applied sciences

MDPI

Article

Low Cost Omnidirectional Sound Source Utilizing a Common Directional Loudspeaker for Impulse Response Measurements

Nikolaos M. Papadakis [1,2,*] and Georgios E. Stavroulakis [1]

1 Institute of Computational Mechanics and Optimization (Co.Mec.O), School of Production Engineering and Management, Technical University of Crete, Chania 73100, Greece; gestavr@dpem.tuc.gr
2 Department of Music Technology and Acoustics, Technological Educational Institute of Crete, Rethymno 74100, Greece
* Correspondence: nikpapadakis@isc.tuc.gr

Received: 5 August 2018; Accepted: 17 September 2018; Published: 19 September 2018

Featured Application: The concept of utilizing a common directional loudspeaker for impulse response measurements is introduced. The proposed source has the potential of being the main alternative low-cost excitation source for acoustic measurements.

Abstract: Alternative low-cost sources (e.g., balloons, gun fires) are used for impulse response measurements when a dodecahedron speaker is not available. This study sets to explore the applicability of a method utilizing a common directional loudspeaker as a sound source. For this purpose measurements were performed in three spaces with three different common directional loudspeakers. Different placements of the loudspeakers were performed (twelve positions similar to the twelve positions of the faces of a dodecahedron speaker, different rotations of the loudspeakers for a total sum of twenty six and fourteen positions). The impulse responses obtained were added up creating a single impulse response for each case. Comparisons of the acoustic parameters measured with the proposed method and with a dodecahedron speaker are presented and suggest the expected mean absolute error and standard deviation for similar measurements. Reverberation time measurements show a mean absolute error of less than 0.08 s, as compared with measurements with a dodecahedron speaker. The proposed method can be the primary method for measuring impulse responses when a dodecahedron speaker is not available. Suggested improvements may lead to better omnidirectionality as compared with a dodecahedron loudspeaker, and set the method applicable to be utilized for auralization purposes.

Keywords: low-cost impulse response measurement; omnidirectional source; acoustic parameters; impulse response; sound source; reverberation time; auralization

1. Introduction

Impulse response is the temporal evolution of the sound pressure observed at a point in a room as a result of the emission of a Dirac impulse at another point in the room [1]. Usually the measurement of an impulse response utilizes a dodecahedron speaker following the sound source requirements according to ISO 3382-1:2009 [2]. For a more complete description of the acoustical conditions in a space, acoustic parameters such as Reverberation Time (RT), Early Decay Time (EDT), Clarity (C_{80}), Definition (D_{50}), Centre Time (T_s) and Source Strength (G) [2] can be obtained directly from the impulse response. These parameters can be used to assess the acoustic quality of a space and provide guidance for possible improvements. Appropriate values of the acoustic parameters are required in spaces according to their usage (classrooms, theatres, music halls, etc.).

As ISO 354:2003 [1] states, it is impossible in practice to create and radiate a true Dirac impulse. However, alternative measurements techniques exist which utilize a dodecahedron speaker. Maximum-Length Sequence (MLS) [3] and Exponential Sine Sweep (ESS) [4] type signals are commonly used, which transform the measured response back to an impulse response. The appropriate choice of excitation signal can be dependent on the background noise [5]. Also, white or pink noise can be used as excitation signals.

Dodecahedron speakers are the most widely used sources for room acoustics measurements, as they produce a good approximation of omnidirectional radiation. Other polyhedron loudspeakers can also be used, which in some cases can be viewed as equally omnidirectional [6]. The directivity of a dodecahedron speaker can be considered uniform in the low-frequency range (namely below 1 kHz), while at higher frequencies sound radiation shows greater deviation [7]. Stepwise rotation of dodecahedron speaker can be employed to improve the accuracy of room acoustic measurements [8]. Constructive interference of the pressure field across the spherical baffle surface and not individual loudspeaker pistonic radiation characteristics is the most significant factor with respect to deviations from omnidirectional radiation [9].

However, there are certain drawbacks associated with the use of dodecahedron speakers for acoustic measurements. The main disadvantage is their high cost which limits their widespread use. Also, their heavy weight combined with large volume makes transportation difficult e.g., transfers to airports. In addition, there are cases where their usage is required in places without electric supply. An external generator or an appropriate dodecahedron speaker with an internal generator can be used, which further increases the cost. Although the dodecahedron speaker is quite expensive, it is possible to use a 3-D printer for its manufacture [10]. Nonetheless, there are alternative low-cost sound sources.

Numerous examples can be found in the literature where alternative sound sources were used instead of a dodecahedron speaker e.g., measuring impulse responses in churches [11], measuring the acoustics of catacombs [12], measurements in Stonehedge [13], in Notre-Dame cathedral [14], Hagia Sofia [15], measurements in urban environments [16] or for the acoustic of caves [17]. The most common low-cost sources are balloons, pistol shots and firecrackers. Other sound sources that have been reviewed in the literature are handclaps, wooden clappers, shotsell primers and inverse horn designs. Important questions concerning their performance are their directionality as a source and the repeatability of measurements. Source omnidirectionality ensures uniform space excitation necessary for correct impulse response measurement. Source repeatability ensures that a similar impulse response is measured each time.

The balloon as a sound source is a common, affordable solution for acoustic measurements. Considering the directionality, there seems to be some evidence to indicate that it cannot be considered as a broadband omnidirectional source. Investigation from Pätynen et al. [18] showed that for different balloon types, magnitude of deviations below the 500 Hz octave band are on the order of 6–9 dB, well above the ISO 3382-1:2009 limits [2]. The balloon as a sound source radiates mostly toward the direction of needle impact. Similar results about the omnidirectionality have been reported by Griesinger [19] and Cheenne [20]. However hydrogen-oxygen balloons seem to show better omnidirectionality [21].

Concerning the question of repeatability, in contrast to Griesinger [19], Pätynen [18] have reported that balloon directivity patterns are stable over repetitions if certain criteria are met. Spectra and radiated sound from a balloon were quite constant for a given balloon type with consistent inflation. Also a study by Cheenne [20] where anechoic recordings of balloon bursts were systematically acquired for various conditions of balloon diameters, puncture location, and inflation pressure, reports that the results are quite consistent when averaged over one-third octave bands. The study reveals that the diameter factor (the ratio between the diameter of the inflated balloon to that of its stated maximum), rather than the overall diameter of the balloon, is a good indicator of the sound pressure level, especially above 200 Hz.

Concerning the measurement of reverberation time with the use of balloons, some research shows good correlation compared with the expected RT [22]. Results suggest that balloons as a sound source can be used with almost no influence on the final result if the measured room is large and reverberant [23]. Also the balloon as a sound source does not offer adequate excitation at the low frequencies which also affects the expected results [24]. However, a technique by Abel et al. [25] can improve the expected results by converting recorded balloon pops into full audio bandwidth impulse responses.

A gun, as an explosive sound source, is explicitly specified in the standard ISO 354:2003 as a possible alternative. Traditionally, acousticians have used pistols with blank cartridges for acoustic measurements. A gun is an impulsive noise source that is lightweight and small enough to be easily transported. However, firearms are also difficult to transport on airlines and are frightening to audiences for in situ measurements.

Concerning the question of directionality, the handgun does not appear to be an omnidirectional sound source [26,27]. The pistol appears to be directional at low frequencies, where there is a rise in energy from the side [19]. A study by Freytag et al. [28] indicates that especially the muzzle blast is directional. Muzzle blast is the most dominant noise source in gunshots. The measured sound levels on axis, ahead of the muzzle, are higher than levels directly behind the muzzle by up to 20 dB. A study on the acoustical characteristics of different guns by Lamothe [29] showed that the details of the wedge in front of the firing chamber also influenced the directional properties of the gun.

Concerning the question of repeatability, Dezelak [30] states that differences in the noise characteristics between individual cartridges for the same gun are usually small so the impulsive source can be replicated to a high degree.

Finally, the frequency spectrum of a gun typically has a peak energy output in the 1 kHz to 2 kHz region [19]. Below this frequency the energy falls off rapidly. A gunshot can also be a preferred alternative when investigating building acoustics and sound insulation measurements compared to conventional steady state noise sources. As an impulsive source offers the possibility of removing flanking transmission, since gun is much more decoupled with a floor, than a heavy loudspeaker [30].

Firecrackers are not used as often as balloons and fire guns, but they do seem to have some extra advantages. Concerning omnidirectionality, Arana et al. states [31] that if the powder charge is exploded directly, the generated impulse is nearly omnidirectional. Its directivity index is, on average, around 1 dB for the octave bands between 125 Hz and 16 kHz.

Concerning repeatability the firecrackers do not guarantee the extraordinary repeatability of techniques based on deterministic signals [7]. However, Topa et al. [32] states their repeatability being better than that of the balloons.

The biggest drawback of firecrackers is the low sound to noise ratio obtained for low frequencies and long distances [7]. Firecrackers and other explosive sources are superior to balloons compared by the maximum peak sound pressure level [33]. The spread of the values obtained with firecrackers for acoustic parameters is smaller than that of the balloons. However, the common difficulty for these sources is to satisfy a suitable dynamic range for low frequencies.

A hand clap is an attractive acoustic stimulus because it can be produced easily and without special equipment. However it also suffers from poor low frequency content and poor omnidirectionality [19]. Compared with other types of impulse sources, it has the lowest repeatability because the spectral characteristics of the generated impulse vary depending on how the claps are generated. Hand clap lacks the high energy and consistency of other impulse sources, such as pistol shots, but signal processing steps can be introduced in order to improve its performance [34].

A specially designed wooden clapper is an alternative sound source intended to operate as an impulse source for acoustic measurements [35]. However, measurements performed in rooms located in urban environments, where the ambient noise level is high, showed that the dynamic range for the lower octave band might be insufficient and that the measurement results have to be considered valid for the octave band at 250 Hz and higher. Diagrams of directivity show that the clapper has a better uniformity of sound radiation compared to a gun or a balloon burst. If the clapper is operated by a trained person the results of its impulse repeatability are better than those of balloons and firecrackers. Nonetheless, the clapper directivity is worse than that of a standard omnidirectional loudspeaker. The radiation of the wooden clapper is within the limits established by ISO 3382-1:2009 only at higher frequencies.

Discharging a shotsell primer down a tube has proved to be a reliable method of producing an impulse sound [36]. It has a peak level of about 145 dB and a useful frequency content varying between 100 Hz and 10 kHz. However the study seems to support that there is lack of omnidirectionality as a sound source.

The inverse horn design is a type of omnidirectional sound source, consisting of a loudspeaker feeding a small aperture through a reverse horn for concentrating the acoustical energy. Results prove that careful design makes it possible to construct a very compact omnidirectional sound source satisfying the international standards and involving only one loudspeaker [37]. However, the total sound power available is lower than with traditional omnidirectional sources (dodecahedron speakers): 85 dB in each one-third-octave band between 100 Hz and 5 kHz, 102 dB full band. On the other hand, the directivity diagram is much smoother. The polar response of the proposed design is omnidirectional between well above 5 kHz, making this design more robust at high frequencies than the popular polyhedral designs [38].

With this in mind, there is still a need for an inexpensive, practical, omnidirectional sound source for measuring impulse responses with good repeatability without the use of a dodecahedron speaker. Few researchers have addressed the question of utilizing a common, directional loudspeaker for acoustic measurements [39]. This study set out to explore the suitability of a common, directional loudspeaker for mimicking the sound field created by a dodecahedron speaker for impulse response measurements. Impulse responses and acoustic parameters between the results obtained with the common directional loudspeaker and dodecahedron speaker were assessed in order to quantify the results. The results of this investigation show that the proposed method utilizing a common directional loudspeaker can provide usable results for impulse response measurements. This method represents a viable, low-cost method for measuring impulse responses without the use of a dodecahedral loudspeaker.

Section 2 is concerned with the methodology employed for this study, while Section 3 presents the findings of the research. The Section 4 analyses the data gathered and addresses the research questions in turn. Our conclusions are drawn in the Section 5.

2. Methodology

In order to investigate our hypothesis, measurements were performed with a dodecahedron speaker and with common directional loudspeakers for the same source and microphone positions. The measurements were carried out in three spaces of the Technological Educational Institute of Crete, Department of Music Technology and Acoustics (Figure 1) with volumes of 88 m^3, 192.4 m^3 and 1088 m^3 (referred to as small, midsized and large in the manuscript respectively). The first space is a small classroom mainly used as an acoustic laboratory with many absorbent and diffusing surfaces, the second one is a typical classroom with minimal absorbent surfaces and the last one is an amphitheater with highly absorbent seats. The microphone and source positions, for which the measurements will be presented in the results section, are shown in Figure 1.

Three different directional speakers were used that belong to different price categories (Figure 2). A Philips PCA220SD/EU (Philips, Amsterdam, The Netherlands) is a typical multimedia speaker (or computer speaker) with an internal amplifier belonging in the low-price range. A Behringer Truth B2031A Active 2-Way Reference Studio Monitor (Behringer, Willich, Germany) [40] is a speaker in the medium/low price range. Finally, a Genelec 8030B Studio Monitor (Genelec, Lislami, Finland) [41] was used which is of the medium to high price range. The Behringer and Genelec are two-way speakers, comprised from a tweeter and a driver speaker, while the Philips is a one-way design comprised of a single driver speaker. A dodecahedron loudspeaker, 01 dB-Stell, Type DO12 (01 dB-Stell, Limonest, France) was employed in order to compare the measurements.

The pair of Philips speaker costs around 50 euros, the pair of Behringer speakers costs around 400 euros and the pair of Genelec speakers costs around 1000 euros. The model of the dodecahedron speaker that we have used (Type DO12) has been discontinued by the company (01 dB), but the price for the newer equivalent models (LS01, LS02) is around 6000 euros.

For all the measurement positions an omnidirectional microphone, Earthworks M30, Type 4190 (Earthworks, Milford, CT, USA) with a flat frequency response was used [42].

Measurements were performed with different placements of the directional speaker (twelve positions similar to the twelve positions of the faces of a dodecahedron speaker, different rotations of the loudspeakers for a total sum of twenty six and fourteen positions). The twelve, twenty six and fourteen impulse responses obtained were added up creating a single impulse response for each case.

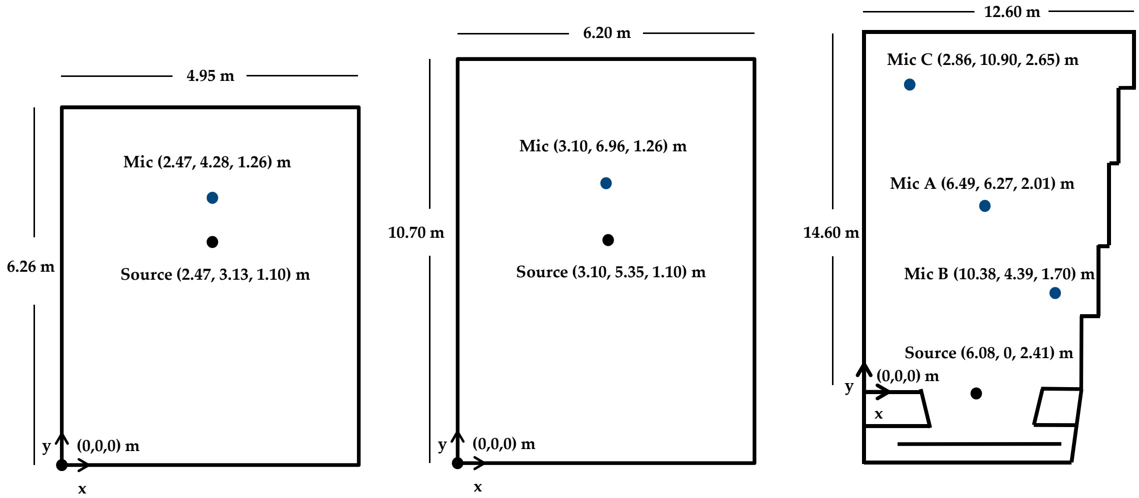

Figure 1. Source and microphone positions for the three spaces with volumes of 88 m^3, 192.4 m^3 and 1088 m^3 (from **left** to **right**) where measurements were performed.

Figure 2. The common directional loudspeakers and the dodecahedron speaker that were used in this study (from left to right: Philips PCA220SD/EU, Behringer Truth B2031A, Genelec 8030B, 01 dB-Stell DO12).

2.1. Measurements with a Dodecahedron Speaker

For the impulse response measurements with the dodecahedron speaker, the ESS signal was used [4]. The sampling frequency for the measurements was 44.1 kHz. The particular excitation signal was preferred because of the low background noise [5,43]. An appropriate sequence length and time constant for the ESS signal was chosen according to the expected RT for each space. Three iterations were performed for each of the measurement points. Averaging was used for a better signal to noise ratio and to reduce the temperature fluctuation effect [44]. The variations of temperature and hence the sound velocity with time and position cannot be entirely avoided but the effects which are caused by these in-homogeneities can be considered to be small. Acoustic parameters were extracted from the impulse responses according to ISO 3382-1:2009 [2].

2.2. Measurements with a Common Directional Speaker

For measurements with the common directional speakers, the same source and microphone positions were used. According to the measurements with the dodecahedron speaker, an ESS excitation signal was used with the same sampling frequency of 44.1 kHz. The same appropriate sequence length and time constant for the ESS signal was chosen according to the expected RT. Three iterations were performed for each of the measurement points for each of the loudspeaker positions. Averaging was used for better signal to noise ratio and to reduce the temperature fluctuation effect. The same microphone was used in the same position for each of the measurements. Different placements of the loudspeakers were performed (twelve positions similar to the twelve positions of the faces of a dodecahedron speaker, different rotations of the loudspeakers for a total sum of twenty six and fourteen positions).

For all the measurements with a directional speaker, the speaker was handheld in the appropriate positions described in the following sections. For all the measurements the same person operated the directional speakers without any contact with the body. We followed this approach in order there will be no differences caused by different absorption by different operators. However, variations of the results are expected when different operators perform the method since they will have different absorption. Also, the combined absorption of the operator and the directional speaker is different from the absorption of the dodecahedron speaker. This is expected to affect the results of the acoustic parameters to some extent e.g., measurement of reverberation time. The effect of these differences remains to be studied in a future work.

We followed this approach so that no further equipment would be needed to conduct measurements in order to maintain the low-cost method. The evolution of the method, which is now underway, is going to address this problem. However, additional equipment will be necessary that will increase the cost.

In order to compare the impulse responses, impulse responses created with the proposed method were normalized. Impulse responses created by the proposed method have generally greater amplitude compared with the impulse responses measured with a dodecahedron speaker. Audio normalization is the application of a constant amount of gain to a recording to bring the amplitude to a target level. Because the same amount of gain is applied across the entire recording, the signal-to-noise ratio and relative dynamics are unchanged. Peak audio normalization was especially applied in the impulse response created with the proposed method, which adjusted the recording based on the highest signal level present in the impulse response measured with the dodecahedron speaker.

2.2.1. Twelve Positions (Similar to a Dodecahedron)

For these measurements, the front face of the directional loudspeaker was placed in twelve positions similar to the twelve positions of the faces of the dodecahedron speaker. The twelve faces of the dodecahedron speaker generally follow two patterns (Figure 3), when the speaker is mounted on its base. According to the pattern of the face of the dodecahedron speaker, the front face of the directional loudspeaker was placed as can be seen in Figure 3. For each of the twelve positions, impulse responses were measured for the same microphone position. The twelve impulse responses obtained were added up with the use of the software 'Matlab' creating a single impulse response. The impulse response was normalized so that it had approximately the same sound level with the impulse response obtained from the dodecahedral loudspeaker.

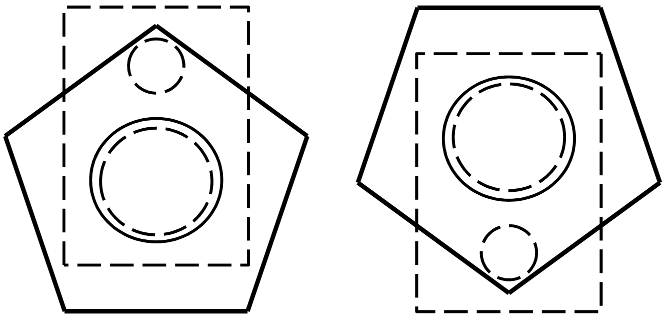

Figure 3. Placement of the face of the directional loudspeaker according to the placement of the face of the dodecahedron speaker (twelve positions measurements).

2.2.2. Twenty Six Positions

For these measurements the directional loudspeaker was placed in twenty six positions. The different positions of the directional loudspeaker were inside a hypothetical sphere with a radius of 32 cm similar to the dimensions of the dodecahedron speaker. As can be seen in Figure 4 (side view), measurements were performed in five different levels. For Level 0 (top view), eight impulse responses obtained by the rotation of the speaker by 45 degrees. The same procedure was followed by tilting the speaker by 45° and −45° for levels 1 and −1 respectively. Finally, two more impulse responses were obtained for the levels 2 and −2, as seen in Figure 4, for a total sum of twenty six positions. For each of the twenty six positions, impulse responses were measured for the same microphone position. The twenty six impulse responses obtained were added up with the use of the software 'Matlab' creating a single impulse response. The impulse response was normalized so that it had approximately the same sound level with the impulse response obtained from the dodecahedron speaker.

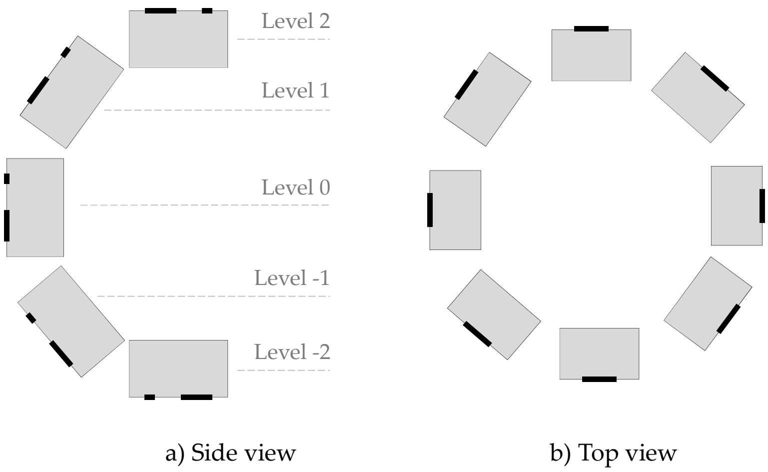

Figure 4. Side (**a**) and top (**b**) view for the measurements with a total sum of twenty six positions.

2.2.3. Fourteen Positions

For these measurements the directional loudspeaker was placed in fourteen positions. The positions of the directional loudspeaker were inside a hypothetical sphere with a radius of 32 cm similar to the dimensions of the dodecahedron speaker. As seen in Figure 5 (side view), measurements were performed in five different levels. For Level 0 (top view), four impulse responses obtained by the rotation of the speaker by 90 degrees. The same procedure was followed by tilting the speaker by 45° and −45° for levels 1 and −1 respectively. Finally, two more impulse responses were obtained for the levels 2 and −2, as seen in Figure 4, for a total sum of fourteen positions. For each of the fourteen positions, impulse responses were measured for the same microphone position. The fourteen impulse responses obtained were added up with the use of the software 'Matlab' creating a single impulse response. The impulse response was normalized so that it had approximately the same sound level with the impulse response obtained from the dodecahedron speaker.

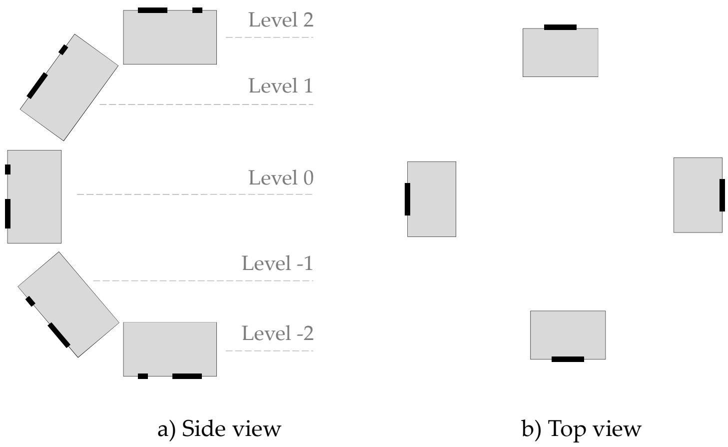

Figure 5. Side (**a**) and top (**b**) view for the measurements with a total sum of fourteen positions.

3. Results

Results of the measurements will be presented in the following cases: in different spaces, in different locations in the same space, with different speaker placement methods and with different loudspeakers.

3.1. Different Spaces

The first set of analyses investigated the performance of sound sources in different environments. Comparison for octave band RT measurements between those obtained with the dodecahedron speaker and the proposed method for the same microphone and source positions are presented in Figure 6, for spaces with volumes 88 m^3, 192.4 m^3 and 1088 m^3 respectively.

Figure 7 presents the comparison for octave band EDT, C_{80} and D_{50} measurements between those obtained with the dodecahedron speaker and the proposed method for the same microphone and source positions again for the same spaces.

For all the measurements, the Behringer speaker was used as the directional speaker. The placement of the directional speaker followed the method of twelve positions (similar to a dodecahedron) that was presented in the methodology. Measurements of the space with volume 1088 m^3 are presented for measuring position A (Figure 1).

Table 1 presents the mean absolute error and standard deviation for RT, EDT, C_{80} and D_{50} measurements between those obtained with the dodecahedron speaker and the proposed method for the same microphone and source positions for all spaces.

The comparison of results in Table 1 is also presented in terms of relative error [45,46] considering the Just Noticeable Difference (JND) of each parameter. In psycho-physics the JND is the smallest difference in sensation that a hearer can perceive. Hence, the relative error represents the differences in sensation caused by the variation of the acoustic parameters between those obtained with the dodecahedron speaker and the proposed method. The associated JND's for the acoustic parameters are 5% for RT, 5% for EDT, 1dB for C_{80} and 5% for D_{50}.

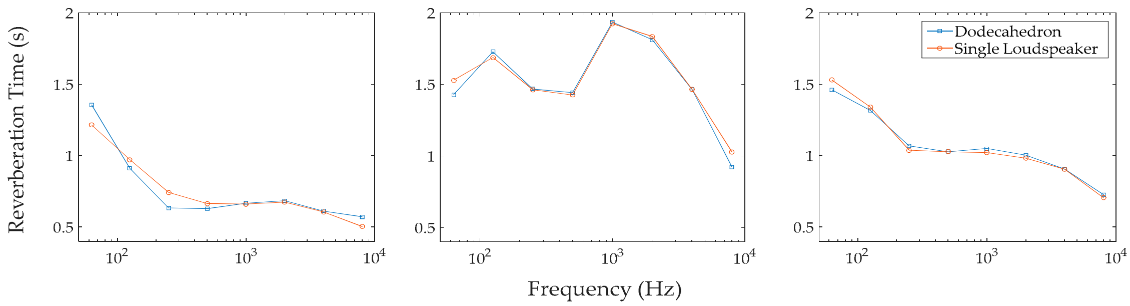

Figure 6. Reverberation Time (RT) for the small, midsized and large space (from **left** to **right**).

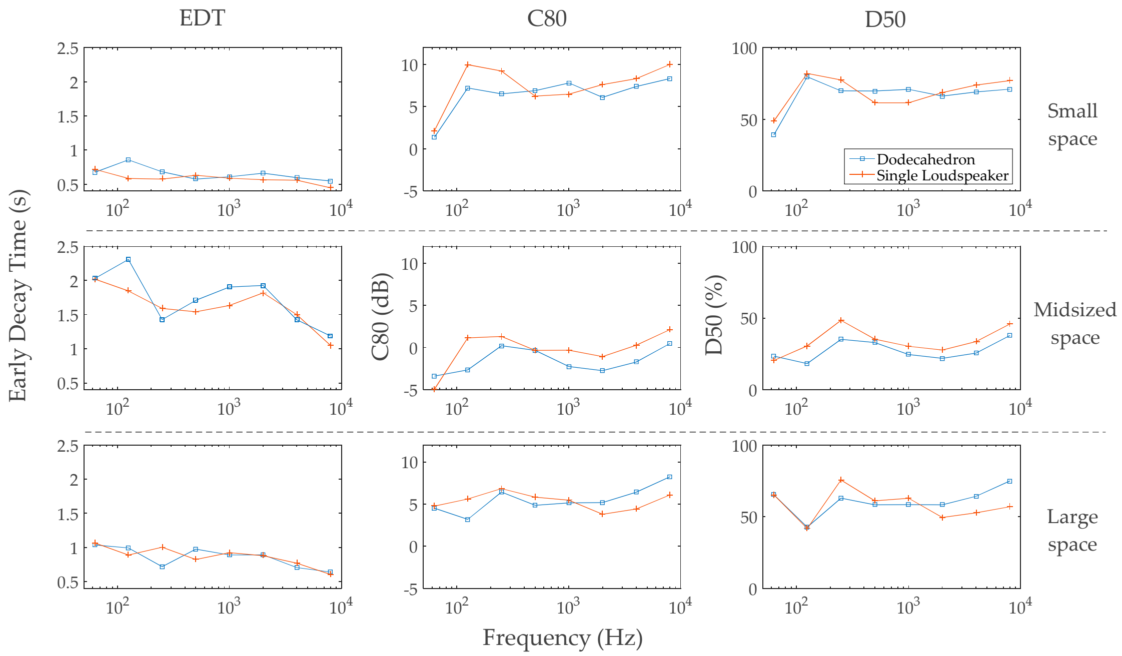

Figure 7. Early Decay Time (EDT), Clarity (C_{80}) and Definition (D_{50}) for the small, midsized and large space.

Table 1. Mean Absolute Error (M.A.E.), Standard Deviation (S.D.) and Relative Error (R.E.) of RT, EDT, C_{80} and D_{50} for measurements with a directional speaker compared with measurements with the dodecahedron speaker for the small, midsized and large space.

Acoustic Parameters	Small Space			Midsized Space			Large Space		
	M.A.E.	S.D.	R.E.	M.A.E.	S.D.	R.E.	M.A.E.	S.D.	R.E.
RT (s)	0.055	0.051	1.384	0.038	0.042	0.607	0.024	0.021	0.435
EDT (s)	0.091	0.080	2.644	0.175	0.140	1.963	0.089	0.091	2.202
C_{80} (dB)	1.548	0.811	1.548	1.708	1.052	1.708	1.235	0.878	1.235
D_{50} (%)	6.300	2.892	2.063	7.325	3.970	5.705	7.423	6.346	2.302

3.2. Different Locations in the Same Space

The second set of measurements aimed to examine the impact of different measuring positions in the same space. Comparison for octave band RT measurements between those obtained with the dodecahedron speaker and the proposed method for the same microphone and source positions are presented in Figure 8, for the points A, B and C in the amphitheater (Figure 1).

Figure 9 presents comparison for octave band EDT, C_{80} and D_{50} measurements between those obtained with the dodecahedron speaker and the proposed method, while Figure 10 presents a comparison between the frequency responses.

For the measurements, the Behringer speaker was used as the directional speaker. The placement of the directional speaker followed the method of twelve positions (similar to a dodecahedron) that was presented in the methodology.

Table 2 presents the mean absolute error and standard deviation for RT, EDT, C_{80} and D_{50} measurements between those obtained with the dodecahedron speaker and the proposed method for the same microphone and source positions for the points A, B and C in the amphitheater.

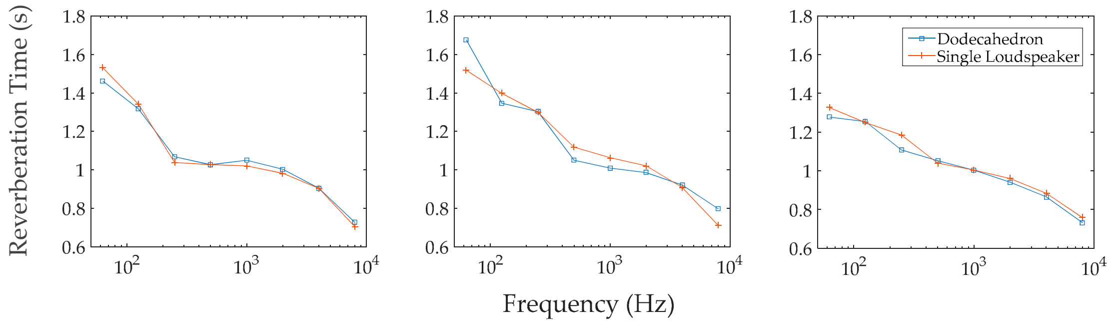

Figure 8. RT for points A, B and C in the amphitheater (from **left** to **right** respectively).

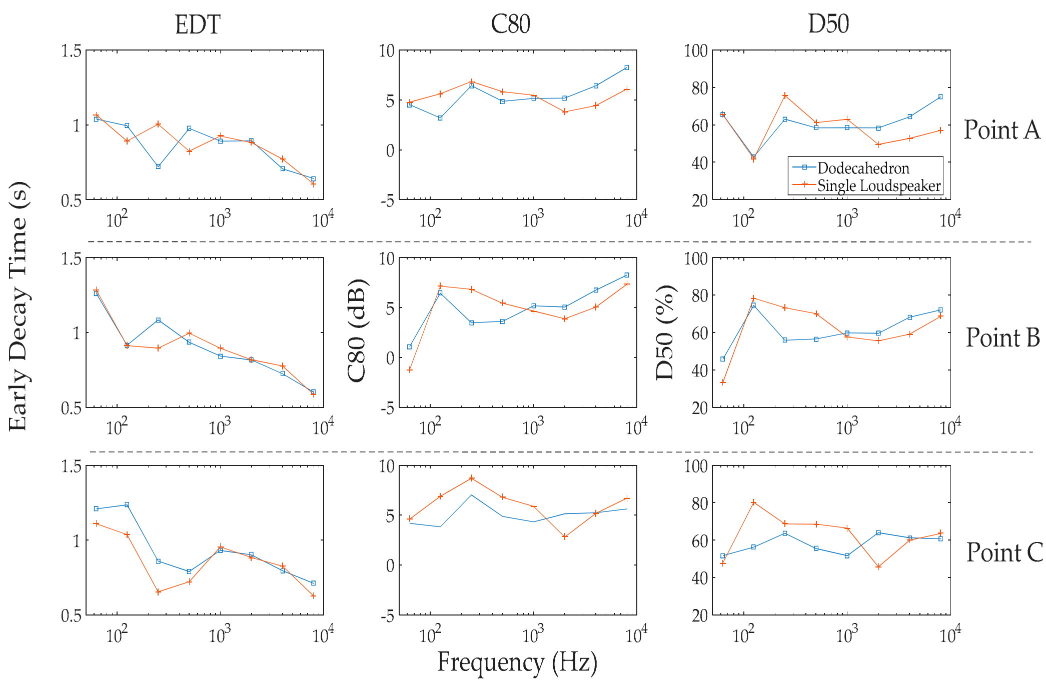

Figure 9. EDT, C_{80} and D_{50} for points A, B and C in the amphitheater.

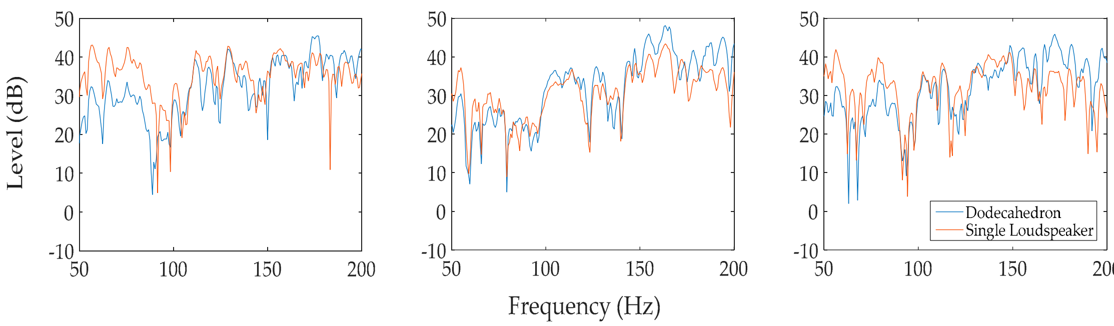

Figure 10. Frequency responses for measurements with the dodecahedron speaker and the proposed method for point A, B and C in the amphitheater (from **left** to **right** respectively).

Table 2. Mean Absolute Error (M.A.E.) and Standard Deviation (S.D.) of RT, EDT, C_{80} and D_{50} for measurements with a directional speaker compared with measurements with the dodecahedral speaker for points A, B and C in the amphitheater.

Acoustic Parameters	Position A		Position B		Position C	
	M.A.E.	S.D.	M.A.E.	S.D.	M.A.E.	S.D.
RT (s)	0.025	0.021	0.059	0.049	0.026	0.025
EDT (s)	0.089	0.091	0.050	0.061	0.091	0.075
C_{80} (dB)	1.235	0.878	1.563	0.946	1.513	0.983
D_{50} (%)	7.423	6.346	8.258	5.673	10.380	8.287

3.3. Different Speaker Placement Method

Comparison for octave band RT, EDT, C_{80} and D_{50} measurements between those obtained with the dodecahedron speaker and the proposed method for the same microphone and source positions are presented in Figure 11, for different placement methods of the directional loudspeakers.

Table 3 presents the mean absolute error and standard deviation for RT, EDT, C_{80} and D_{50} measurements between those obtained with the dodecahedron speaker and the proposed method utilizing different placement methods of the directional loudspeakers for the same microphone and source positions

For the measurements, the Behringer speaker was used as a directional speaker. Measurements are presented for point A in the amphitheater.

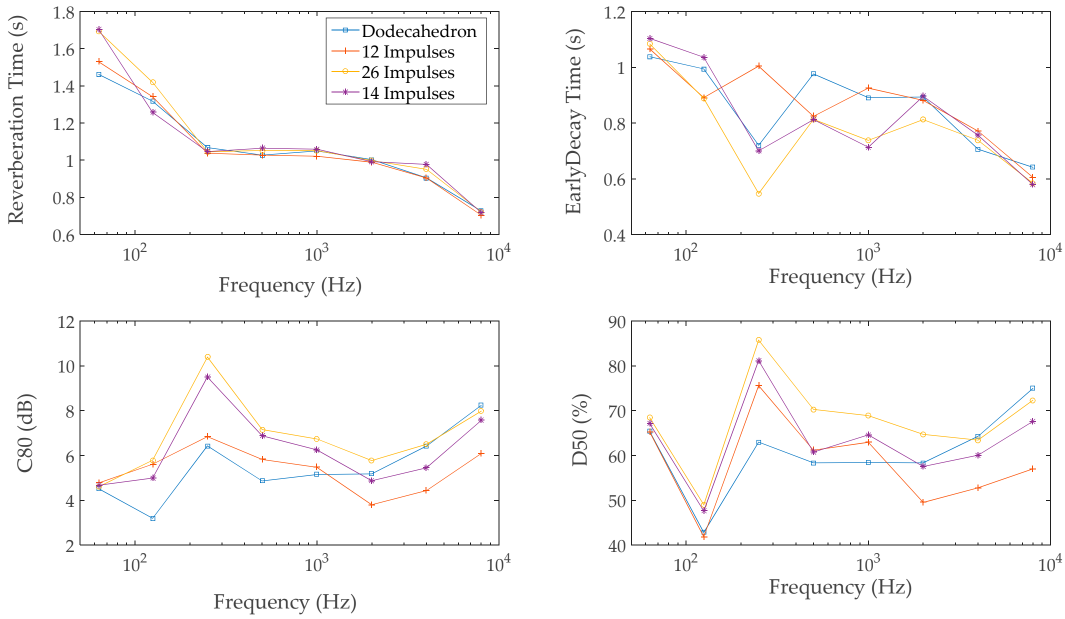

Figure 11. RT, EDT, C_{80} and D_{50} measured with different speaker placement methods.

Table 3. Mean Absolute Error (M.A.E.) and Standard Deviation (S.D.) of RT, EDT, C_{80} and D_{50} for measurements with different speaker placement methods compared with measurements with the dodecahedron speaker.

Acoustic Parameters	12 Impulses		26 Impulses		14 Impulses	
	M.A.E.	S.D.	M.A.E.	S.D.	M.A.E.	S.D.
RT (s)	0.025	0.021	0.055	0.079	0.058	0.078
EDT (s)	0.089	0.091	0.102	0.056	0.073	0.064
C_{80} (dB)	1.235	0.878	1.434	1.430	1.263	0.984
D_{50} (%)	7.423	6.346	8.043	7.080	5.724	5.518

3.4. Different Speakers

Comparison for octave band RT, EDT, C_{80} and D_{50} measurements between those obtained with the dodecahedron speaker and the proposed method for the same microphone and source positions are presented in Figure 12, for different directional loudspeakers. The method of 12 positions was used for the directional speakers. Figure 13 presents a comparison between the frequency responses. Measurements are presented for point B in the amphitheater.

Table 4 presents the mean absolute error and standard deviation for RT, EDT, C_{80} and D_{50} measurements between those obtained with the dodecahedron speaker and the proposed method utilizing different directional loudspeakers for the same microphone and source positions.

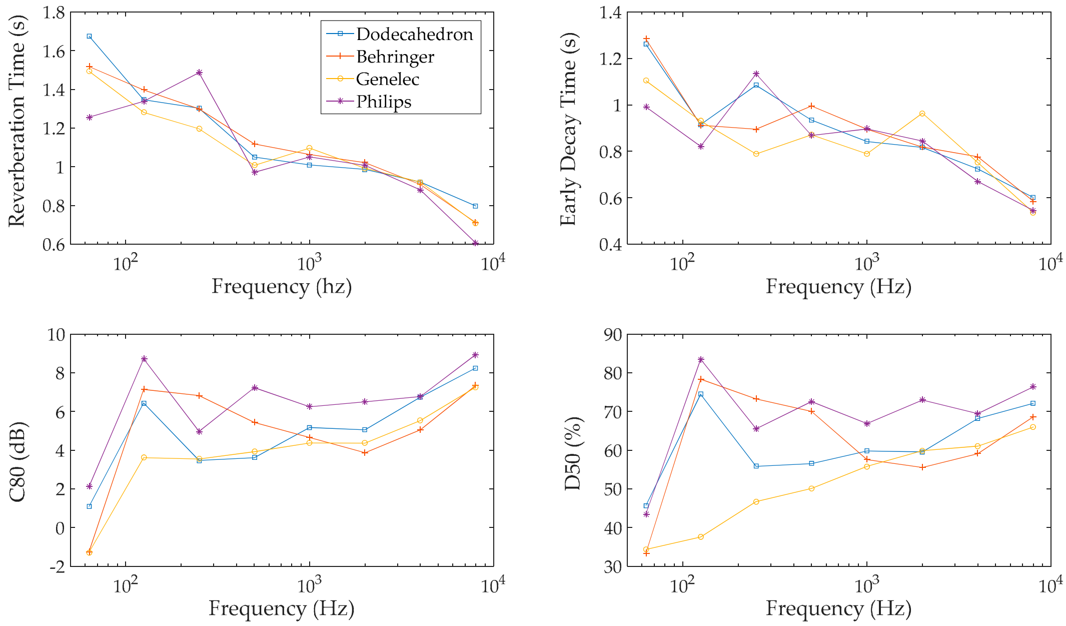

Figure 12. RT, EDT, C_{80} and D_{50} measured with different speakers.

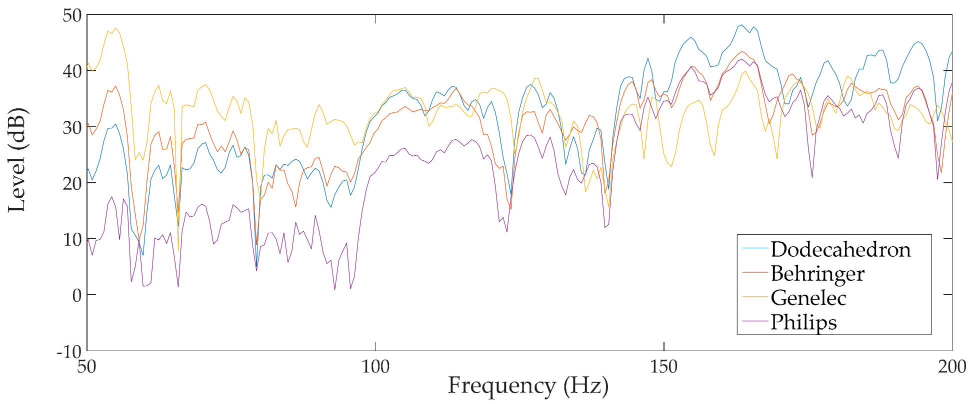

Figure 13. Frequency responses for measurements with the dodecahedron speaker and the proposed method with different speakers.

Table 4. Mean Absolute Error (M.A.E.) and Standard Deviation (S.D.) of RT, E.D.T., C_{80} and D_{50} for measurements with different speakers compared with measurements with the dodecahedron speaker.

Acoustic Parameters	Behringer		Genelec		Philips	
	M.A.E.	S.D.	M.A.E.	S.D.	M.A.E.	S.D.
RT (s)	0.059	0.049	0.072	0.059	0.123	0.139
EDT (s)	0.050	0.061	0.090	0.065	0.084	0.077
C_{80} (dB)	1.563	0.946	1.159	0.967	1.459	1.090
D_{50} (%)	8.258	5.673	9.766	11.297	7.851	5.225

4. Discussion

The main goal of this study was to attempt to utilize a common directional loudspeaker as a source for impulse response and acoustic measurements. The results seem to support our hypotheses. Overall, the results presented above show that the proposed method represents a viable alternative to the other low-cost sources that can be used for acoustic measurements for practical applications.

The efficiency of the method, the differences between the proposed method and measurements with a dodecahedron for measuring acoustic parameters, the justification of the results, comparison with other low-cost methods and finally future work are discussed in the following sections.

4.1. Acoustic Parameters

A primary concern of this study was to assess whether the proposed method can be used for the measurement of acoustic parameters. Therefore, the calculation of the deviation of the acoustic parameters measured with the proposed method in comparison to the parameters measured with the use of a dodecahedron speaker was of vital importance. Similar measurements utilizing the proposed method would benefit from these calculations since the expected deviation from actual values could be estimated. In particular, measurement of RT is very important since low-cost methods usually focus on this parameter.

4.1.1. Reverberation Time

The most striking result to emerge from the data is that of the small differences for RT measurements of the proposed method as compared with measurements with a dodecahedron speaker. Even at low frequency range, where other low-cost methods usually do not accurately predict the RT, the proposed method seems to provide excellent results.

The RT is evaluated from the slope of the integrated impulse response curves according to ISO 3382-1:2009. For all measurements (Figures 6 and 8, Tables 1 and 2) with the Behringer speaker, the mean absolute error compared with measurements with a dodecahedron speaker was less than 0.06 s if the 12 positions method was utilized. Greater mean absolute error (0.08 s) was found for the Genelec speaker. Also, the relative error of the RT with respect to the corresponding JND as presented in Table 1 is below 1.5 JND units for all spaces. Therefore, in acoustic measurements, similar results can be expected if a two-way full frequency range common directional loudspeaker is utilized. However it is worth mentioning that RT is the most stable parameter in acoustic measurements [46].

The Philips speaker did not provide similar results especially in the low frequency range (Figure 13) probably because of the low signal to noise ratio. Hence, one-way design multimedia speakers should be avoided for acoustic measurements with the proposed method.

4.1.2. EDT

As ISO 3382-1:2009 states ‘The early decay time (EDT) shall be evaluated from the slope of the integrated impulse response curves (as the conventional reverberation time). The slope of the decay curve should be determined from the slope of the best-fit linear regression line of the initial 10 dB (between 0 dB and −10 dB) of the decay. The decay times should be calculated from the slope as the time required for 60 dB decay'. Results for EDT (Figures 7 and 9, Tables 1 and 2) present a mean absolute error compared with the measurements of the dodecahedron speaker of less than 0.1 s. One unanticipated finding of the results was that for the midsized room the mean absolute error was 0.17 s, significantly higher than the other spaces.

The results for the EDT are satisfactory, but to a lesser extent, in relation to the results for the reverberation time. A possible explanation of the aforementioned result might be that the differences of the sound fields created between the dodecahedron speaker and the proposed method are more profound in the early stages of the impulse response measurements.

4.1.3. C_{80} and D_{50}

C_{80} and D_{50} parameters are an indication of balance between early- and late-arriving energy as ISO 3382-1:2009 states. The clarity measure C_{80} describes the temporal transparency of musical performances and is calculated from the tenfold logarithm of the ratio between the sound energy arriving at a reception measuring position up to 80 ms after the arrival of the direct sound and the following sound energy. D_{50} ("definition" or "Deutlichkeit") is sometimes used for speech conditions and results from the ratio between the sound energy arriving at the reception measuring position up to a delay time of 50 ms after the arrival of the direct sound and the entire energy.

Results for C_{80} and D_{50} (Figures 7 and 9, Tables 1 and 2) for all measurements (12 positions method) compared with measurements with a dodecahedron speaker show a mean absolute error of less than 1.7 dB. For D_{50} the results show a mean absolute error of 10%. These results are satisfactory but not as much as the results for the RT.

Again, a possible explanation might be that the differences of the sound fields created between the dodecahedron speaker and the proposed method are more profound in the early stages of the impulse response measurements created for each case. Hence, since C_{80} and D_{50} parameters are an indication of early-to-late arriving sound energy, these differences affect the measurement of C_{80} and D_{50} more than the measurement of RT.

Furthermore, there seems to be a deviation of the results at high frequency range, which should be due to the different speaker directivity compared to the dodecahedron speaker. More on this will be discussed in the next section.

4.2. Justification of the Results

One possible explanation for the relative satisfactory results may be due to the fact that requirements for an omnidirectional sound source acquired from ISO 3382-1 and ISO 18233-2006 are met to a certain extent by using a directional speaker. The requirements from ISO 3382-1 are:

1. A maximum deviation of directivity of source in decibels for excitation with octave bands of pink noise and measured in free field is expected (details of the maximum deviation of directivity are presented in the ISO 3382-1).
2. The dodecahedron speaker shall produce a sound pressure level sufficient to provide decay curves with the required minimum dynamic range, without contamination by background noise.
3. Synchronous averaging is possible.

Requirement 2 is sufficiently fulfilled by the proposed method since a common directional loudspeaker can provide sufficient levels of sound pressure without distortion in the whole frequency range. Requirement 3 is also met since synchronous averaging is possible if excitation signals such as ESS and MLS are applied for the measurement of impulse response. So if the requirement for directivity is covered to a satisfactory degree, then the results are justified to a certain extent.

The dodecahedron speaker in essence is a 'dodecahedron arrangement of drivers to approximate the omnidirectional sound radiation characteristics of a monopole' [47]. The method that we propose (12 positions method) mimics the sound field created by a dodecahedron speaker by breaking it down in 12 different sound fields created from a single speaker following the placements presented in the methodology. As a next step these sound fields are summed to mimic the sound field created by the dodecahedron speaker. Hence the directivity of the proposed method as a source will resemble that of the dodecahedron speaker.

However, two of the speakers (Behringer, Willich, Germany and Genelec, Iisalmi, Finland) that were used in this study are a two-way design. This means that above a certain frequency (cross-over frequency) the sound is emitted by the tweeter (or treble) speaker that is designed to produce high audio frequencies, typically from 2000 Hz to 20,000 Hz. Below the cross-over frequency, the sound is emitted from a driver speaker. The dodecahedron speaker is usually comprised from twelve driver speakers. In general, tweeter speakers have higher directivity compared with the typical driver speakers. Hence, differences of the sound field emitted by the dodecahedron speaker and by the proposed method are to be expected. This probably has a profound effect in the measurements of C_{80} and D_{50} with the proposed method, since these parameters are an indication of early-to-late arriving sound energy ratio. In Figure 9 there is a deviation for C_{80} and D_{50} parameters in the high frequency range. These results are likely to be related to the different directivity in the high frequency range of the proposed method compared with the directivity of the dodecahedral speaker.

Concerning the synchronization of the measurements we have noted in the introduction that the impulse response is the temporal evolution of the sound pressure observed at a point in a room as a result of the emission of a Dirac impulse at another point in the room [1].The dodecahedron speaker produces an approximation of a Dirac impulse since the sound filed is not produced in a point in space but rather from 12 drivers emitting sound in synchronization in the same moment in time. Again, the proposed method mimics this approximation by breaking it down in 12 different sound fields created from a single speaker in different moments in time. As a next step the impulses responses are summed in the time domain in such a way that the starting point in time is common for all the impulses.

Finally since the proposed method utilizes MLS or ESS signals, it should also satisfy the additional requirements from ISO 18233-2006 [48]. Enhancement of the signal-to-noise ratio by 20 dB to 30 dB or more compared to the classical method may be obtainable with the use of a proposed method. Also as ISO states the use of loudspeakers typically introduces non-linear distortion in the system. Distortion violates the requirement for linearity in this method. Distortion due to the loudspeaker increases with the excitation level. The user of the proposed method can experiment with the excitation level to obtain the optimum signal-to-noise ratio as ISO 18233-2006 states without distortion from the speaker.

4.2.1. Different Speakers

The results, as shown in Figure 12 and Table 4, indicate that the two-way speakers that were used in the measurements have roughly similar results especially for RT and EDT measurements, which may indicate that similar results may be expected for other two-way speakers. However, it can be seen that the Behringer speaker performs better than the Genelec for RT and EDT measurements. A possible explanation, might be due differences between speakers, such as different cross over frequencies, resonances, energy storage in the cone, different internal volume, phase inaccuracies e.g., This is also presented in the frequency domain (Figure 13) where the excitation of a space with different speakers results in differences of the level spectrums with respect to the dodecahedron speaker. The same is presented in Figure 10, which also occurs for different points in space. It can be seen that while there are differences between the proposed method and measurement with a dodecahedron speaker, there is a similar excitation of the resonant frequencies of the space with both methods. This is an indication of the similarities of the sound fields created from the proposed method and the dodecahedron speaker that is manifested in the frequency domain. Probably some speakers utilizing the proposed method will resemble better the sound field created from a dodecahedron speaker and provide better results.

The Philips speaker which is a one way design has the least satisfying mean absolute error compared with the other speakers for RT measurements, especially for the low frequency range. This is probably due to the low signal to noise ratio caused by the low output of the speaker in this frequency range. However, one unanticipated finding was that the Philips speaker performed better than the other speakers for C_{80} and D_{50} measurements in the high frequency range. Since Philips is a one-way driver design, it seems possible that this result is due to the directivity of the speaker which is closer to that of the dodecahedron speaker. Nonetheless these results need to be interpreted with caution.

4.2.2. Different Speaker Placement Method

For different speaker placements, results (Figure 11, Table 3) indicate that the best method for measuring RT is the method of 12 positions. This method has the least mean absolute error and standard deviation compared with measurements with the dodecahedron speaker. Therefore, this method is to be preferred for RT measurements.

A surprising aspect of the data (Figure 11, Table 3) was that for C_{80} and D_{50} measurements, the methods of 26 and 14 positions have smaller mean absolute error in the high frequency range than the method of 12 positions. Those results were obtained with a two-way speaker (Behringer, Willich, Germany) with a tweeter for the high frequency range It can thus be conceivably hypothesized that because of the higher directivity of the tweeter speaker for the high frequency range, higher number of impulses is necessary in order the emitted summed sound field to resemble the one emitted from the dodecahedron speaker. This rather contradictory result may have possible implications for the improvement of the method that are going to be discussed in the future research section (design of a speaker for high accuracy measurements and auralization).

4.3. Comparison with the Other Low Cost Excitation Sources

The most significant drawbacks of the low-cost sources that have been presented in the introduction are: lack of omnidirectionality (balloon, gunshot, handclap, wooden clapper, shotsell primer), lack of repeatability (handclap), uneven frequency response (balloon, gunshot, firecracker, handclap, wooden clapper) and lack of sound power (handclap, inverse horn design).

The proposed method does not have any of the above drawbacks. With the correct implementation of the method presented in this paper, a common directional speaker can perform as an omnidirectional source. Also, excellent repeatability can be achieved since for every measurement the same sound field is generated. In addition, signal energy tends to be evenly distributed across a wide range of frequencies in the case of a directional loudspeaker of good quality. Hence, if a common directional speaker with a flat frequency response is utilized for the proposed method, then the emitted sound could presumably also approach a flat frequency response. Satisfactory sound power can also be achieved if a directional speaker with enough sound power is used. Research in improving omnidirectionality and the frequency response of the proposed method, is already underway.

Concerning the measurement time of the specific method, it depends on the experience of performing the method and on the number of positions. There is not much time difference compared to measuring with a dodecahedron speaker, since impulse responses can be measured consecutively by changing the speaker position.

Finally, the low-cost of the method can be further enhanced by commercially free software available for impulse response measurements [49]. Also for the generation of the impulse response from the sum of the impulse responses, beside the software that was used (Matlab), digital audio workstations can also be employed with minimum or no cost [50].

4.4. Future Research

The observations from this study have many implications for research on how a single loudspeaker can be used for impulse response measurements. In our view the results constitute an excellent step for the development and utilization of the proposed method. This research has raised many questions in need of further investigation. In terms of directions for future work, research could focus on better utilization of existing directional speakers and also for the design of a single speaker for high accuracy impulse response measurements and possibly auralization.

4.4.1. Database Creation for Existing Directional Speakers (for Impulse Response Measurements)

Our results are encouraging and should be validated for a larger size of existing directional speakers. The current study found differences in the results for different speakers. One possible direction for future research could be the creation of a database for different directional speakers concerning their results for acoustic measurements compared with a dodecahedron speaker. The database will be useful for estimating the expected results when using a conventional speaker for acoustic measurements. The database could also include high gain one-way speaker designs, which because of the similar directivity characteristics with the dodecahedron speaker, could also possibly provide excellent results.

4.4.2. Design of a Speaker for High Accuracy Measurements and Auralization

Results from this study showed that a single directional loudspeaker can be used for acoustic measurements. However our study revealed certain limitations, such as that in the high frequency range the directivity of the two-way speaker design has a negative effect on the results. Future research might help to suggest several courses of action in order to solve this problem and lead to a specific design of a speaker for measurements with better results compared with a dodecahedron speaker. This could hypothetically point to a method with even better results for omnidirectionality than the current dodecahedron speakers. This approach could be utilized for auralization purposes since high accuracy impulse responses could be obtained. Research into solving this problem is already underway. We hope that our research will serve as a base for future studies since this would be a fruitful area for further work.

5. Conclusions

This study provides the first comprehensive assessment of the utilization of a common directional loudspeaker for impulse response and acoustic parameter measurements. It has enhanced our understanding of how impulse responses can be measured with the use of a single speaker. Different common directional loudspeakers were used for mimicking the sound field created by a dodecahedron speaker for impulse response measurements. Different placements of the loudspeakers were performed (twelve positions similar to the twelve positions of the faces of a dodecahedron speaker, different rotations of the loudspeakers for a total sum of twenty six and fourteen positions). Acoustic parameters obtained with the dodecahedron speaker and the common directional loudspeakers were assessed and compared in order to quantify the results. The evidence from this study points towards the idea that RT can be measured with the proposed method with a mean absolute error less than 0.08 s, as compared with actual measurements with a dodecahedron speaker. Our technique is a clear improvement on current low-cost measurement methods and provides the framework for a new way to perform acoustic measurements with minimum cost. The strength of our work lies in the fact that minimum equipment is necessary to perform acoustic measurements. We believe this solution will assist researchers to measure impulse responses at a low-cost in many fields of interest. Our proposed method clearly has some limitations. The most important limitation lies in the fact that a common 2-way directional loudspeaker has a high directivity in the high frequency range when the tweeter speaker is employed which leads to some variations of the results for certain acoustic parameters compared with measurements with a dodecahedron speaker. However this observation has a promising implication for research. This could hypothetically lead to a method with even better results for omnidirectionality than the current dodecahedron speakers, which could also possibly be utilized for auralization purposes. Our investigations into this area are ongoing and seem likely to confirm our hypothesis. This topic is reserved for future work.

Author Contributions: N.M.P. designed the study, conducted the experiment, analyzed the experimental data and wrote the manuscript; G.E.S. supervised the project, provided suggestions and guidance for the work, reviewed and edited the manuscript.

Funding: This research was partially funded by the Technical University of Crete, School of Production Engineering and Management, grant number 81314.

Acknowledgments: We gratefully acknowledge the help provided by Anargyros Serras especially in the early stages of this work. We are also indebted to Smaro Antoniadou for her help during the final measurement section.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. ISO 354: 2003. *Acoustics–Measurement of Sound Absorption in a Reverberation Room*; ISO: Geneva, Switzerland, 2003.
2. ISO 3382-1: 2009. *Measurement of Room Acoustic Parameters*; ISO: Geneva, Switzerland, 2009.
3. Schroeder, M.R. Integrated impulse method measuring sound decay without using impulses. *J. Acoust. Soc. Am.* **1979**, *66*, 497–500. [CrossRef]
4. Farina, A. Simultaneous measurement of impulse response and distortion with a swept-sine technique. In Proceedings of the 108th Audio Engineering Society Convention, Paris, France, 19–22 February 2000.
5. Antoniadou, S.; Papadakis, N.M.; Stavroulakis, G.E. Measuring Acoustic Parameters with ESS and MLS: Effect of Artificially Varying Background Noises. In Proceedings of the Euronoise 2018, Heraclion, Greece, 27–31 May 2018.
6. Leishman, T.W.; Rollins, S.; Smith, H.M. An experimental evaluation of regular polyhedron loudspeakers as omnidirectional sources of sound. *J. Acoust. Soc. Am.* **2006**, *120*, 1411–1422. [CrossRef]
7. San Martin, R.; Arana, M.; Machin, J.; Arregui, A. Impulse source versus dodecahedral loudspeaker for measuring parameters derived from the impulse response in room acoustics. *J. Acoust. Soc. Am.* **2013**, *134*, 275–284. [CrossRef] [PubMed]
8. Martellotta, F. Optimizing stepwise rotation of dodecahedron sound source to improve the accuracy of room acoustic measures. *J. Acoust. Soc. Am.* **2013**, *134*, 2037–2048. [CrossRef] [PubMed]
9. Quested, C.; Moorhouse, A.; Piper, B.; Hu, B. An analytical model for a dodecahedron loudspeaker applied to the design of omni-directional loudspeaker arrays. *Appl. Acoust.* **2014**, *85*, 161–171. [CrossRef]
10. Steele, A. Development of a 3D-Printed Dodecahedron Loudspeaker for Improved Omni-directional Sound Radiation. In Proceedings of the Institute of Acoustics (IOA) 2015 Conference, Harrogate, UK, 15 October 2015.
11. Martellotta, F.; Cirillo, E.; Carbonari, A.; Ricciardi, P. Guidelines for acoustical measurements in churches. *Appl. Acoust.* **2009**, *70*, 378–388. [CrossRef]
12. Trematerra, A.; Iannace, G. The acoustics of the catacombs of San Callisto in Rome. In Proceedings of the Meetings on Acoustics, Montreal, QC, Canada, 2–7 June 2013.
13. Fazenda, B.; Drumm, I. Recreating the sound of Stonehenge. *Acta Acust. United Acust.* **2013**, *99*, 110–117. [CrossRef]
14. Postma, B.; Katz, B. Acoustics of Notre-Dame Cathedral de Paris. In Proceedings of the International Congress on Acoustics, Buenos Aires, Brazil, 11–13 September 2016.
15. Pentcheva, B.V. Hagia Sophia and multisensory aesthetics. *Gesta* **2011**, *50*, 93–111. [CrossRef]
16. Stevens, F.; Murphy, D. Spatial impulse response measurement in an urban environment. In Proceedings of the Audio Engineering Society Conference, Helsinki, Finland, 27–29 August 2014.
17. Iannace, G.; Trematerra, A. The acoustics of the caves. *Appl. Acoust.* **2014**, *86*, 42–46. [CrossRef]
18. Pätynen, J.; Katz, B.F.; Lokki, T. Investigations on the balloon as an impulse source. *J. Acoust. Soc. Am.* **2011**, *129*, EL27–EL33. [CrossRef] [PubMed]
19. Griesinger, D. Beyond MLS-Occupied hall measurement with FFT techniques. In Proceedings of the Audio Engineering Society Convention 101, Los Angeles, CA, USA, 8–11 November 1996.
20. Cheenne, D.J.; Ardila, M.; Lee, C.G. A qualitative and quantitative analysis of impulse responses from balloon bursts. *J. Acoust. Soc. Am.* **2008**, *123*, 3909. [CrossRef]
21. Vernon, J.A.; Gee, K.L.; Macedone, J.H. Acoustical characterization of exploding hydrogen-oxygen balloons. *J. Acoust. Soc. Am.* **2012**, *131*, EL243–EL249. [CrossRef] [PubMed]
22. Rusiana, A.A.; Aves, J.M.C.; Hofileña, K.C. Validation of Balloon Burst Method in Measurement of Reverberation Time in a Classroom. *Int. J. Innov. Sci. Res.* **2015**, *17*, 131–135.

23. Jambrosic, K.; Horvat, M.; Domitrovic, H. Reverberation time measuring methods. *J. Acoust. Soc. Am.* **2008**, *123*, 3617. [CrossRef]
24. Horvat, M.; Jambrosic, K.; Domitrovic, H. A comparison of impulse-like sources to be used in reverberation time measurements. In Proceedings of the Acoustics 2008, Paris, France, June 29–4 July 2008.
25. Abel, J.S.; Bryan, N.J.; Huang, P.P.; Kolar, M. Estimating room impulse responses from recorded balloon pops. In Proceedings of the Audio Engineering Society 129, San Francisco, CA, USA, 4–7 November 2010.
26. ISO 17201-1:2005. *Acoustics—Noise from Shooting Ranges*; ISO: Geneva, Switzerland, 2005.
27. Szłapa, P.; Boron, M.; Zachara, J.; Marczak, W. A Comparison of Handgun Shots, Balloon Bursts, and a Compressor Nozzle Hiss as Sound Sources for Reverberation Time Assessment. *Arch. Acoust.* **2016**, *41*, 683–690. [CrossRef]
28. Freytag, J.C.; Begault, D.R.; Peltier, C.A. The acoustics of gunfire. In Proceedings of the INTER-NOISE 2006, Honolulu, HI, USA, 3–6 December 2006.
29. Lamothe, M.R.; Bradley, J. Acoustical characteristics of guns as impulse sources. *Can. Acoust.* **1985**, *13*, 16–24.
30. Deželak, F.; Čurović, L.; Čudina, M. Determination of the sound energy level of a gunshot and its applications in room acoustics. *Appl. Acoust.* **2016**, *105*, 99–109. [CrossRef]
31. Arana, M.; Vela, A.; San Martin, L. Calculating the impulse response in rooms using pseudo-impulsive acoustic sources. *Acta Acust. United Acust.* **2003**, *89*, 377–380.
32. Ţopa, M.D.; Toma, N.; Kirei, B.S.; Homana, I.; Neag, M.; De May, G. Comparison of different experimental methods for the assessment of the room's acoustics. *Acoust. Phys.* **2011**, *57*, 199–207. [CrossRef]
33. Jambrošić, K.; Horvat, M.; Bogut, M. Comparison of impulse sources used in reverberation time measurements. In Proceedings of the ELMAR 2009, Zadar, Croatia, 28–30 September 2009.
34. Seetharaman, P.; Tarzia, S.P. The hand clap as an impulse source for measuring room acoustics. In Proceedings of the Audio Engineering Society Convention 132, Budapest, Hungary, 26–29 April 2012.
35. Sumarac-Pavlovic, D.; Mijic, M.; Kurtovic, H. A simple impulse sound source for measurements in room acoustics. *Appl. Acoust.* **2008**, *69*, 378–383. [CrossRef]
36. Don, C.G.; Cramond, A.J.; McLeod, I.D.; Swenson, G.G. Shotshell primer impulse sources. *Appl. Acoust.* **1994**, *42*, 85–93. [CrossRef]
37. Polack, J.D.; Christensen, L.S.; Juhl, P.M. An innovative design for omnidirectional sound sources. *Acta Acust. United Acust.* **2001**, *87*, 505–512.
38. Ortiz, S.; Kolbrek, B.; Cobo, P.; Gonzalez, L.M.; De la Colina, C. Point source loudspeaker design: Advances on the inverse horn approach. *J. Audio Eng. Soc.* **2014**, *62*, 345–354. [CrossRef]
39. Papadakis, N.M.; Serras, A.; Stavroulakis, G.E. Mimicking the Sound Field of a Dodecahedral Loudspeaker by a Common Directional Loudspeaker for Reverberation Time Measurements. In Proceedings of the Euronoise 2018, Heraclion, Greece, 27–31 May 2018.
40. Truth B2031A. Available online: https://www.musictribe.com/Categories/Behringer/Loudspeaker-Systems/Studio-Monitoring/B2031A/p/P0252 (accessed on 18 August 2018).
41. 8030B Studio Monitor. Available online: https://www.genelec.com/studio-monitors/8000-series-studio-monitors/8030b-studio-monitor (accessed on 18 August 2018).
42. M30 Measurement Microphone. Available online: https://www.earthworksaudio.com/products/microphones/measurement-series/m30/ (accessed on 15 August 2018).
43. Guidorzi, P.; Barbaresi, L.; D'Orazio, D.; Garai, M. Impulse responses measured with MLS or Swept-Sine signals applied to architectural acoustics: An in-depth analysis of the two methods and some case studies of measurements inside theaters. In Proceedings of the 6th International Building Physics Conference, Torino, Italy, 14–17 June 2015.
44. Elko, G.W.; Diethorn, E.; Gansler, T. Room impulse response variation due to thermal fluctuation and its impact on acoustic echo cancellation. In Proceedings of the International Workshop on Acoustic Echo and Noise Control (IWAENC2003), Kyoto, Japan, 8–11 September 2003.
45. Rindel, J.H.; Shiokawa, H.; Christensen, C.L.; Gade, A.C. Comparison of computer simulation of room acoustical parameters and those measured in concert halls. *J. Acoust. Soc. Am.* **1999**, *105*, 1173. [CrossRef]
46. Segura, J.; Gimenez, A.; Romero, J.; Cerda, S. A comparison of different techniques for simulating and measuring acoustic parameters in a place of worship: Sant Jaume Basilica I Valencia, Spain. *Acta Acoust. United Acoust.* **2011**, *97*, 155–170. [CrossRef]

47. Kleiner, M. *Acoustics and Audio Technology*, 3rd ed.; J. Ross Publishing Inc.: Fort Lauderdale, FL, USA, 2012; p. 8, ISBN 978-1-60427-052-5.
48. ISO 18233-2006. *Acoustics–Application of New Measurement Methods Inbuilding and Room Acoustics*; ISO: Geneva, Switzerland, 2006.
49. Room Eq Wizard. Available online: https://www.roomeqwizard.com/ (accessed on 30 July 2018).
50. Audacity. Available online: https://www.audacityteam.org/ (accessed on 30 July 2018).