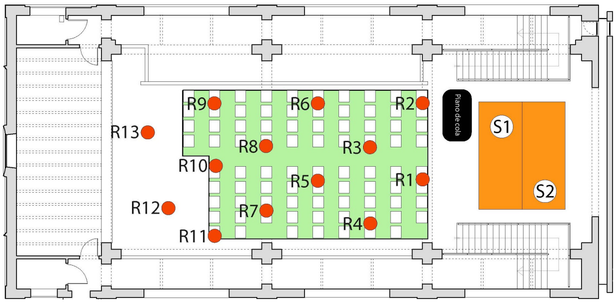

Figure 2. Map of Pere Pruna civic center with the locations of the sources ($S_i, i = 1, 2$) an receivers ($R_j, j = 1, 2, \ldots 13$). The orange color indicates the stage, while the green color delimits the audience area.

the stage. Despite its modern repurposed, the room retains many original features, such as high reflective walls, a vaulted and painted ceiling, and expansive stained glass windows. From an acoustic standpoint, the hall has remained largely untreated and unchanged, apart from the addition of a partial curtain and small speakers positioned alongside the audience. Notably, the total volume of the hall is approximately 2600 m^3, while the audience area measures 74 m^2, resulting in a volume-to-surface area ratio V/S_A = 35 m, slightly bigger than typical values for chamber music halls [13].

2.2 Acoustical measurements

On 10 February 2023, in situ acoustic measurements were performed in accordance with the ISO 3382-1 standards [12]. The aim was to determine monaural time parameters that characterize the hall's acoustic properties from the listener's perspective and to compare the performance of the conventional dodecahedral loudspeaker with the new Omnidirectional Parametric Loudspeaker (OPL). The hall has been set up in its typical configuration for concerts or conferences, with chairs in their usual positions, and all curtains left open. All doors were kept closed to prevent sound leakage.

Figure 2 shows the map with all source and receiving positions. A total of 13 receiver positions were established within the audience area. Two distinct sound source positions were defined on the stage: one at the front (aligned with the strings or piano area) and one at the rear (coinciding with the percussion and wind section). While 13 receiver positions for each of the two source locations would

(a)

(b)

Figure 3. Measurement campaign: (a) the omnidirectional parametric loudspeaker (OPL) facing the audience area, and (b) the dodecahedral loudspeaker and the OPL positioned on the stage of the Pere Pruna Civic Center.

nominally yield 26 measurements, the use of two distinct sound sources resulted in a cumulative total of 52 measurements.

The measurement equipment included a CESVA/BP012 dodecahedron loudspeaker and the OPL [8] as sound sources (see Figure 3). Two 1/2" random incidence GRAS 46AQ microphones were connected to a Brüel & Kjær NEXUS 2690-A-0F2 microphone conditioner and then routed through a DT9847 audio interface controlled by a computer. To obtain the 60 impulse responses, the exponential sine sweep (ESS) method was used [14], following the methodology detailed in [9, 10] for the OPL. The ESS was generated in Matlab from 20 Hz to 14 kHz. A linear fade-in from 20 Hz to 80 Hz and a linear fadeout from 12 kHz to 14 kHz were applied to the ESS to reduce preringing artifacts [15]. Each sweep lasted 30 seconds for the dodecahedron (with two repetitions for each position), and 50 seconds for the OPL. An additional 10 seconds of silence was added for capturing the tail of the impulse response. The ESS was amplified with an ECLER XPA3000 and then driven to the sound source.

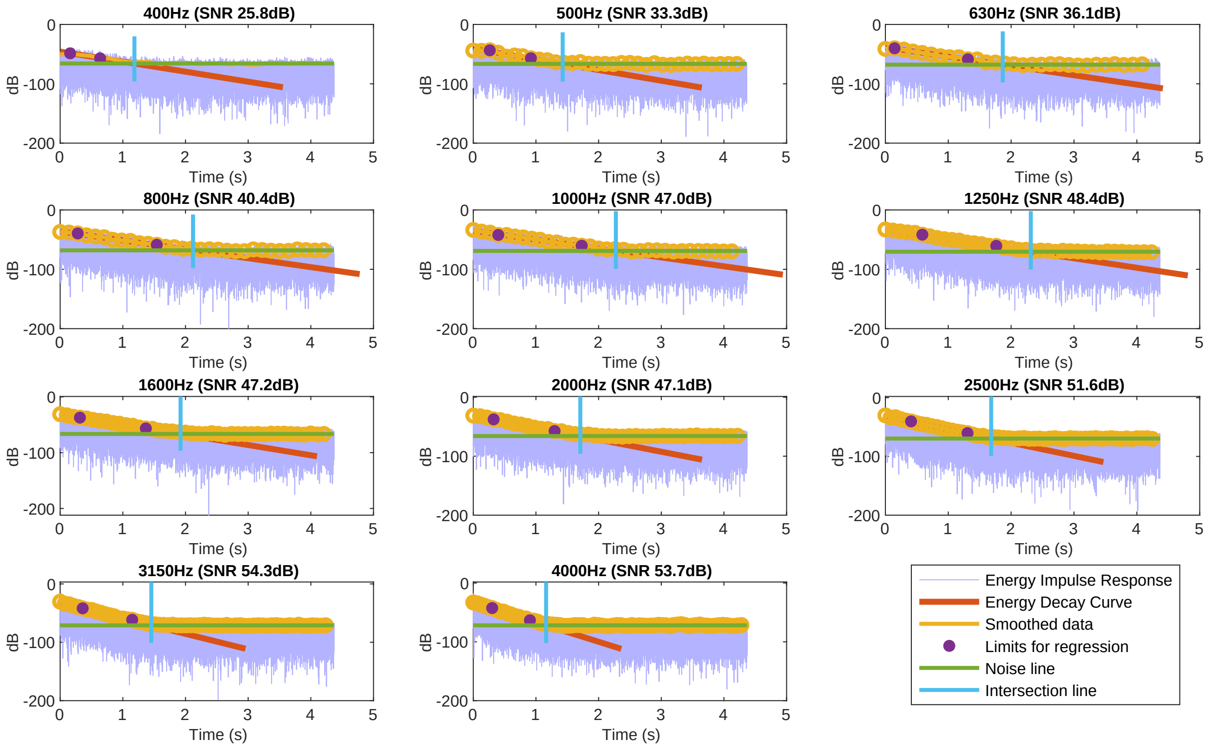

Figure 4. Impulse Responses and Energy Decay Curves obtained from measurements with the OPL positioned in S_1, for the receiver R_{10}, at the rear of audience area. Parameters used for application of method "E" when calculating T_{20}, as presented in [16], for noise mitigation, are also shown.

2.3 Room acoustic parameters

The following monaural room acoustic parameters were extracted from the impulse responses:

- Reverberation time (T_{20}).
- Early decay time (EDT).
- Music clarity (C_{80}).
- Central time (T_s).
- Speech definition (D_{50}).

To calculate them, we used MATLAB scripts incorporating functions from the ITA-Toolbox [17]. Method "E" was employed, as described in [16], which subtracts the estimated noise level, truncates the Energy Decay Curve at intersection time, and corrects for the truncation. The UTF-Toolbox was also used for softer data processing [1] .

[1] `https://gitlab.com/Phxuibs/utf-toolbox`.

3. RESULTS

3.1 Impulse responses and energy decay curves

Figure 4 shows as example the impulse response and the energy decay curve obtained when the OPL is located at S_1 and the microphone at R_{10}. Note in Figure 2 that R_{10} is positioned at the rear of the audience area, representing a worst-case scenario for the OPL. The figure shows the filtered impulse responses in 1/3 octave bands from 400 Hz, using the noise compensation method "E" from the ITA Toolbox [16] to obtain the energy decay curves. It also illustrates the T_{20} estimation process, indicating the signal-to-noise ratio (SNR) for each frequency band. It can be seen that the SNR is sufficient to calculate a T_{20} for frequencies above 500 Hz. Other room acoustic parameters will also suffer from this reduced SNR, and will start to give values from about 400 Hz.

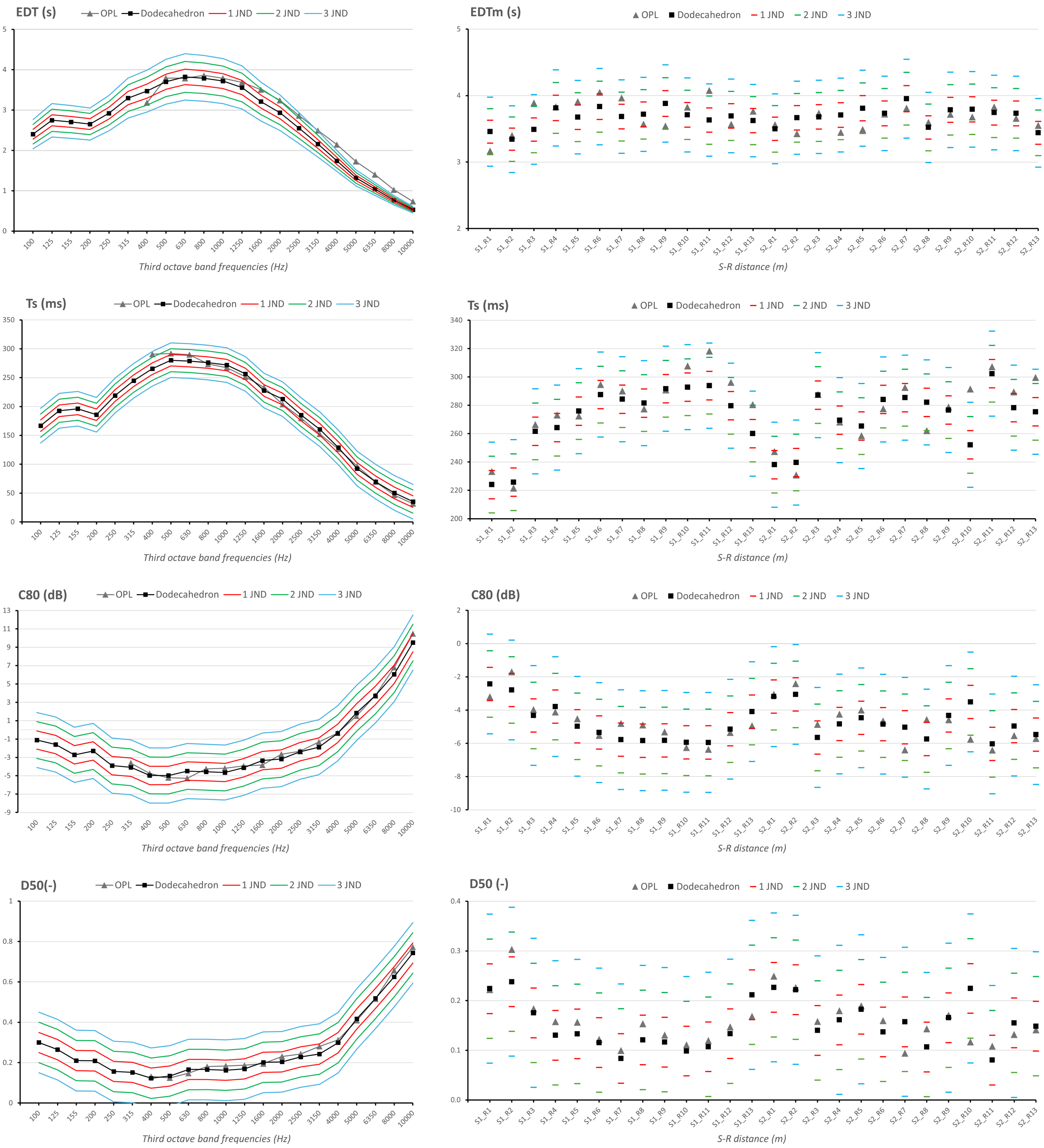

Figure 5. Room acoustic parameters for the OPL and the dodechaedron: (left column) spectral behaviour spatially averaged for each frequency band, (right column) frequency mean in the 500-1000 Hz 1/1 octave bands in each source-reciever position. From top to bottom, EDT, T_s, C_{80} and D_{50}. The values for 1 JND, 2 JND, and 3 JND are also included to facilitate comparison between the two sound sources.

		125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	Single number
T_{20} (s)	Dodechaedron	2.79	2.97	3.72	3.60	2.89	1.71	3.66
	OPL	—	—	—	3.81	2.98	1.79	3.81
EDT (s)	Dodechaedron	2.62	2.96	3.67	3.69	2.90	1.74	3.68
	OPL	—	—	3.59	3.78	3.20	2.12	3.68
C_{80} (dB)	Dodechaedron	-1.73	-3.32	-4.80	-4.43	-2.95	0.14	-4.61
	OPL	—	—	-5.06	-4.11	-2.89	0.12	-4.56
T_S (ms)	Dodechaedron	185	217	275	268	209	127	271
	OPL	—	—	291	264	206	176	277
D_{50} (%)	Dodechaedron	25.8	17.3	14.1	16.6	21.2	32	15.4
	OPL	—	—	13.6	18.4	22.3	33.4	16
SNR (dB)	Dodechaedron	61.6	65.5	67	69.6	72.4	80.3	68.5
	OPL	—	—	40.6	46.9	51.5	60	44.8

Table 1. Room acoustic parameters obtained for the dodecahedron and the OPL as sound sources, spatially averaged for each frequency band. Frequency mean in the $500-1000$ Hz bands (single number).

3.2 Spectral behavior and source-receiver analysis of room acoustic parameters

Figure 5 presents a comparison between the results obtained using the OPL and those from the conventional dodecahedral loudspeaker for the EDT, C_{80}, D_{50}, and T_s. The left columns shows the spectral behavior of the parameters (analyzed over third-octave bands), averaged for all receivers and sound sources, whereas the right column shows the mean value ($500-1$ kHz) for each source-receiver combination. The Just Noticeable Difference (JND, i.e., the minimum perceptible difference between two acoustic stimuli) is incorporated as a threshold for perceptible variations. Values corresponding to 1 JND, 2 JND and 3 JND are included to facilitate comparison between the two sound sources. Note in Figure 5 that the OPL has values starting at 400 Hz. This is due to an insufficient signal-to-noise ratio at lower frequencies, which did not allowed us to calculate values in this range, as also observed for the impulse responses in Figure 4.

Let us first focus on the frequency-dependent trends (see left column in Figure 5). Compared to the dodecahedral sound source, observe that the OPL gives higher EDT values especially above $1-2$ kHz. These values, while remaining fairly constant in terms of distance to the dodecahedron, diverge more and more from the JND threshold, exceeding the 3 JND limit at 4 kHz and above. Conversely, the T_s parameter displays an almost opposite trend, gradually falling within the 1 JND threshold from 1 kHz onward. In contrast, the C_{80} and D_{50} parameters maintain similar values to the dodecahedron, remaining within the 1 JND threshold throughout the entire frequency range.

Focusing now on the right column of Figure 5, the values obtained for the OPL and dodechaedron match to a large extend for all source-receiver positions, with only a few exceptions. Most values fall within the 1 JND threshold, and under no circumstances they exceed the 3 JND limit. Overall, a closer match is observed at shorter source–receiver distances (i.e. small values of j in R_j) compared to configurations where the receiver is positioned farther from the source (i.e. large values of j in R_j). As observed for the frequency analysis (left column), the parameters with a best match are the C_{80} and D_{50}, followed by the T_s and EDT, which exhibit larger differences.

3.3 Overall performance of the hall

Table 1 shows the values of the room acoustic parameters for both sound sources, spatially averaged to facilitate comparison and expressed in frequency octave bands. The single value averaged in the $500-1000$ Hz is also reported. The Pere Pruna Hall, as previously discussed, exhibits a hybrid acoustic-architectural configuration, situated midway between that of a church and a chamber music hall. Several research studies have enabled the identification of a favorable range of target values, both for chamber music halls [13] and churches [18]. For instance, an optimal reverberation time (T_{20}) is generally considered to be around 2 seconds, while ideal values for the clarity index (C_{80}) typically range between 0 and 2 dB. As shown in the table, the measured results reveal T_{20} values that are significantly higher than recommended, with a reverberation time of 3.72 seconds at 500 Hz. Similarly, the clarity index (C_{80}) is markedly low, reaching -4.80 dB at that frequency. These results clearly indicate that the current acoustic conditions are far from optimal and unsuitable for hosting chamber music performances. Regarding the Center Time (T_s), optimal values for music applications typically range around 150 ms. However, the measurements conducted in the Pere Pruna hall reveal significantly higher values, such as 275 ms at 500 Hz. On other hand, the Definition index (D_{50}), expressed as a percentage, is primarily associated with speech intelligibility. Values above 20% are generally considered acceptable for spoken word events in churches, and even more so for music halls. The measured value of 14.1% at 500 Hz indicates that the space also lacks the necessary acoustic conditions to effectively support conferences or other speech-based activities. On a positive note, the measured values of T_{20} and EDT are relatively close across all frequency bands. This implies a uniform decay profile and a relatively homogeneous sound field, which is favorable from an acoustic perspective. Finally, although the signal-to-noise ratio (SNR) obtained using the dodecahedral loudspeaker was approximately 20 dB higher than that of the OPL, the overall values derived for the different acoustic parameters remain comparable between the two sources. This suggests that, despite the lower SNR, the OPL is still capable of providing consistent and reliable measurements in such environments.

4. CONCLUSIONS

This study has evaluated the performance of an OPL in measuring room acoustic parameters. A converted chapel used for choral music performances was selected as the test environment, and the results were compared with those obtained using a standard dodecahedral sound source.

The OPL demonstrated strong performance for frequencies above 400 Hz, providing similar results to those of a dodecahedron for clarity C_{80}, definition D_{50}, and central time T_s. Larger values were observed for the EDT, primary attributed to the reduced OPL's lower signal-to-noise ratio. However, it is noticeable that values of T_{20} are well in accordance at higher frequencies for the two sound sources, contrary to the authors' expectations, due to the difference in sound directivities. As previously known [9], the OPL has a more omnidirectional pattern. However, a hypothesis is that, in highly reverberant rooms, the sound field becomes more homogeneous, even if the sound source is not omnidirectional.

Future work will involve repeating the measurement campaign with spectral shaping of the ESS to improve low-frequency performance, as demonstrated in [11], where reverberation time was measured with the OPL from 100 Hz. Additionally, measurements will be conducted in rooms with varying volumes and reverberation times.

5. ACKNOWLEDGMENTS

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