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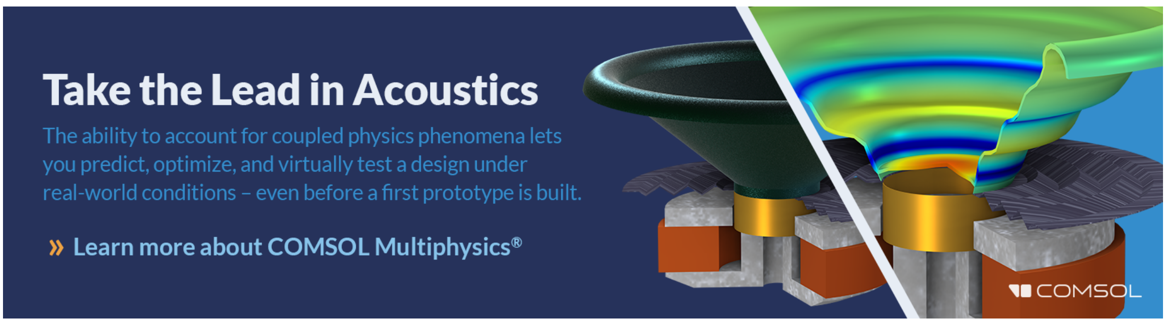

JASA ARTICLE

A proposal for the acoustic characterization of circular bullrings[a)]

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ABSTRACT:
The aim of this paper is to facilitate the experimental measurement of acoustic metrics in circular bullrings in accordance with the ISO 3382 standards and to enable the comparison of acoustic measurements and simulations for the various types of bullrings. The proposal analyzes those items in the standard that exert a certain influence on acoustic measurement in bullrings. Based on the identification of the sound sources and audience areas characteristic of bullfights, several locations are proposed, and the most suitable source-receiver combinations are recommended for the description of the acoustic field of bullfighting. Practical considerations are also made, such as typologies and axes, to be taken into account when referencing sources and receivers, as are the environmental conditions in a space strongly influenced by direct sunlight. As an illustration of the procedure, an experimental campaign in the bullring of Las Ventas in Madrid is carried out. The analysis shows that the proposed procedure is highly suitable for this type of building and provides detailed acoustic information regarding the seats for all the sound sources that participate in the spectacle.
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I. INTRODUCTION

Spanish legislation recognizes bullfighting as an essential part of the historical, artistic, cultural, and ethnographic heritage of Spain. In the diversity of Spanish society, great fans and also many citizens can be found who have expressed their concern regarding the treatment that animals receive during bullfights. The history of bullfighting is also the history of anti-bullfighting, its disputes, and its prohibitions, both religious and civil. It is true that the controversy has changed its axis over time, shifting from the most humanistic, religious, ethical, or utilitarian concepts of classic anti-bullfighting to the current discussion focused on animalism today.

The current bullfighting spectacle is the evolution of the work of the driving, confinement, and slaughter of wild cattle in urban slaughterhouses, which began to be built in Spain during the 16th century.[1] The professionals in this field brought creativity and virtuosity to the most perilous tasks, which were immediately of interest to a diverse range of public spectators.[2,3] In the era when bullfighting festivals were mainly carried out on horseback, the shows were public and took place in city squares. Only in the 18th century, when bullfighting evolved towards slaughter on foot, did the creation of spaces that appropriately housed the public become prevalent. These buildings are similar to ancient Roman amphitheaters; in fact, the Roman amphitheaters of Nimes and Arles (Fig. 1) in France[4] are currently used as bullrings. Once part of the Roman Empire, the Iberian Peninsula owes its bullfighting origins to ancient Roman traditions performed in amphitheaters.

Bullrings are closely related to Roman traditions and therefore a very possible origin in amphitheaters. This origin is shown in the fact that the composition of both venues has the same components: the arena, where the action takes place, and the stands. Even the construction materials usually coincide: bricks, rock, wood, and concrete. Bullrings are generally circular-shaped enclosures and present a wide variety of architectural styles, while amphitheaters usually have an ellipse- or an ovoid-shaped layout and a very similar architectural style. Another main geometric difference, at present, is due to the dilapidated state of the amphitheaters, and hence the stands and/or other areas are often incomplete or absent.

The sounds that are heard in a bullfight, such as music, the audible expressions of the spectators, the bullfighter's taunts, the actions of the animal, and the intercalation of silences, form its unique sound environment. Therefore, for the purpose of these guidelines, it can be considered that voice, music, and ambient sound constitute the main sources of sound, which together form an intrinsic part of the spectacle and allow it to be better interpreted. At this point, it should be borne in mind that a bullfight is mainly a visual spectacle, where sound enriches it in such a way that it can be properly appreciated.

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FIG. 1. (Color online) View of a bullfight in Arenes D'Arles, France. (Source: Carlos Sarrio Yuste).

There is a large body of literature seeking a correlation between objective measurements and subjective perception of the acoustics in halls for mainly classical music and speech performances[5–7] that have been included in the ISO 3382 standards.[8,9] Conversely, there are very few peer-reviewed papers in international journals on enclosures for other types of music and performances.[10] In unroofed performance spaces, the sound field substantially differs from that of a diffuse field and the calculation of decay curves and reverberation times may be questionable.[11] Nevertheless, the most relevant pieces of research on classical theaters[12,13] characterize their sound fields by using impulse responses and their derived parameters in accordance with the protocol of the ISO 3382 standard.

For the purpose of this study, the objective metrics established in the standard have been assumed to characterize the sound field of these venues. The existence of a reference standard for acoustic measurements of all types of performance venues has meant that, in recent years, several studies have agreed on methodological guidelines and the adaptation of parameters, but depend on the peculiar acoustic characteristics of the spaces under study: opera houses, places of worship, places of historical heritage,[14] and ancient Greek and Roman theaters. These studies include that by Pompoli and Prodi,[15] who propose guidelines for conducting acoustic measurements in Italian opera houses, where they integrate certain characteristic aspects in the acoustic study, such as the coupling of the large stage box and the measurement conditions of curtains, stage furniture, and the orchestra pit, and propose the positioning of sound sources and receivers. Bradley,[16] regarding the minimum number of source-receiver combinations required in order to understand the acoustic properties of concert halls, argues that the analysis should be approached based on the purpose of the study: whether it be to compare with the acoustic criteria, to better understand the phenomena, to compare with predictions, or to diagnose acoustic problems.

Martellotta *et al.*[17] propose a set of guidelines to standardize the choice of the positions of sources and receivers in Catholic churches, as well as the configurations of the measurement equipment depending on the purpose of the study. A similar context is found in the contributions on cathedrals by Álvarez-Morales *et al.*[18,19] for whose acoustic description it is essential to contemplate the various liturgical and cultural uses, both spoken and musical, in the different areas of the congregation and audience.

Sharing the character of an open-air space with bullrings, project ERATO[20] researched the real and virtual sound heritage of ancient theatres based on the ISO standard,[13,21] while Bo *et al.*[22] investigate how to accurately measure impulse responses in classical outdoor theatres in accordance with ISO 3382, and include meteorological influences and the effect of background noise.

International publications related to these bullfighting spaces neither exist nor is the bibliography extensive in studies of the natural acoustics of Roman amphitheaters compared to that of the ancient Greco-Roman theaters,[13] despite the fact that their circulation designs are used in modern stadia.[23] Roman amphitheaters are also currently used for various genres of live performances and festivals: musicals, drama, and dance, some of which are staged with seasonal continuity[24] and enjoy fame around the world. Along these lines, the study by Galindo *et al.*[25] of the two performance buildings of the archeologic park of Segobriga, Spain, deserves mention, with analyses of the room impulse-response signals measured in the two venues following the recommendations of the ISO 3382–1 standard and a study of focalization phenomenon in the amphitheater. Non-linear energy-decay curves existed only in the amphitheater for certain sound-source positions in the arena zone (36.9% in the worst case). In addition, the application of beamforming combined with computer simulation by Navvab *et al.*[26,27] to provide the relevant acoustical aspects of the most impressive of the Roman amphitheaters, the Flavian amphitheater in Rome (The Coliseum) and other historical buildings is also worthy of note. The method includes ISO standard descriptors and a 3D format of the sound signals. Data were measured with an Acoustic Camera spherical array, 120 channel data recorders, and a range of acoustic software for data reduction, analysis, computer modelling, and simulation.

Even though these spaces are circumscribed to a specific geographical area in south-western Europe and Hispano-America, their cylindrical symmetry makes them especially interesting from an acoustic point of view.[28] Bullrings are venues for holding bullfights and festivities, and most are conceived as open-air venues.

This paper presents a procedure for the acoustic characterization of circular bullrings based on the reverberation time and other acoustic parameters in accordance with the guidance of the ISO 3382 standards, and for the comparability of acoustic measurements and simulations to be carried out in the various bullrings. These guidelines are to be implemented by the authors in an experimental campaign of the most important bullrings of the Iberian Peninsula, and in the Roman amphitheater of Italica in Seville, which is currently under development.

II. METHODS

A. Natural sound sources in a bullfight

In a bullfight, its sound field is determined not only by the environment to which the sounds belong, by their configuration, and by the way in which they are produced, but also by the way in which they propagate naturally in the environment. Sounds exist that are characteristic of a particular environment, and these determine its unique sonic environment.

The sound sources that play a major role in a bullfight voice, music, and ambient sound, are described in detail below, together with several basic concepts thereof.[29,30] How the combination of these sounds helps to understand the bullfighting event itself is also described.

1. Voice

During the bullfight, although the silence of its protagonists predominates, they do not remain entirely mute. There is dialogue between bullfighters, between bullfighters and their assistants, picadors, and banderilleros (who stab the bull with banderillas), with the people of the passageway, and even with the attending public. There is also an irrational dialogue between bull and bullfighter.

The physical characteristics of the voice themselves (duration, tone, timbre, and intensity) transmit values when one speaks, which listeners perceive and interpret as emotions, sensations, or feelings.

2. Music: Bugle calls and band music

"The bullfight is a festival with music. Music is part of the bullfighting ritual … Music, during the bullfight, is like one more dimension of the colorfulness itself, and is inseparable from the festival."[29] This quote limits, to two manifestations, that which is directly related to the celebration of the bullfight: the bugle calls to signal the change in the three stages of the bullfight (the *cambios de tercio*); and the interpretations of *pasodoble* music in the repertoire of the musical bands that perform in the bullrings.

Commanded by the president of the bullring, these changes in the stages of the bullfight are announced to the public through sounds of bugles and timpani. The fanfares are usually played by two bugles and a set of two timpani. Bugles are frequently replaced by one or two trumpets, and timpani are sometimes dispensed with or replaced by another type of drumroll. In certain bullrings, traditional instruments typical of the region are used, such as shawms and bagpipes.

The musicians in charge of playing these bugle calls are located, as a rule, in the seating area of the bullring diametrically opposite to the presidency. Currently, there are a great variety of bugle calls, most of which have a common origin, based on four or five prototypes. It can be stated that each bullring has its own modality of bugle calls.

In all bullrings, since the beginning of the 19th century, the intervention of a music band has become mandatory. The purpose of the music band is to offer spectators a sample of the unique, genuinely Spanish, and very popular sound of the joyous "*pasodoble*." The *pasodoble* is a musical composition, written in 2/4 time signature subdivided into quavers and tempo *allegro moderato*, which has a clear origin in military marching (late 18th century and early 19th century).[29,30]

The music band is made up of wind instruments (wood and brass), with the minimal addition of percussion. These bands are usually located in the upper part of the bullring, generally in a box reserved for this purpose, in the area out of direct sunlight, and the number of musicians that makeup each band is highly variable. Interventions from the music band take place at certain moments of the bullfight, in the interims, at the request of the public, and when the director of the band considers it opportune.

3. Ambient sound

Ambient sound is of vital importance since it contextualizes and locates the listener in the space and even in the time in which events occur. Ambient sound encompasses two environments:

- The public, including sounds that have highly visible and specific sources and are easily identified, such as the appreciative shouts of *olé!* and applause.
- The sound of the surroundings, including sounds that may have no clear source and are not as audible, such as the sound of the city, breeze, rain, and other weather conditions that emit largely unnoticed sounds.

Since a bullfight is an act involving a great influx of people, the actions of the protagonists can be masked by sounds that overshadow them, mainly from the public and the band. The expressions of the public that form part of the sound environment of the bullfight, however, should not be left aside.

In a bullfight, all the aforementioned sources of sounds and silence are present, and since this is a multi-source environment, they should not be considered separately. In a bullfight, all sounds are essential, without one of which the soundscape could not be fully understood; this means that they are naturally mixed, even though each has its function and plays a specific role.

B. Receiver positions in a bullring

For the purposes of this work, the part of the bullring intended for the public is considered a listening or audience area. For greater precision, the barrier or fence that surrounds and separates the circle of arena, where bulls run and fight from the rest of the bullring delimits it into two acoustic zones: the ring, also called the arena, where two white circular lines delimit three concentric areas, and the listening area, which includes the passageway, stalls, grandstands, and boxes.

The fence or barrier immediately next to the ring itself, which serves as a defense for the bullfighter over which he/she can jump when pursued by the bull, is, as a general rule, 1.6 m tall, and is 1.3 m tall for that of the passageway, since the level of the floor of the latter barrier is higher than that of the ring. The circular passageway where the bullfighters, their assistants, and employees of the bullring take refuge, and which runs between the main barrier and the fence delimiting the first-row seats, is usually 1.6 m wide. In the fence, on the inside of the ring, there are a convenient number of rectangular "*burladeros*," which are short fences of the same height and construction as the barrier but placed parallel to it within the ring, with a separation of only approximately 35 cm from the main perimeter, so that the bullfighter can take refuge behind them by entering from the side and the bull cannot enter. Moreover, within the passageway, there are "*burladero*s" to shelter employees and assistants who maintain permanent communication with the bullfighter, and due to the nature of their work, must remain between the barriers. All these people follow the spectacle with special attention through sight and hearing, which is why the passageway is considered a listening area of prime importance.

It is common practice for each spectator who attends a bullfight to do so while occupying a particular seat or specific location from among those arranged in the various designated areas. These localities are grouped into areas with different names.[29] The stalls occupy the lower circular part of the building, built of stonework or brick, that surrounds the arena behind the barrier in a stepped graduated way, as in Roman circuses and amphitheaters. This constitutes the widest area for spectators in bullrings. The first row of the first tier of the stalls is called the barrier, and the counter barrier is the name of the first row of the second tier of stalls. A circular access aisle is usually located between these two tiers in the stalls and the large number of rows that continue upwards, of which the first row is called the front row, with the other rows numbered in ascending order from bottom to top.

All the stands that make up the two tiers are divided into various segments, also numbered and separated from each other. The separation and price for a seat in each of these segments varies depending on whether it is in the shade or direct sunlight, and whether it is close to the center of the arena. Each segment has access through an opening in the form of a short tunnel called a vomitorium.

Above these segments, one or two more stories are erected in the form of a continuous circular balcony with a railing and the grandstand area that its width allows. In the shaded part of the lower balcony or grandstand, and some bullrings of the upper grandstand, there are usually private boxes: compartments of seats that have the same characteristics as those in theatres. The central box, called the presidency or royal box, is usually elaborately decorated, especially in bullrings where the presence of royalty and/or military leaders has been frequent.

C. Reference axes in bullrings

In this section, practical considerations are made for the better execution of acoustic measurements in a bullring, such as the axes and coordinates, in order to reference sources and receivers, and for the environmental conditions to be controlled in a space influenced by the sunlight in certain areas.

Bullrings are organized according to the logistics of their use and construction based on axes that determine the layout and composition of their elements.[31] There are therefore three differentiated axes:

(1) Presidency-bullpens axis. Formerly, the main entrance (exterior) was made to coincide with the presidency balcony, usually located in the shade, and, on the opposite side of the bullring, the bullpens were located.
(2) Sun-shade (geographical N-S) axis. The orientation of this axis of sun and shade, which varies according to the latitude of the building and is relative to the time of day of the spectacle, is especially interesting in the analysis of bullrings, since it explains the location of the defining elements on the floor plan of the building.
(3) Urban area-main entrance axis. With the passage of time, this axis has gained greater interest, thereby making the main gate of the bullring coincide with the main routes of urban growth.

These systems of axes are found in many bullrings, although they are not fulfilled perfectly in every case. In certain cases, the urban axis, the interior axis of the presidency-bullpens, and the solar axis all coincide.

From the acoustic point of view, for the correct location of the positions of sound sources and receivers, and especially for better comparability of acoustic measurements between the different types of bullrings, the sun-shade axis, or simply the solar axis, is the most pertinent for several reasons: the disposition of the public for the different segments of shade and sun; the performance of the bullfight itself, which is concentrated most of the time in the shaded zone; and the influence on the sound propagation by certain factors. These factors include the geometric divergence from the main sources of voice and music that are located in the shaded area, and the backscattering effect from the atmosphere depending on temperature and humidity: factors that are difficult to verify with *in situ* measurements, but with due consideration, could be analyzed in acoustic model simulations.

In order to graphically show the arrangement of these axes, and also as a tribute to a building that today would stand as a magnificent monument had it not been demolished in 1930, the Monumental Bullring of Seville is presented. This bullring, inaugurated in 1918, was of major significance[32] and can be observed in Fig. 2.

Starting from the solar axis, to facilitate positioning, the 12-h clockwise nomenclature is proposed.

D. Location and combinations of sound sources and receivers for acoustic measurements

Having identified the main sound sources that exist in the bullfights and how they are mixed in a multi-source

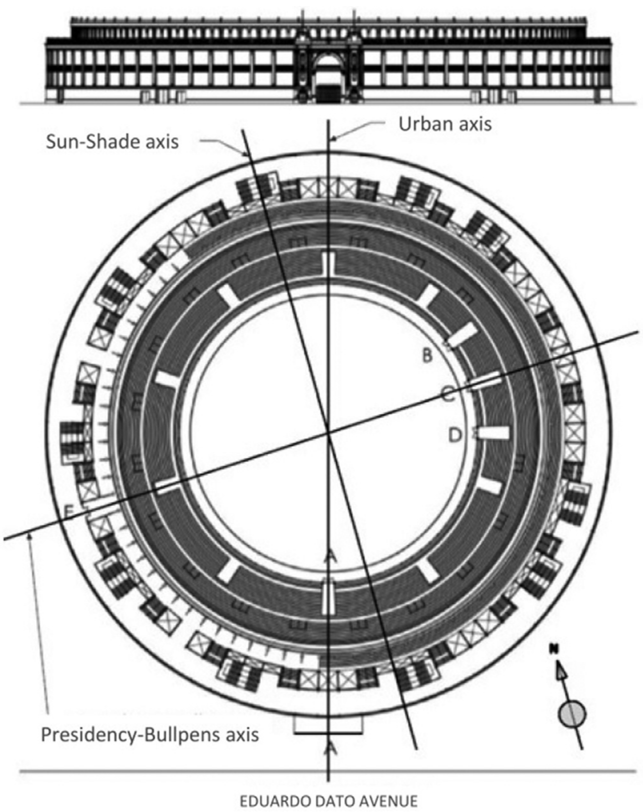

FIG. 2. Main elevation and floor plan of the stalls, grandstands, and boxes of the Monumental Bullring of Seville demolished in 1930: (A) Main Entrance; (B) Gate of Bullfighters and their assistants; (C) Bullpens; (D) Gate for the removal of dead bulls; (E) Royal Box. (Source: Carrasco *et al*. Ref. 32)

environment, the *a priori* detailed analysis of the sound field in bullrings appears to be complex. Nevertheless, to successfully carry out measurements for the acoustic characterization and comparability of the bullring of Las Ventas in Madrid with other bullrings, the following locations of sound sources are proposed in accordance with previous[33] conference data:

- S1: In the center of the ring, also called "in the watering mouth," due to its central symmetry and equidistance to all the points of the bullring.
- S2: In the second of the three delimited concentric areas of the arena, where most of the bullfighting takes place. Specifically, at the intersection of the 7 m line, which indicates the terrain where picadors should be located, with the reference radius of 6 o'clock, close to the "burladero" of the bullfighters (Segment 9).
- S3: In a central place in the box reserved for the music band. Specifically, Box 29 of the band, on the lower tier of the grandstand (Segment 2).
- S4: Where the buglers and timpani musicians are seated. Front row of the vomitorium tunnel (Segment 4).
- S5: In order to characterize the ambient sound of the audience. Specifically, at the intersection of the reference radius of 4 o'clock with row 7 of the lower tier of the stalls (Segment 7), where the most bustling and critical audience is seated.

However, there are bullrings that, due to either their size or custom, may not encounter all the sound sources indicated, which would therefore entail precise changes to be made, while always maintaining a minimum of three positions of sources, in order to comply with the specifications in the ISO 3382–1 standard.

Taking Las Ventas de Madrid as an example, Fig. 3 graphically shows the proposed location of these sound sources.

Recent pieces of research on other types of enclosures have analyzed the influence of the location of sound sources on the acoustic parameters measured, and have made use of the concept of the Just Noticeable Difference (JND) to identify the perceptible differences (see Table A.1 of ISO 3382–1). They have concluded that, although the position of the source bears little influence on the spatial averaging of the reverberation time, it does affect the remaining acoustic parameters, especially the value of *G*, the sound strength, which decreases with the source-receiver distance, and hence the importance of standardizing the source and receiver positions, such as those observed below.

The arrangement of the public around the passageway, stalls, grandstands and boxes, and the central symmetrical configuration of most of the bullrings, facilitates the location of the receiving positions. However, it must be taken into account that certain bullrings present irregularities in the outline of the ring itself: some are octagonal, and others are even quadrilateral, which would entail making adjustments in the positioning. There are also bullrings that incorporate elements and areas that break the uniformity of their architecture, such as special boxes and sectors with uneven seating, that force corrections to be made and alternatives to be sought to the proposal presented below.

The number and location of receiver positions is a function of the bullring capacity and the expected spatial variability of the results. Bullrings are venues with a large capacity: most can contain in excess of 2000 occupants, as indicated in Table A2 of the ISO 3382–1 standard, and therefore a number greater than the ten microphone positions specified in the standard would be necessary. The final choice regarding their number and location is a result of a compromise between the need to have an acceptable level of precision in the variation of the results in terms of the JND of the acoustic parameters of interest, and the time available to carry out the measurements. A good practice, once the measurements are carried out, would be to analyze the spectral average values of each of the acoustic parameters and their spatial dispersions in terms of the respective differential thresholds (JNDs).

The receiver positions should be selected taking the sun-shade axis as a reference, between the listening areas in which listeners are usually found, more specifically at the intersections of the passageway barrier or the rows of the lower tier of stalls, grandstands, and boxes with any of the 12 reference radii. They are distributed by taking advantage of the central symmetry and by avoiding those areas that lack direct sound, which in turn depends on the

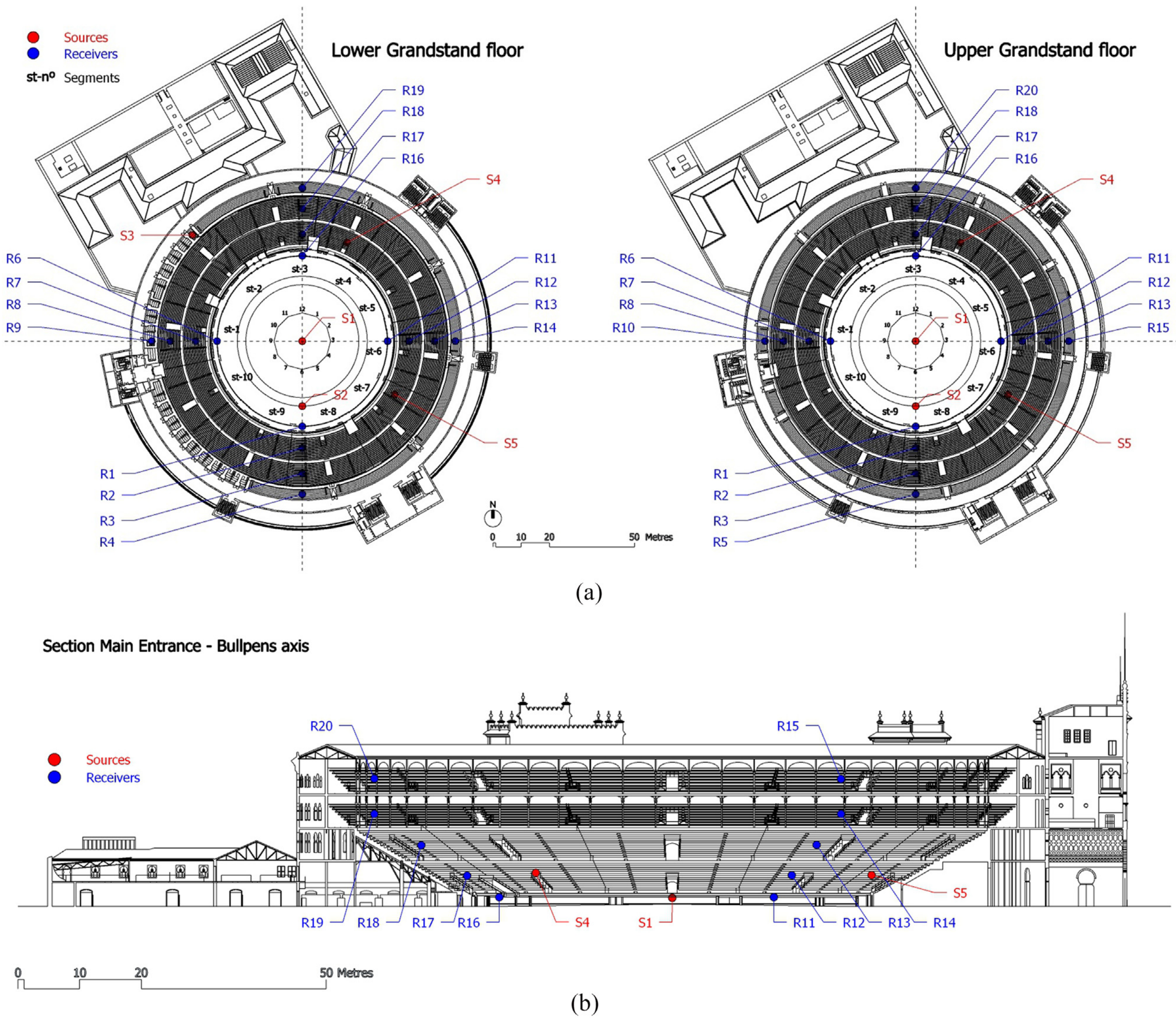

FIG. 3. (Color online) The bullring of las Ventas in Madrid showing its segments (st), and the source (S) and receiver positions (R); (a) Grandstand floors; (b) Section.

positions of the sources, especially in the grandstands and boxes when the sources are displaced from the center of the ring, which determine the source-receiver configurations as can be observed in the following section.

Certain criteria must be met in order to meet the requirements of the ISO 3382 standard: the microphone positions should be arranged away from each other by at least 2 m; reflective surfaces at a distance of less than 1 m should be avoided; and receivers should be moved away from source positions, and placed at a height of 1.2 m above the ground to represent the seated public. Measurements are repeated with the source rotated in at least three directions. The resulting parameters related to the various directions of the source are arithmetically averaged. For listeners who are standing in the passageway, the height should be 1.6 m, as an exception to the rule.

The configuration of the bullrings as open buildings that are generally circular and uncovered does not present any spatial complexity as occurs in other types of venues. The multi-source character in which the bullfight takes place does require a reasonable number of combinations for the correct definition of its sound field, and therefore for sufficient acoustic information to form a good understanding of its sounds.

Special attention should be paid when establishing the various source-receiver combinations in terms of the different zoning of sun and shade, and of the existence of areas that lack direct sound depending on the position of the source, which often happens in certain stands and boxes when the sources are out of sight of the spectator.

A measurement setup should include at least three source locations (S1 and two others) to comply with standardized protocol, depending on the primary purpose of the measurement. However, in order to make better use of the measurement session, it is recommended that apart from the S1 source position (which should always be used in combination with all receivers), when more than two source positions are used, a smaller number of receivers can be employed. The number of source-receiver combinations that are proposed according to the authors' experience[33] in Las Ventas bullring amount to 71, as indicated in Table I. These are complemented by the floor plans and section plan of Fig. 3. It can be observed that given the large dimensions of the enclosure, and in order to facilitate the movement of equipment and cables in acoustic measurements, the microphone receivers have been located concentrated in the hourly directions 3, 6, 9, and 12 o'clock, respectively, which correspond to the East, South, West, and North directions, respectively.

E. Experimental setup

Measurements were carried out on the bullring of Las Ventas in Madrid without the presence of the public, while following the recommendations of the ISO 3382–1 standard.[8] There was no wind during measuring times (air velocity less than 0.5 m/s) and environmental conditions were monitored by means of measuring the temperature with $\pm 1\,^{\circ}$C of accuracy (mean value of 18 °C for the whole measurement) and relative humidity with an accuracy of $\pm 5\%$, (mean value of 51.7% for the whole measurement). In order to carry out the measurements *in situ*, the following equipment has been used:

The signal generation, acquisition, and analysis process have been carried out with the IRIS software package,[34] and through the MOTU 4PRE HYBRID sound card (MOTU Inc., Cambridge, MA). The excitation signal is a sweep of sinusoidal signals with a duration of 30 s in order to achieve an adequate signal-to-noise ratio and a frequency range from 20 to 20 000 Hz. The excitation signal was reproduced in the space using a DD5 García Calderón ultralight dodecahedral omnidirectional source (Ingeniería Acû¤stica García-Calderón, Madrid, Spain) located at 1.50 m above floor level, amplified with a B&K 2734-type power amplifier (Hottinger Brüel & Kjaer A/S. Nærum, Denmark) (Fig. 4). The room Impulse Responses (IRs) were captured with the Core Sound TetraMic microphone array (Core Sound, LLC, Teaneck, NJ) pointed in the same direction as the seat, which allows temporal and spatial (three-dimensional, 3D) information to be incorporated.

The binaural IRs were captured with a Head Acoustics HMS III torso simulator (Head Acoustics GmbH, Herzogenrath, Germany) (Code 1323) and a B&K 2829 microphone polarization source. In all cases, microphones were placed at 1.20 m from the floor except when placed in the passageway at 1.60 m (Fig. 4). Recordings correspond to five source positions (center of the ring, displaced ring, music band, bugles, and audience) and 20 microphone positions (four in the passageway, eight in stalls, and eight in the grandstands) with a total of 71 source-receiver combinations, as noted in Sec. II D, instead of the possible $20 \times 5 = 100$.

Impulse responses recorded by the IRIS system show a sufficient range in the impulse-response-to-noise ratio (INR) (INR > 45 dB in each octave band) for the decay ranges in each band of interest; see Fig. 5. The background noise level was recorded with a PCE-430 Class I Sound Level Meter (PCE Instruments, Meschede, Germany) in the various sessions of measurements, whereby the background noise level was found to be very constant and its spectrum to

TABLE I. Distribution of receivers in the bullring of Las Ventas in Madrid in accordance with the recommendations.[a]

Source	Receivers in passageway and stalls	Receivers in boxes and grandstands
S1	R (1,2,3,6,7,8,11,12,13,16,17,18) Total 12 (100%)	R (4,5,9,10,14,15,19,20) Total 8 (100%)
S2	R (1,2,3,6,7,8,11,12,13,16,17,18) Total 12 (100%)	R (4,5,9,10,14,15) Total 6 (75%)
S3	R (1,2,3,6,7,8,11,12,13) Total 9 (75%)	R (4,5,14,15) Total 4 (50%)
S4	R (1,2,3,11,12,13) Total 6 (50%)	R (4,5,14,15) Total 4 (50%)
S5	R (1,2,3,6,7,8) Total 6 (50%)	R (4,5,9,10) Total 4 (50%)

[a]See Ref. 33.

FIG. 4. (Color online) View of the segments 2, 3, and 4, stalls, lower and upper grandstands of Las Ventas bullring in Madrid, with the sound source at position S2 and the receiver with the tetrahedral microphone without wind protection in the passageway, R1. (Source: the authors).

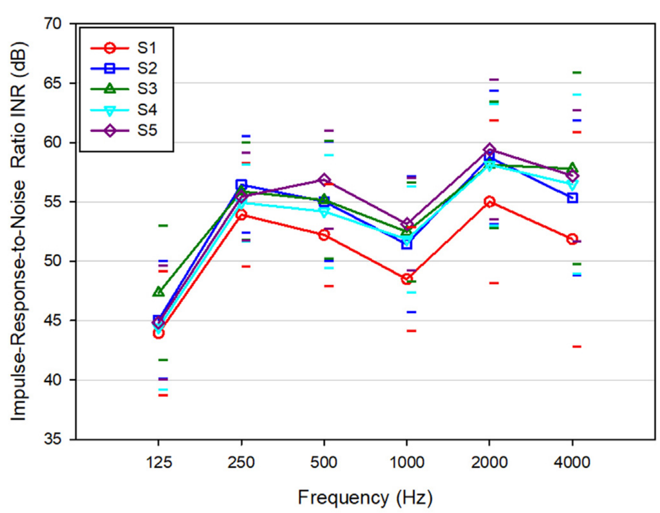

FIG. 5. (Color online) Spatial average per source in octave bands of the INR parameter. The spatial dispersion corresponds to the standard deviation shown with horizontal bars.

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correspond to traffic noise, averaging 5 min of silence and measuring 37.4 dBA.

III. APPLICATION OF THE METHODS TO LAS VENTAS BULLRING

The development of buildings with specific characteristics for holding bullfights is related to the popularization and professionalization of bullfighting performances.

The bullrings, also known as bullfighting arenas, are generally circular and uncovered enclosures, where bullfights are held. Of more modern construction there are also covered bullrings. Their architectural styles are diverse and depend on their greater or lesser degree of antiquity.[31]

Between the years 1913 and 1920, bullfighting acquired such popularity in Spain that it prompted the construction of a large bullring in Madrid (called the Monumental Plaza), which would open the performance to the entire city and lower the price of tickets.

The architect José Espelius Anduaga designed the bullring of Las Ventas, projected in the neo-Mudejar style in exposed brick on a metallic structure, and construction began in 1919. Following his death ten years later, the work was continued by Manuel Muñoz Monasterio until its conclusion in 1931. Since 1994, Las Ventas bullring has been considered "an asset of cultural interest as a historical and artistic monument."

Its geographical coordinates are 40°25′55″ N, 3°39′48″ W, and it is the largest bullring in Spain. With a capacity of 23 798 spectators, it is the third-largest bullring in the world, after those in Mexico City (CDMX, Mexico) and Valencia (Carabobo, Venezuela). It is also the second largest in terms of the diameter of its ring, at 61.5 m, after the bullring in Ronda, (Malaga, Spain), which is 66 m in diameter.[29] The width of the passageway of Las Ventas is 2.2 m. Its locations are distributed across ten segments (four segments of shade, numbered 1, 2, 9, and 10; two of sun and shade, numbered 3, and 8; and four of sun, numbered 4, 5, 6, and 7), whereby each segment is divided into stalls, and grandstands (see Fig. 3).

The number and arrangement of segments in bullrings changes from one place to another: in general, the presidency box and the royal or authority box are in the shade, and hence in the western area. It is also common in all bullrings that the action of the picador is carried out diametrically opposite to the bullpen gate.

In accordance with the bullfighter's wishes and the temper of the bull, the bullfight is generally proceeded in this bullring in the following way: the action of the picador in front of segment 7, or between segments 7 and 8; the muleta (crutch) in the shade, in front of segments 9, 10, or 1, 9 being the most common; and the killing of the bull in front of segment 9 or between segments 9 and 10.

The music band is located in box number 29 and the bugles and timpani are found in segment number 4.

Segment 9 is therefore the best seating area in this bullring to see the work up close, and it is also where the matadors' burladero is located. Segment 8 is known as "the cape segment" because bullfighters usually hang their riding capes on the barrier seats in this segment.

Segment 7 is where a more boisterous audience is seated: these spectators tend to be more critical in terms of the actions of the bull and the bullfighter.

This bullring is divided by heights into stalls, boxes, and grandstands (Fig. 4):

- The stalls themselves have three more divisions. The first tier of stalls comprises the lowest part for the "barrier" (first row of public seats), "counter barrier," and "low front" seats. The second tier consists of 14 rows of stone seats. And the third tier comprises a first row of seats called "high front" seats, and 13 more rows of seats also made of stone.
- The boxes are in the first covered section of the bullring above the stalls. On this story, segments 1, 9, and 10 house boxes, with the remaining segments holding seven rows of seats.
- The highest part of the bullring presents the second covered section of the bullring. Where this story of grandstands holds seven rows of seats of which the first row is called the "front of the grandstands."

Most materials of the bullring surfaces have low coefficients of absorption, with the exception of the sand in the arena, the fictitious surface of the sky over the bullring, and that of the audience (if in attendance). All these elements remain constant with the exception of the attending public. Not all bullfights are held with the same number of people: the audience can vary from just a few spectators to full capacity. As an indication, the absorption properties of the materials of the Madrid bullring, which will be employed in future simulations, are indicated in Table II.

IV. PARAMETRIC ACOUSTIC ANALYSES OF LAS VENTAS BULLRING

In this section, three types of analyses are proposed versus the frequency of the acoustic descriptors grouped in pairs: decay-time parameters, T_{30} and EDT; energy parameters, C_{80} and D_{50}; energy parameters, T_s and G; directional parameters, J_{LF} and L_J; and spatial parameters, $IACC_E$ and $IACC_L$. Finally, two acoustic indicators are discussed as a function of source-receiver distance, STI and G_m (average of mid-frequencies); the spatial variation in terms of JND and the mean or averaged single value of each acoustic parameter for the positions to the center in the bullring are also plotted.

The first analysis studies the averaged behavior at all receivers for each position of the sound source in Las Ventas bullring. In this case, there are five source positions (average values of 20 measurements at S1, 18 measurements at S2, 13 measurements at S3, 10 measurements at S4, and 10 measurements at S5), and therefore five curves are obtained. The second analysis studies the averages of the results of the acoustic parameters corresponding to the radial positions: 6 o'clock or South direction (25 measurements), 9 o'clock or West (18 measurements), 12 o'clock or North (8

TABLE II. Finishes of the Madrid bullring: materials, surface (%), and absorption coefficients.

Material	Area (%)	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
Smooth concrete, painted or glazed	15.1	0.01	0.01	0.01	0.02	0.02	0.02
Walls, plasterwall	4.4	0.12	0.10	0.08	0.06	0.06	0.06
Solid wooden door	3.3	0.14	0.10	0.06	0.08	0.10	0.10
80% absorbent	1.7	0.80	0.80	0.80	0.80	0.80	0.80
Marble or glazed tile	9.9	0.01	0.01	0.01	0.01	0.02	0.02
Lime cement plaster	4.9	0.02	0.02	0.03	0.04	0.05	0.05
Pine wood	3.6	0.10	0.10	0.10	0.09	0.10	0.12
Empty chairs, upholstered with vinyl	1.0	0.10	0.15	0.25	0.25	0.25	0.25
Granite stone	16.5	0.11	0.10	0.10	0.10	0.08	0.08
Brick, unglazed	7.7	0.03	0.03	0.03	0.04	0.05	0.07
Smooth unpainted concrete	1.8	0.01	0.01	0.02	0.02	0.02	0.05
Sandy soil	6.6	0.11	0.13	0.15	0.23	0.25	0.33
5 mm rubber carpet on concrete	0.6	0.04	0.04	0.08	0.12	0.10	0.10
Free field	23.0	1.00	1.00	1.00	1.00	1.00	1.00
Mean absorption coefficient		0.258	0.260	0.265	0.276	0.294	0.364

measurements), and 3 o'clock or East (20 measurements) in Las Ventas bullring. These are all recorded for each position of the source, depending on the frequency, and therefore four curves are obtained. Finally, the third analysis takes place by studying the averages of the results of the acoustic parameters in Las Ventas bullring by averaging the results obtained for each source according to the distance from the receivers to the center of the arena: passageway, 15 measurements; lower tier of stalls, 15 measurements; upper tier of stalls, 15 measurements; lower grandstand, 13 measurements; and upper grandstand, 13 measurements. Consequently, five curves are obtained. Results corresponding to the objective acoustic parameters correlated with musical perception have been included for all positions of the sound sources and not strictly for the position of the music band S3, and that of the buglers and timpani musicians S4, since other musical events are usually held in bullrings with the musical source in the arena (centrally and/or displaced) or in the audience area as in other roofed circus-theaters.[35]

In all cases, the spatial dispersion is studied through the standard deviation, and perceptual differences in terms of JND are obtained from the standard deviation of the measured values. In all the plotted graphs of the acoustic parameters, the horizontal marks correspond to the standard deviation values, while the dashed black lines, as a reference of the perceptual variability, correspond to $\pm$ 1 JND of the values obtained with source S1, at the South radius, and the lower tier of stalls, respectively. The analysis is completed with the study of the dispersion of the results in terms of the number of JNDs of each parameter in each of these situations.

A. Decay-time parameters

Impulse responses recorded by the IRIS system show a sufficient range in the INR (INR $>$ 45 dB in each octave band; see Fig. 5) for the decay ranges in each band of interest. Astolfi *et al.*[12] pointed out in the ancient open-air theater of Tyndaris that "the application of the ISO recommendations to the open-air case study is questionable in the evaluation of the correct decay curves, of the measurement uncertainty (using Integrated Impulse Response method) and of the repeatability of the IRs." In the present case, the only limitation to the recommendations of the standard is the correct evaluation of the energy decay curves. In order to evaluate these curves, the authors use the values (provided by IRIS platform) of T_{20} reverberation time, parameter C, curvature, and the non-linearity parameter, ξ, defined in Annex B of the ISO 3382–2: 2008 standard[9] to study the linearity of the decay curves. These results show that the criteria established in the ISO standard are verified in 87.2% of the combinations (71 source-receiver combinations for 6 octave bands and for 2 non-linearity parameters). In no case are both criteria violated at the same time in all frequencies. Of the 12.8% that fail to comply, 10.1% correspond to failures in ξ with the highest contribution for the extreme bands of 125 and 4000 Hz. The most notable non-linearity occurs when the source is in the S2 position at all frequencies for receivers R1 to R5, and for low and high frequencies in receivers R16 to R18 (all of these receivers with the source on the same radial axis). For receivers R1 to R5, this fact is due to the proximity of the barrier, which decreases (compared to other source positions) the number of arriving early and late reflections. For receivers R16 to R18 it is due to late energy focalizations (Fig. 6). The behavior of the energy decay curves is fundamentally of two types: cliff decay and plateau decay[36] (see Fig. 6). In the first case, the sudden decrease occurs in the first 5 dB of the decay, which allows linear falls to be obtained for the calculation of T_{30} and justifies the high percentage of IR according to the standard. The comparison of the spatially averaged values of T_{20} as a function of frequency shows an almost total coincidence with T_{30} in all analyses, with only small variations between the two at 125 Hz.

Figures 7(a), 7(c), and 7(e) show the spatially averaged T_{30} results for each source, for the bullring receivers according to the geographic directions for all sources, and the receivers according to their distance from the center of the

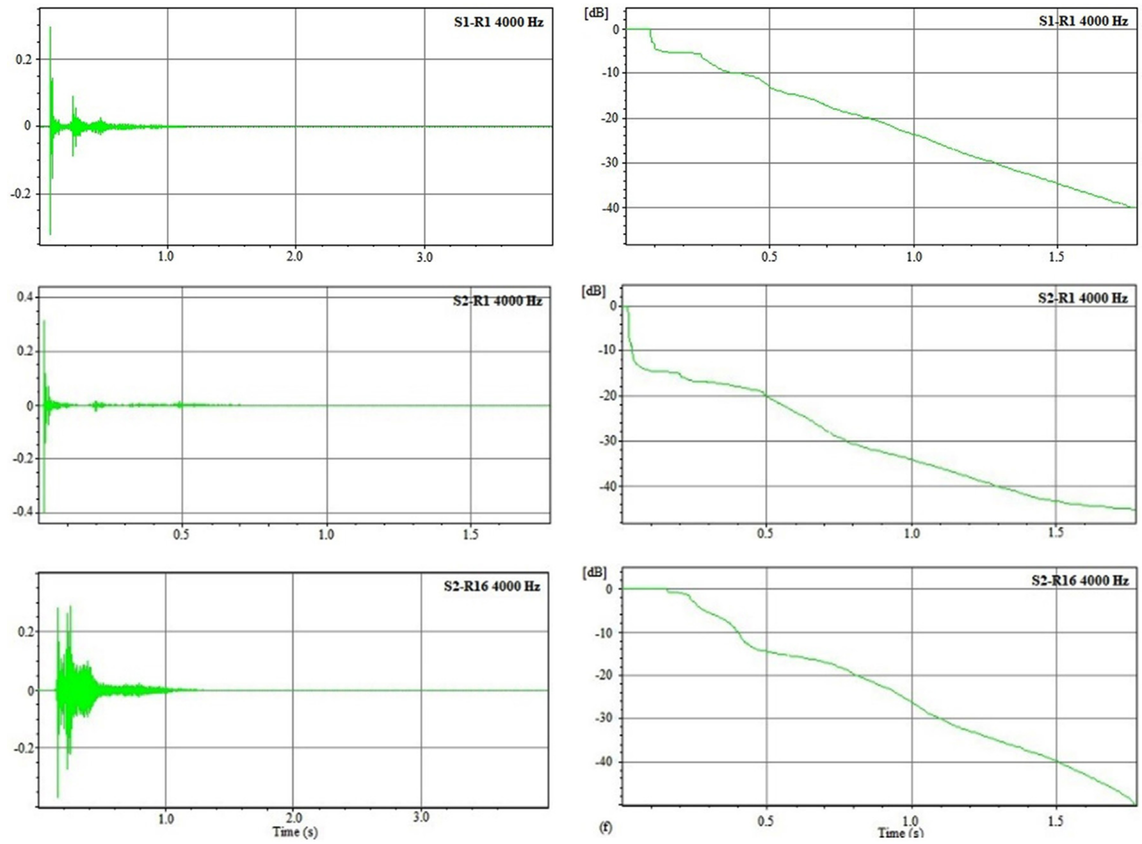

FIG. 6. (Color online) Normalized impulse responses (left) and Schroeder curves (right) for the sound source-receiver combinations S1–R1, S2–R2, and S2–R16 for the 4000 Hz octave band in Las Ventas bullring.

bullring for all sources, respectively. The three graphs show that the results present very little variation for the different curves obtained. The reverberation time presents a maximum for the frequency of 250 Hz in all cases with a drop at high frequencies as a consequence of air absorption. The mean reverberation time T_{30m} of the space is approximately 3.21 s (spatially averaged considering 71 measurements with each source, at frequencies of 500 and 1000 Hz). The spatial dispersion is similar at all frequencies, and the maximum value is presented in all cases at the frequency of 125 Hz. In terms of the number of JNDs, the worst results are obtained at low frequencies. For the average of all 71 measurements carried out, the spatial dispersion in terms of the number of JNDs lies between 0.8 and 2 for the six octave bands, and, for the average value of mid-frequency bands, T_{30aver} is 0.8 JND. In the case of the EDT parameter, correlated with the perceived reverberance of listeners, Figs. 7(b), 7(d), and 7(f) present, as expected, a more complex behavior with frequency due to the high dependence on the source-receiver position in this type of enclosure, with maximum values at the frequencies of 250 and 1000 Hz. Figure 7(b) shows how there are appreciable differences in the spectral behavior of the different positions of the sound source, with the highest values of the parameter at medium and high frequencies when the source is located in the center of the arena. These differences in the average values are smoothed out, although subjectively perceptible when the analysis is carried out in terms of radii or concentric rings. The mean early decay time EDT_m (single values obtained by averaging the 71 measurements at the mid-frequency octave bands) of the space is approximately 2.87 s. Spatial dispersion is much higher at all frequencies, especially at low frequencies, with high variations (up to 13 JNDs) in terms of JND numbers in all analysis circumstances. For the average of all 71 measurements, the spatial dispersion is between 6.6 and 9.6 JNDs for the six octave bands, and the average value of mid-frequencies, EDT_{aver}, is 6.8 JNDs.

B. Energy parameters

Regarding the energy parameter C_{80} [Figs. 8(a), 8(c), and 8(e)], associated subjectively to the perceived musical clarity, it should be noted that they present the inverse behavior of reverberation time versus frequency and that there are variations of the parameter according to the different source positions. The highest values of the clarity parameter are presented for the S2 position due to the contribution of the receivers closest to that source, and the lowest values occur for the position of the receivers located in the N direction. These differences in the averages are subjectively perceptible when the analysis is carried out in terms of sound sources or radii and are smoothed out for concentric rings. Spatial dispersion is very similar at all frequencies and, in terms of the number of JNDs, the greatest variations

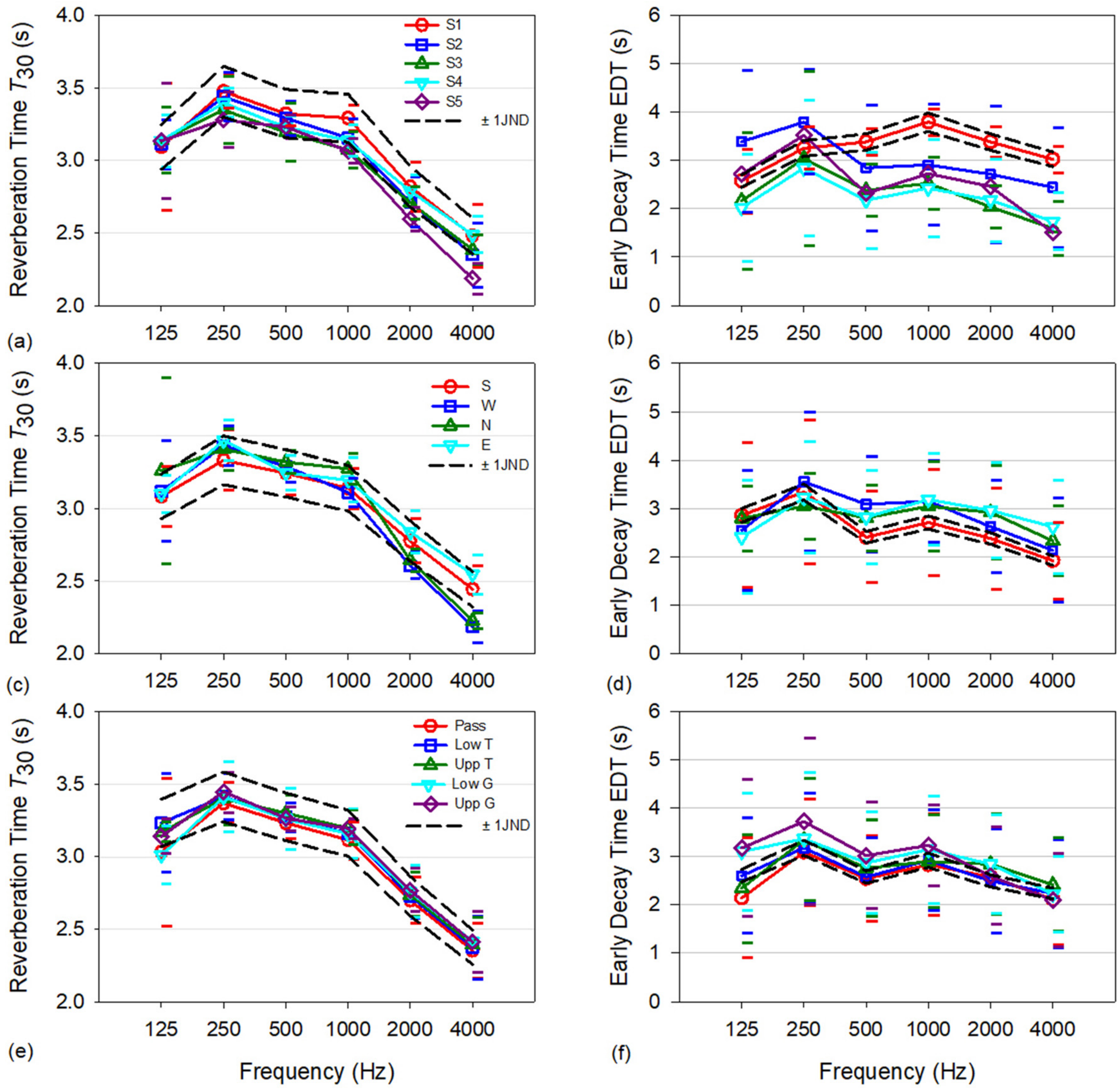

FIG. 7. (Color online) Spatial averages as a function of frequency in the bullring of Las Ventas in Madrid: (a) for Reverberation Time for the five source positions S1–S5; (c) for the four geographical directions, S, W, N, E; and (e) for the positions of the receiver to the center of the bullring (passageway, Pass; lower tier of stalls, Low T; upper tier of stalls, Upp T; lower grandstand, Low G; and upper grandstand, Upp G). The same is given for Early Decay Time in (b), (d), and (f), respectively. Horizontal bars correspond to the standard deviations. Dashed black lines correspond to ± 1 JND of the values obtained with source S1, at the South radius, and at the lower tier of stalls, respectively.

occur in the positions of the source displaced from the center of the bullring S2–S5, reaching up to 6 JNDs at certain frequencies. For the average of all 71 measurements carried out, the spatial dispersion ranges between 3.6 and 4.4 JNDs for the six octave bands, and the average value of mid-frequency bands, C_{80aver}, is 4.0 JNDs. The average results are more consistent when the analysis is performed in terms of zones. The mean C_{80m} of the whole bullring is on the order of 1.52 dB, when considering all the sound sources.

Regarding D_{50}, the definition of speech, the spectral behavior is very similar to C_{80}, as expected, and this similarity is maintained in the three cases of analysis of the averages [Figs. 8(b), 8(d), and 8(f)]. The spatial dispersion is similar in all frequencies and analyses; in terms of the number of JNDs, such as in C_{80}, the greatest variations are presented in the positions of the source displaced from the center of the bullring S2–S5, reaching up to 6 JNDs at certain frequencies. For the average of all 71 measurements, the result is also similar to C_{80}, the spatial dispersion ranges between 3.9 and 4.3 JNDs for the six octave bands, and the same average value of the mid-frequency bands, D_{50aver}, is 4.0 JNDs. The mean D_{50m} value for the whole bullring is approximately 0.51.

The center time T_S, also associated with the perceived clarity of sound of a listener, represented by its averages in Figs. 9(a), 9(c), and 9(e), presents a similar behavior for all sources, radial directions, and positions in concentric rings, with only certain low-frequency variations for upper-tier and lower-grandstand receivers. Moreover, although not with great differences, the most unfavorable values of the parameter are observed at low frequencies for the source position S5 and the receivers located in the

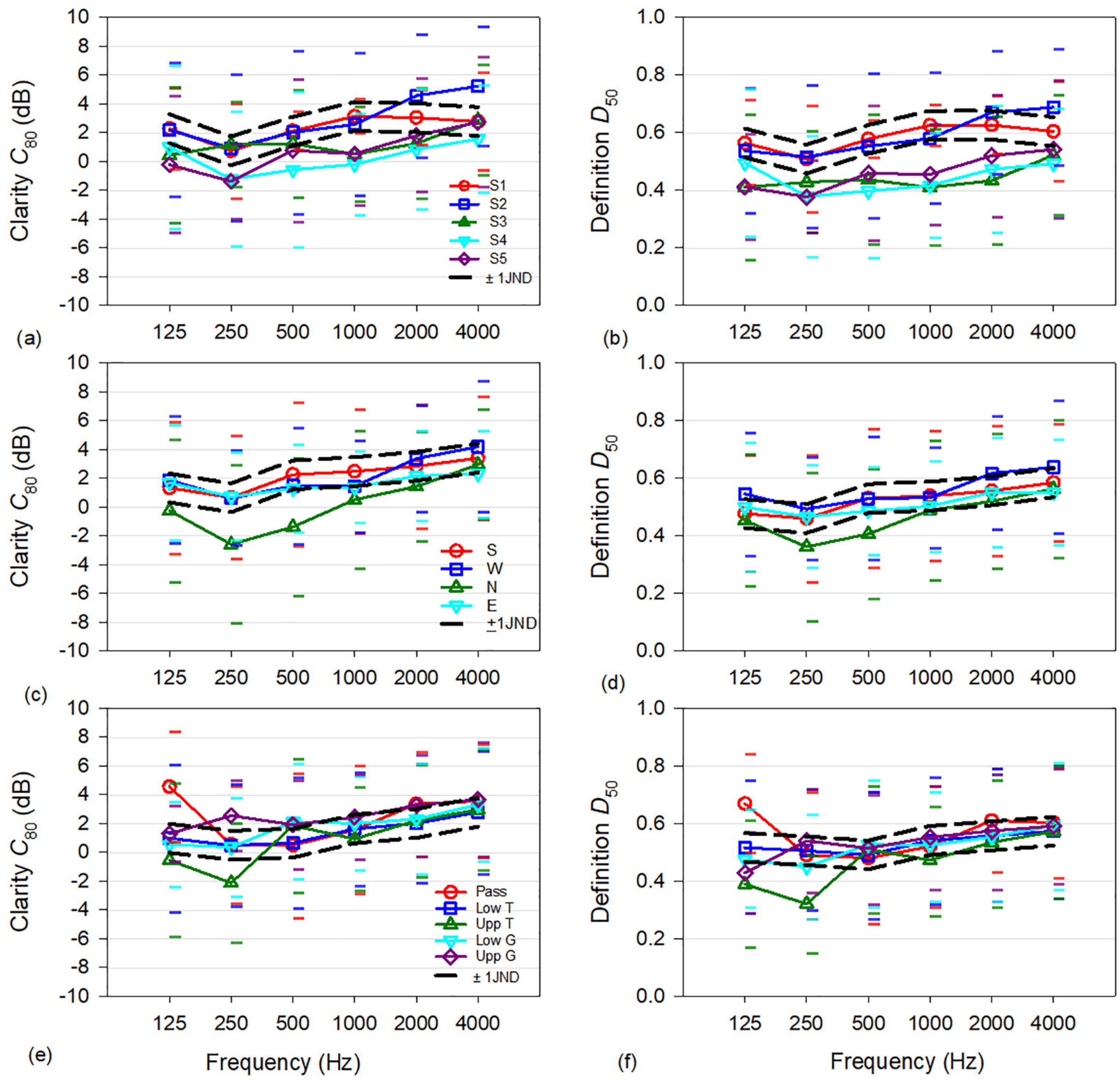

FIG. 8. (Color online) Spatial averages as a function of frequency in the bullring of Las Ventas in Madrid: (a) for Clarity for the five sources S1–S5; (c) for the four geographical directions, S, W, N, E; and (e) for the positions of the receivers to the center of the bullring (passageway, Pass; lower tier of stalls, Low T; upper tier of stalls, Upp T; lower grandstand, Low G; and upper grandstand, Upp G). The same is given for Definition in (b), (d), and (f), respectively. Horizontal bars correspond to the standard deviations. Dashed black lines correspond to ± 1JND of the values obtained with source S1, at the South radius, and the lower tier of stalls, respectively.

N direction at low and medium frequencies. At low frequencies, variations of the parameter are observed according to the location of the receivers with respect to the center of the bullring. The differences in the averages are subjectively perceptible in all the analyses carried out. Spatial dispersion is high, especially at low frequencies (up to 7 JNDs) and lower in all analyses at medium and high frequencies. For the average of all measurements, the spatial dispersion ranges between 3.9 and 4.3 JNDs for the six octave bands, and the average value of mid-frequency bands, T_{Saver}, is 3.8 JNDs. T_{Sm} in the bullring as a single value is 136 ms.

The frequency analysis of the energy parameter G, which assesses the subjective level of sound, is represented in Figs. 9(b), 9(d), and 9(f). This parameter presents a smooth decrease in levels from low to high frequencies, and a maximum of levels is observed in the 250 Hz octave band in certain cases, with a minimum at 2–4 kHz. This behavior is similar for all the configurations of the five sources, of the four geographical directions, and the five rings of receivers distant from the center of the bullring. In general, the low levels of G recorded are due to the low reverberant energy density that this open space presents, in contrast to the higher levels found in closed rooms. The differences in the averages are subjectively perceptible in all the analyses carried out. The spatial dispersion of G, in its analysis in terms of frequency, is also similar to the other energy parameters and shows majorities of numbers of JNDs between 2 and 3. For the average of all 71 measurements, the spatial dispersion ranges between 2.6 and 4.0 JNDs for the six octave bands, and the average value of the medium frequency results, G_{aver}, is 2.8 JNDs. The mean value of the mid-frequency results considering all 71 measurements, G_{m}, is –4.17 dB.

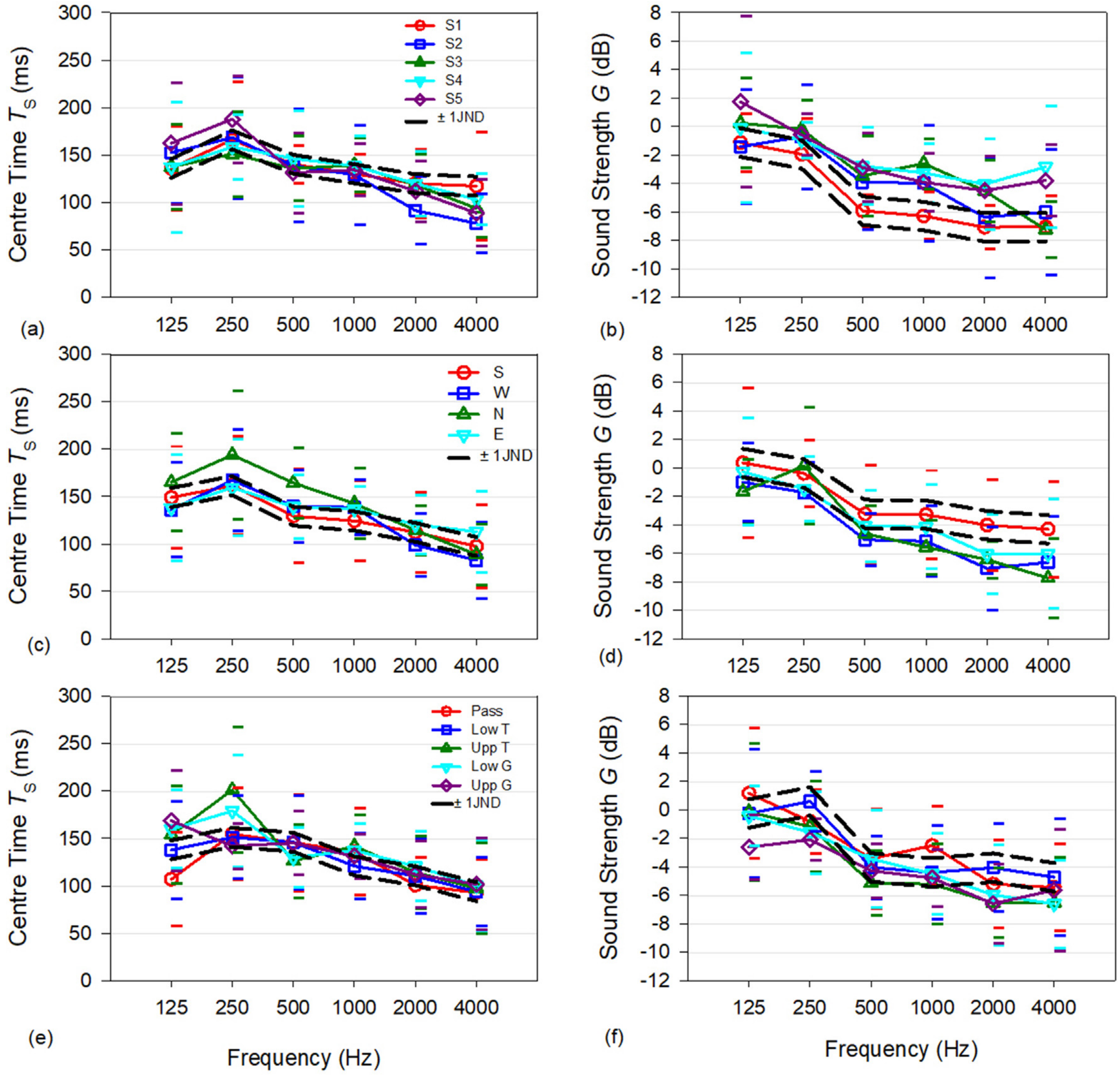

FIG. 9. (Color online) Spatial averages as a function of frequency in the bullring of Las Ventas in Madrid: (a) for Center Time for the five source positions S1–S5; (c) for the four geographical directions, S, W, N, E; and (e) for the positions of the receiver to the center of the bullring (passageway, Pass; lower tier of stalls, Low T; upper tier of stalls, Upp T; lower grandstand, Low G; and upper grandstand, Upp G). The same is given for Sound Strength in (b), (d), and (f), respectively. Horizontal bars correspond to the standard deviation. Dashed black lines correspond to ± 1JND of the values obtained with source S1, at the South radius, and at the lower tier of stalls, respectively.

C. Directional parameters

The monaural directional parameters related to the subjective aspects of apparent source width, J_{LF}, and listener envelopment, L_J, are studied in this section in Fig. 10. The IRIS system can determine the lateral parameters (J_{LF} and L_J) directly. IRIS automatically aims a virtual lateral figure-of-8 microphone in post-processing. It detects the direct sound using the first 2 ms of the recorded impulse response and points the null of the virtual lateral microphone in this direction.

It should be noted that the highest values of the J_{LF} parameter are presented for the position of source S3, the location of the music band, while the most unfavorable values are presented when the source is located in the center of the ring, related to the predominance of radial reflections and scarce lateral reflections when the receivers are facing the source. When the radial positions of the receivers are studied taking into account all sources, those in the East positions present the best value of the parameter at all frequencies; the South and West radial positions present similar behavior, while the most unfavorable values occur in the North direction. In terms of the positions of the receivers from the center of the bullring, there is a similarity between the various sources. The spatial dispersion in terms of the number of JNDs acquires a maximum value of 3.7 at 4 kHz in several configurations, with the smallest dispersion detected for the averages of source S1. For the average of all 71 measurements, the spatial dispersion ranges between 2.0 and 3.3 JNDs for the six octave bands. A single-number value of the early lateral energy fraction is obtained arithmetically by averaging over all microphone positions from

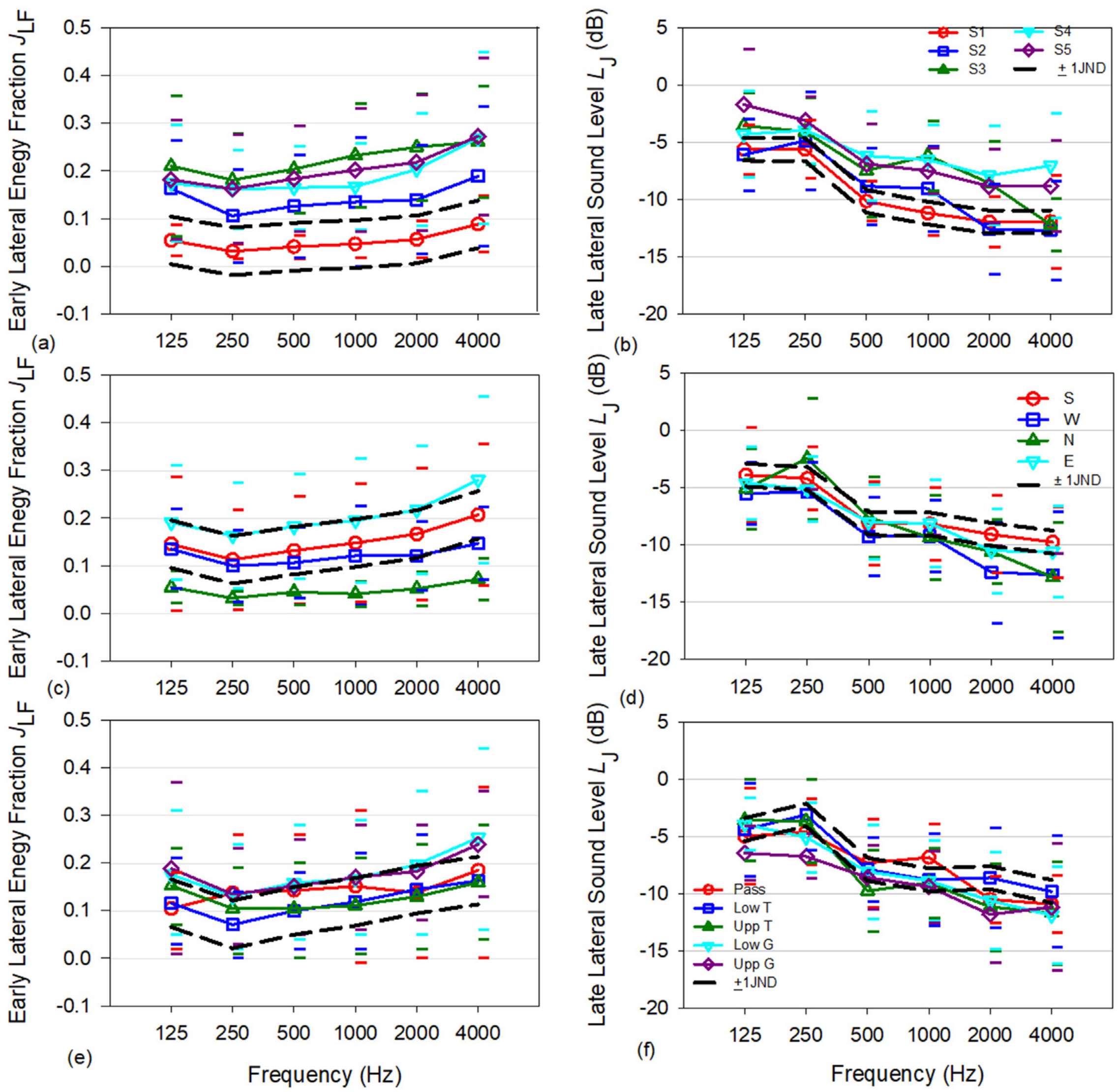

FIG. 10. (Color online) Spatial averages as a function of frequency in the bullring of Las Ventas in Madrid: (a) for Early Lateral Energy Fraction for the five source positions S1–S5; (c) for the four geographical directions, S, W, N, E; and (e) for the positions of the receiver to the center of the bullring (passageway, Pass; lower tier of stalls, Low T; upper tier of stalls, Upp T; lower grandstand, Low G; and upper grandstand, Upp G). The same is given for Late Lateral Sound Level in (b), (d), and (f), respectively. Horizontal bars correspond to the standard deviation. Dashed black lines correspond to ± 1JND of the values obtained with source S1, at the South radius, and the lower tier of stalls, respectively.

125 to 1000 Hz octave bands.[8] In this space, this value is J_{LFm} 0.13 when considering the average of all 71 measurements.

The L_J parameter [Figs. 10(b), 10(d), and 10(f)], shows relative levels of late lateral energy in all the analyzed configurations between –1.7 and –12.8 dB, with maximum values in the octave bands of 125 and 250 Hz. Again, the configurations with source-receiver combinations with higher energy from nearby surfaces present more favorable values. A single-number L_{Jm} value is obtained by energetically averaging the four octave bands from 125 to 1000 Hz.[8] Subjectively perceptible differences in the average value can be found when the analysis is carried out by sound sources or concentric rings. The mean value of the 71 measurements is –6.10 dB. The spatial dispersion given by the standard deviation of the averaged values in each configuration is pronounced at all frequencies. However, in terms of JND referred to as 1 dB, most of the cases studied do not exceed 4 JNDs. For the average of all 71 measurements made, the spatial dispersion in terms of JND ranges between 3.2 and 4.4 for the six octave bands, and the average value, L_{Javer}, is 3.4 JNDs.

D. Spatial parameters

Binaural impulse responses have been measured in the bullring to obtain the inter-aural cross correlation coefficients IACC to describe the dissimilarity of the signals arriving at both ears, with the time limits 0 and 0.08 s for the early reflections, $IACC_E$, and with time limits 0.08 s and ∞ for the late reflections. $IACC_L$. Both parameters are respectively correlated with the spatial impression in their two attributes: apparent source width (ASW) and listener envelopment (LEV).

Figures 11(a), 11(c), and 11(d) show opposite behavior to that of the J_{LF} parameter, and take the most unfavorable values of the value (1-$IACC_E$) for the positions of sources S1 and S2, in this order. Subjectively perceptible differences in the average values are found when the analysis is carried out in terms of sound sources. As expected, a more similar behavior takes place when studying the averages of the parameters in the different radii and between the different positions of the circular crowns of the bullring, with greater differences at 4000 Hz. For a single-number value in the bullring, the arithmetic average at all microphone positions and sources and of frequencies from 500 to 2000 Hz[37] corresponds to 0.59. The spatial dispersion of the parameter, in terms of the number of JNDs, is not very high, not exceeding 5 JNDs, and this value is presented sporadically in certain frequencies and cases. For the average of all 71 measurements, the spatial dispersion in terms of JNDs ranges between 1.5 and 4.0 for the six octave bands, and the average value, $IACC_{Eaver}$, is 3.3 JNDs.

In the case of $IACC_L$, Figs. 11(b), 11(d), and 11(f) show a greater detriment of the subjective aspect LEV for source S1, and the radial position located in the geographic North of the bullring. Subjectively perceptible differences in the average values are found when the analysis is carried out in terms of sound sources. The single-number value in the bullring of this parameter is 0.26. The spatial dispersion of the parameter, in terms of the number of JNDs, is lower than that for the early parameter and does not exceed 4 JNDs: this value is reached only in a couple of cases at 125 Hz. For the average of all 71 measurements, the spatial dispersion in terms of numbers of JNDs ranges between 1.8 and 2.3 for the six octave bands, and the average value, $IACC_{Laver}$, is 2.0 JNDs.

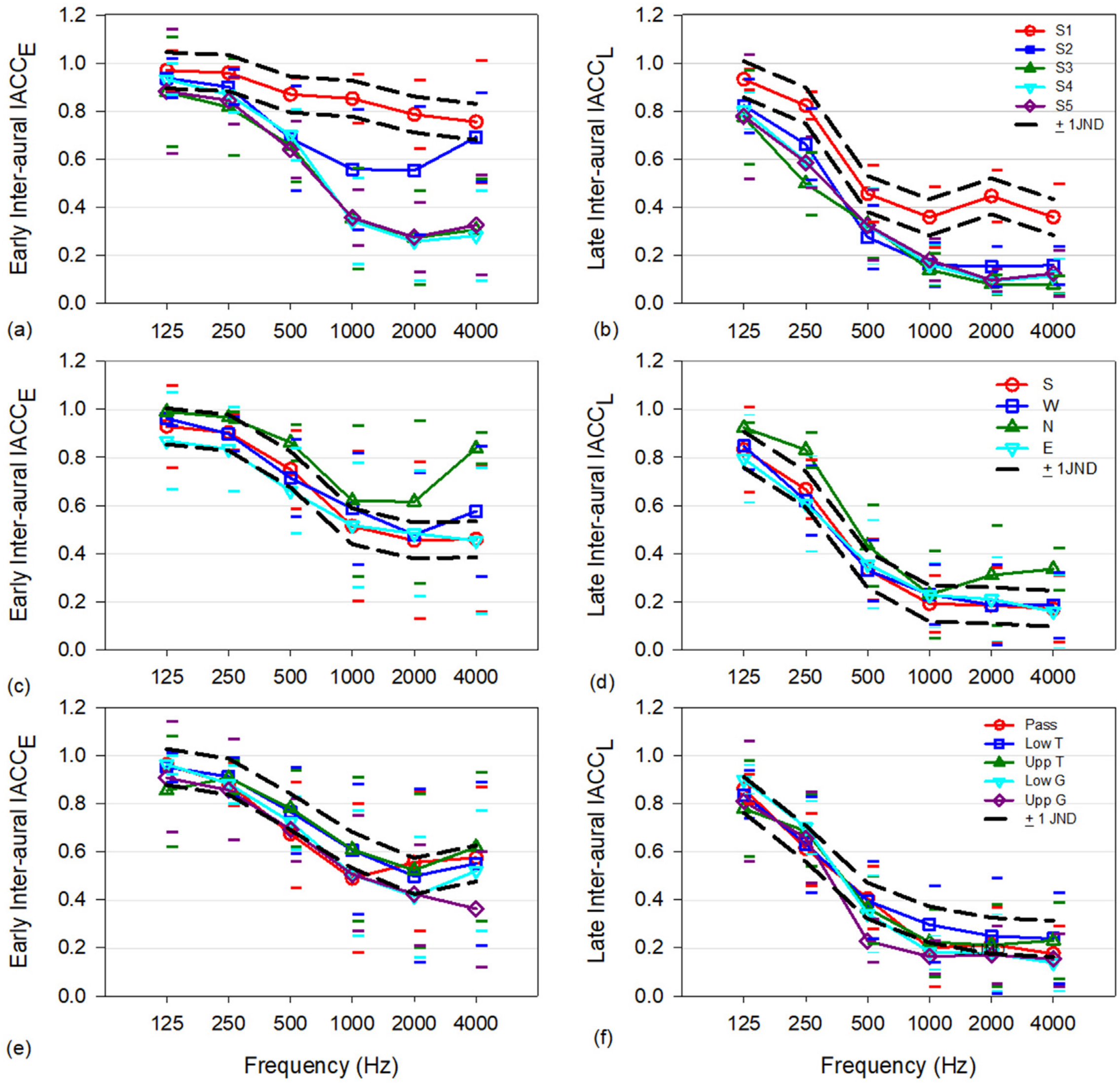

FIG. 11. (Color online) Spatial averages as a function of frequency in the bullring of Las Ventas in Madrid: (a) for Early Inter-Aural Cross-Correlation Coefficient for the five source positions S1–S5; (c) for the four geographical directions, S, W, N, E; and (e) for the positions of the receiver to the center of the bullring (passageway, Pass; lower tier of stalls, Low T; upper tier of stalls, Upp T; lower grandstand, Low G; and upper grandstand, Upp G). The same is given for Late Inter-Aural Cross-Correlation Coefficient in (b), (d), and (f), respectively. Horizontal bars correspond to the standard deviations. Dashed black lines correspond to ± 1JND of the values obtained with source S1, at the South radius, and at the lower tier of stalls, respectively.

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E. Parameters as a function of distance

In order to conclude the analysis of the measurements performed in the bullring of Las Ventas, the influence of the distance from the receiving position to the sound source is shown by two acoustic descriptors related to loudness and intelligibility, G_{mid} and STI. According to the results, an acoustic symmetry of the bullring has not been detected in symmetric receivers with respect to the distance to the source (S1, S2, and S3) and the geometry of the bullring.

Figure 12(a) shows the STI voice index as a function of source-receiver distance. The word intelligibility parameter, the STI target index, is calculated from the impulse response measured with the IRIS system following the indirect method validated by Cabrera *et al.*[38] In particular, the Male STI has been estimated from the manual configuration of the voice level (Male Loud Speech Effort) and the background noise (measured *in situ*). The results show that, even at a great distance from the source, the values are in the *fair-good* range and that only those receivers closest to the source are in the *excellent* range.

The sound propagation curves corresponding to the five sources are now considered through the parameter G_{mid}, which is the average of G for the 500 and 1000 Hz medium frequencies. All data, measured for each source-receiver combination, is shown in Fig. 12(b). In order to facilitate comparison, this figure shows the variation of the sound strength versus source-receiver distance for the five sources and the predictions of source propagation in the free field. In general, the sound pressure levels are similar for all sources, where changes of more than 12 dB can occur in the parameter depending on the receiver. This suggests that sound energy is mainly concentrated in the first part of the impulse response, which includes direct sound and reflections produced from the arena when it is present, and also includes other energy coming from the surrounding rows of seats, where reflections from these surfaces contribute more energy at the receiving positions. In contrast, for the further distances, the reflections from the grandstands cause a rise in level and render the propagation curve less pronounced. In general, the G_{mid} values are low compared to those in closed rooms and the trend steadily decreases with a slope close to that of the free field [$y = 20–20\ \log(x)$]. Linear regression with all the data yields $y = 15.71–12.25\ \log(x)$; coefficient of the determination $r^2 = 0.713$.

F. Spatial variation of the measurements

As pointed out in Sec. II D, and in contrast with other type of venues, circular bullrings do not present significant spatial variation with the sound source located in the center of the ring. However, the multisource character of a bullfight, with several sound sources located in different positions, does present greater spatial variation, as would be expected. As an example of this spatial dispersion, Figs. 13(a) and 13(b) show the interior section of Las Ventas bullring corresponding to the south-west view with the perceptual differences in terms of JND and the mean or averaged single value of each acoustic parameter for each receiving position R1 (passageway), R2 (lower tier of stalls), R3 (upper tier of stall), R4 (lower grandstand), and R5 (upper grandstand).

The values in Fig. 13(a) show acceptable precision in the variation of the results in terms of JND, when a single sound source, S1, and the spatial average of 20 receiver positions (from R1 to R20) are considered. On the other hand, the spatial variation increases when five sound sources (from S1 to S5) are considered with an average of 71 source-receiver combinations, as shown in Fig. 13(b).

V. CONCLUSION

This work describes a proposal for the acoustic characterization of circular bullrings in terms of the various sound sources commonly present in a bullfight.

The dilapidated state of many of the amphitheaters, with stands and/or other areas incomplete or absent, is responsible for the differences in the acoustic results obtained in this case study and the amphitheaters. In this regard, it is necessary to point out the few pieces of research published regarding the two types of enclosures. The high and large stands of the bullring of Las Ventas cause a considerable increase in reverberation compared to the amphitheaters studied in the literature, and even more differences

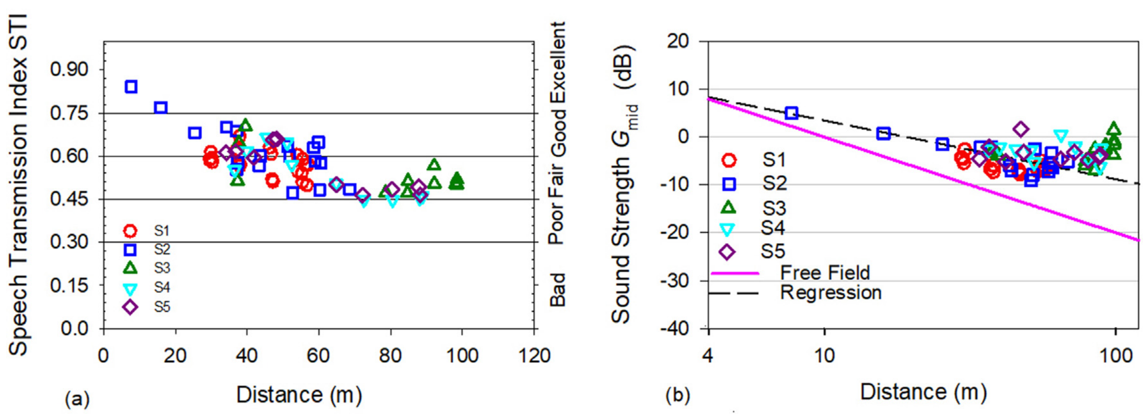

FIG. 12. (Color online) Acoustic parameters as a function of source-receiver distance for the five source positions in the bullring of Las Ventas in Madrid: (a) speech transmission index; (b) mid-sound strength.

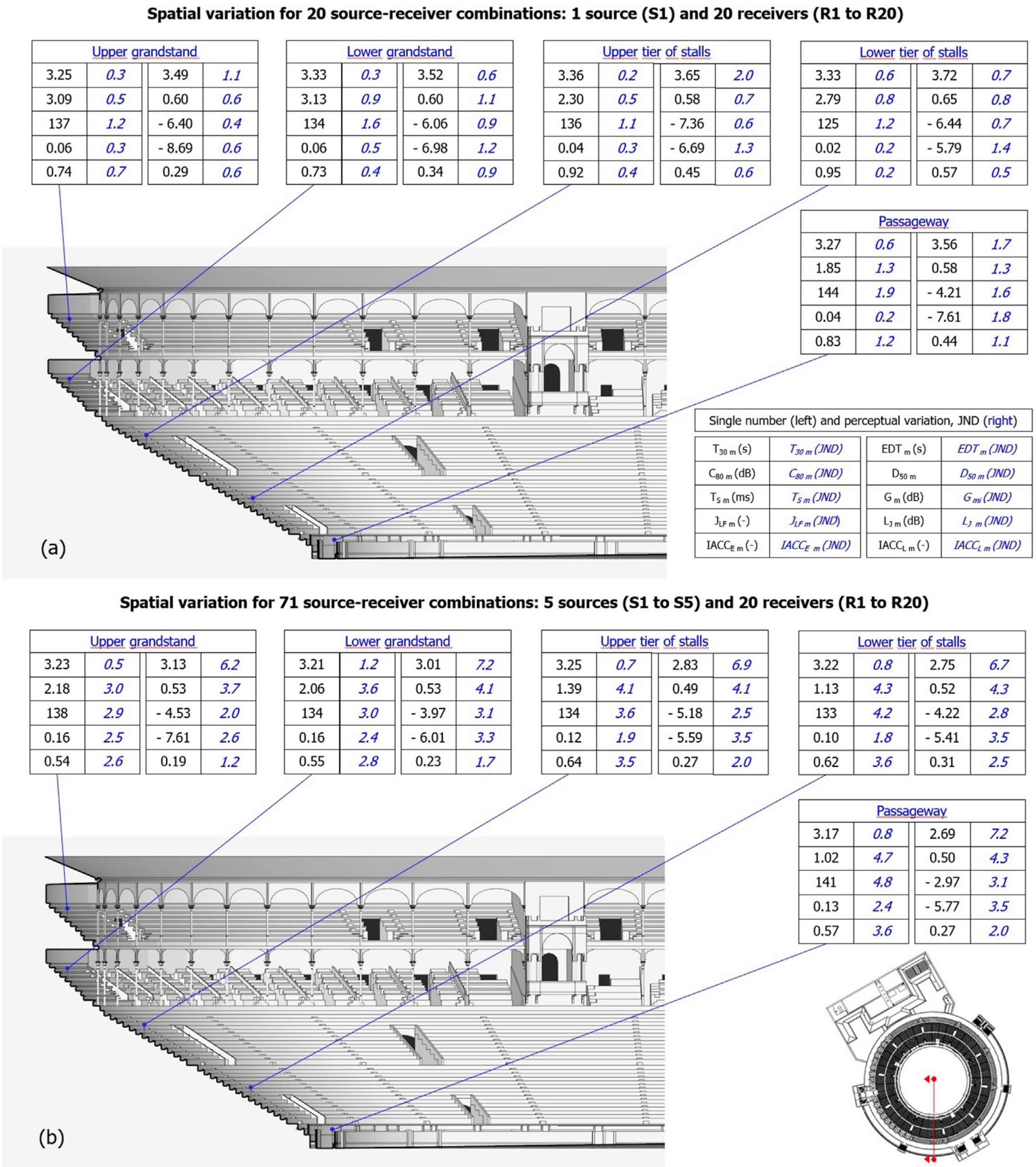

FIG. 13. (Color online) Single values and spatial variability of the acoustic parameters listed in the legend table for the positions to the center in the bullring of Las Ventas in Madrid, located in the passageway, lower tier of stalls, upper tier of stalls, lower grandstand, and upper grandstand: (a) for 20 source-receiver combinations, with one source (S1) and 20 receivers (from R1 to R20); (b) for 71 source-receiver combinations, with five sources (S1, S2, S3, S4, and S5) and 20 receivers (from R1 to R20).

arise with Roman theaters. In addition, in Las Ventas, compared to the amphitheaters, musical clarity decreases although it maintains similar levels of clarity of speech, intelligibility, and the listener's enveloping sensation. It is estimated that the differences found would be minimized if the amphitheaters had been found in their original state. The methodology in both types of buildings is the same (ISO 3382–1). In the case of bullrings, this norm has only been adapted to the particularity of the venue. In particular, the natural sound sources and receivers of the different areas, the axes of the bullring, and the location and combinations of sound sources and receivers for acoustic measurements have been identified.

The proposal adopts the standards provided in ISO-3382 in its first and second parts, for the recording of impulse responses in closed rooms and regarding the set-ups of sound sources and microphones for seated and standing listeners. The study reports the number of recommended source-receiver combinations for the most exhaustive acoustic description possible, which depends on the spatial and temporal limitations that are present in an empirical campaign in this type of large outdoor space.

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TABLE III. Summary of single number rating[a] of the main acoustic parameters.

$T_{30\ m}$ (s)	3.21 s	EDT $_{m}$ (s)	2.87 s
$C_{80\ m}$ (dB)	1.52 dB	$D_{50\ m}$ (−)	0.51
$T_{S\ m}$ (ms)	136 ms	G_{m} (dB)	−4.17
$J_{LF\ m}$ (−)	0.13	$L_{J\ m}$ (dB)	−6.10 dB
$IACC_{E\ m}$ (−)	0.59	$IACC_{L\ m}$ (−)	0.26

[a]The single number rating for T_{30}, EDT, C_{80}, D_{50}, T_S, and G is calculated from the arithmetical average from 500 and 1000 Hz octave bands, J_{LF} from 125 to 1000 Hz, and IACC from 500 to 2000 Hz, defined by ISO 3382-1. Except for the L_J parameter, which is calculated as the energy average of 125 to 1000 Hz octave bands.

The measurements made according to the proposed method have been successfully applied to Las Ventas bullring in Madrid. A total of 71 impulse responses have been measured in various combinations for five source positions and 20 microphone positions, located in the four geographical directions and at various distances from the center of the arena (see Table III). It is observed that the spatial variability obtained in terms of standard deviation and subjective perception of the listener, especially in the middle frequencies of octave bands and for the average acoustic parameters, enables the acoustic characterization of bullrings as performance venues by means of the reverberation time, while the remaining acoustic descriptors follow the guidelines of the ISO 3382–1 standard.

The recommendations of the ISO 3382–1 standard are, therefore, evoked for the complete characterization by sources with a minimum number of receivers, and the characterization of the various areas of the listener positions of complex architectural buildings, such as in the case studied herein.

Limitations of time and human dedication to acoustic measurements have prevented the exhaustive measurements from including further positions of the source in the arena and others in the public seating areas: these inconveniences can be avoided with an appropriate virtual study of this space and other bullrings of the Iberian Peninsula, which is currently under development.

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