

Case Report

The Acoustics of the Palace of Charles V as a Cultural Heritage Concert Hall

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Abstract: This paper analyses the acoustic behaviour of the Palace of Charles V from a room acoustics perspective but also ponders the uniqueness of the space and its ability to engage and enhance the audience experience. The Palace of Charles V is a relevant part of the historical heritage of Granada. It has an architectural but also an acoustic uniqueness that deserves research. A measurement campaign was made to calculate parameters such as T₃₀, IACC, C₈₀ or Gm, and to explain the behaviour of the Palace. The BQI is quite high, but the late part of the impulse response ($t > 80$ ms) has strong unwanted reflections causing low clarity (C₈₀) and listener envelopment (LEV). Nevertheless, the Palace is a successful concert venue with good feedback from musicians and the audience.

Keywords: room acoustics; open-air auditorium; heritage acoustics



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1. Introduction

The Palace of Charles V (from now on referred to as the Palace, in capital letters), inside the Alhambra fortification, has been used as a concert hall for a long time with quite a degree of success. Previous acoustic research in the Alhambra covers soundscape [1] and concert noise [2] but not room acoustics. Analysing the Palace as a concert hall is not straightforward for several reasons: it is open-air, part of the cultural heritage of the city and it was not designed for speech or music transmission.

Open-air venues lack reflections from a ceiling, so most of the energy is reflected from walls that usually have low absorption. Scattering depends on the geometry. Some researched cases are Greek or Roman theatres [3,4], or public squares [5]. The shape of the Palace and its porticoed gallery has some similitudes to the use of arcades in squares [6]. Using room acoustic parameters in urban squares is useful, according to Thomas et al. [7]. The listener position has a strong influence on the space wideness assessment, and C₅₀ and T₃₀ are important in urban spaces according to the research of Calleri et al. [8]. Paini et al. [6] conclude that the addition of arcades to a public square increases T₃₀, while decreasing C₈₀. Previous research has discussed the applicability of the ISO 3382-1 [9] standard to unroofed spaces [10] and the relevant objective parameters to describe them [11].

The use of heritage buildings as concert venues is a common practice. Being in a historical place can improve the concert experience of attendants from an emotional point of view [12]. Brezina [13] divides the studies of historical places into two: the measurement of acoustic parameters and the storage of acoustics as audio heritage. The safeguard of the acoustic behaviour was pioneered by M. Gerzon [14] and continued by others such as Farina or Katz [15–17]. This work proved to be very important when the Gran Teatro La Fenice in Venice burned in 1996, but its sonic behaviour was saved because several acoustic

measurements had been performed prior by Tronchin and Farina [18]. Furthermore, a fire destroyed the Notre Dame Cathedral in Paris and works by Katz et al. stored the original acoustics [19]. Recording of Ambisonic RIR allows the reconstruction of the sound field and the estimation of the direction-of-arrival (DOA) of the reflections [20]. This also allows the calculation of the impulse responses of virtual microphones, such as dipoles for lateral fraction or binaural microphones by Menzer and Faller [21], enabling the calculation of IACC or auralisation. Other reasons to keep Ambisonic RIRs are documentation and safeguarding of the historical heritage, visualisation of spatial information such as the research by Martellotta [22] or Alary and Valimaki [23], or using different available 3D reproduction techniques to recreate concerts, as shown by Tronchin and Farina [16].

There is not a lot of research regarding the room acoustics of heritage places that are not designed for music or speech transmission. Previous work by Iannace [24] showed that historical courtyards can be used for concerts without acoustic issues and good feedback from the performers. Heritage places have different sizes and shapes, and can even be open-air or squares. Most of them were not thought to be used for music or even speech transmission. Those singularities may suggest that their acoustics and their suitability for different kinds of music should be studied in each heritage place. Suitability, in this case, should be interpreted as 'eignung', used in sound quality. Blauert [25] groups sound-quality aspects into several degrees of abstraction. The same author [26] explores the idea of the composers and performers using the acoustic properties of a room to relay messages to the audience. Musical programmers should also take decisions based on the venues they have available. Farina [27] and Pätynen-Lokki [28] moved forward to improve the understanding of the relationship between measurements and preferred acoustics.

Lots of research has been carried out for historical concert hall acoustic measurements and there are some guidelines such as those by Pompoli and Prodi [29], but not too much concerning cultural heritage places not built as concert halls, excluding churches and different religious buildings as some guidelines for churches [30], cathedrals [31] and mosques [32] exists. The main musical use of the Palace is for orchestral music but it is also used for opera, jazz, flamenco or even rock [33].

This paper aims to review the physical descriptors that may explain the different and high aural quality of the Palace. The claim of good acoustics in the place is something explained in every guided visit, but it had never been scientifically researched. The descriptors used in this paper are included in the ISO 3382-1 [9] and the IEC 60268-16 [34] standards. The focus will be on measuring the objective parameters and discussing the results but the chance of safeguarding the acoustics must not be wasted. Ambisonic room impulse responses (RIR) were computed, used to estimate the direction of arrival of several reflections and to calculate the IACC. The Palace and its use as a concert hall will be discussed as part of this introduction. The material and Methods section will explain the tests made during the measurement campaign. The results and Discussion section will explain the outcomes with attention to the singularities of the space. Finally, some conclusions will be set forth.

1.1. The Palace of Charles V and the Alhambra of Granada

On both sides of the river Darro rise two hills that have seen several cultures throughout the history of the city. The Albaycín hill, where the city started, and the Sabica hill. The fortification of the Alhambra is on the Sabica hill. Inside, the Palace of Charles V is located (see Figure 1), an example of the best Italian Renaissance in Spain. Names such as Enrique de Egas, Diego de Siloé and Pedro Machuca have imprinted the history of the construction of the Palace in the style of the best Italian Renaissance. More information about the building and its historical circumstances can be found in the work by Rosenthal [35] and Brothers [36].

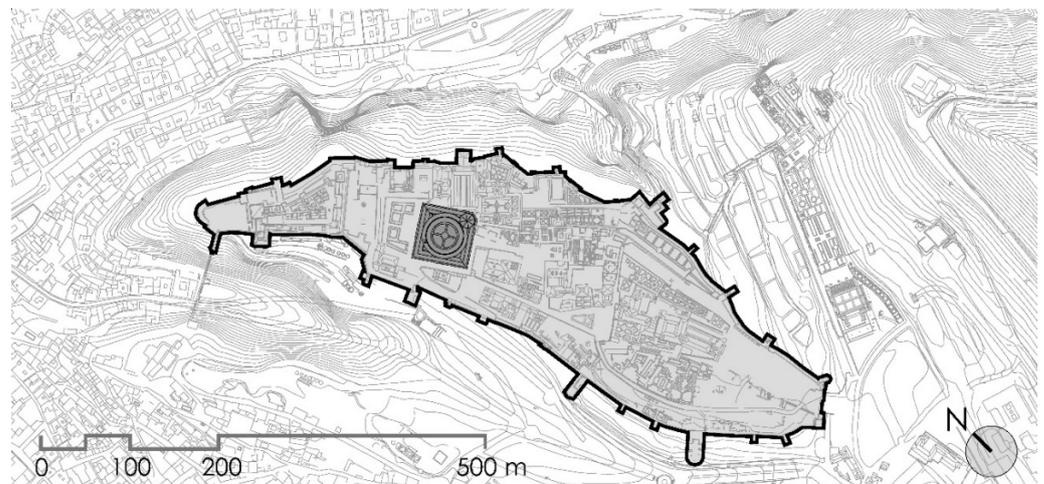


Figure 1. Location plan of the Palace inside the Alhambra.

In 1637, the construction process was finally abandoned due to the decline in the Spanish Empire and political factors. We owe the appearance of the Palace that we admire today to Leopoldo Torres Balbás and later to Francisco Prieto Moreno, who finally carried out a master plan for the Palace restoration, including the covering (the roof), all between 1923 and 1958. The first known musical event held in the Palace of Charles V was in 1883 as part of the city's Corpus Christi festival. It was also used to hold international flamenco competitions, such as the one held in 1922 by García Lorca, Manuel de Falla, Andrés Segovia and other intellectuals of that time. More recently, every year since 1952, the International Festival of Music and Dance of Granada has been using it as a concert hall. In this important musical event, the Palace of Charles V always occupies a central position. According to the local press [37], Daniel Barenboim said "The sound of the Palace of Charles V is much better than that of many enclosed halls. The shape of its walls makes it a wonderful acoustic shell."

The space used as a concert hall is circular and open-air with a diameter of 30 m (see Figure 2). On its perimeter, there is a 5 m wide porticoed gallery covered with a toroidal vault with basket-handle arches whose height from the keystone to the floor is 5.80 m. On the upper floor, another porticoed gallery crowns the building, this time covered by recent wooden porticoes and wooden coffered ceilings from 1958. The entire solid cylinder enclosing the interior of the arcaded galleries is around 17,907 m³ (see Table 1), with built-in stone with bas-reliefs, half-columns and pediments framing various openings to the interior of the palace.

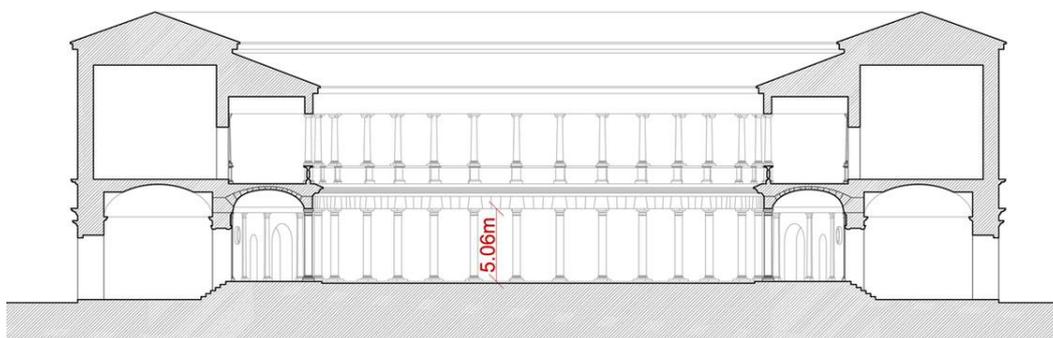


Figure 2. Elevation section of the Palace. Reproduced with permission from the authors.

Table 1. Volumes and area of the Palace.

	Surfaces [m ²]			Volume [m ³]	
	Seating Area	Scenario	Residual Spaces	Total Area	Total Volume
Main floor (uncovered)	430	257	-	687	9391
Main floor	303	-	433	736	4136
Upper floor	303	-	313	616	4380
Total	1036	257	746	2038	17,907

The cylinder enclosing the interior of the courtyard is a sequence of voids between stone columns and other elements enclosing the galleries. In the interior cylinder of the courtyard, the closing element located halfway up the building, between heights of 5 and 8.12 m, stands out, with a thickness of more than 3 m; this is the group of friezes, triglyphs and metopes that cover the development of the bell-shaped arches of the toroidal vault, together with the height of the parapet. Most of the concerts are orchestral music but some others can include public address systems. The sound engineers working at the Palace deal with the strong delayed reflections and reverberation using high-directivity line arrays. The PA projects are not straightforward as they must cover the central area but also the second floor. This is problematic for rock but especially flamenco concerts.

1.2. Audience

The layout for the concerts has slight variations every year. The maximum audience is 1200 people, but restrictions due to COVID-19 had a big impact on the audience size in terms of distance among members of the audience. Being an open-air venue helped to safely keep enough seats and did not affect the layout. A big proportion of the audience is located in the patio; there are side stalls in the lower gallery and an audience arch in the upper floor gallery. All of the audience is seated on plastic chairs. On the upper floor, the chairs are on grandstands to enable the visibility of the stage (see Figure 3).

**Figure 3.** The Palace during the measurement campaign.

1.3. Stage

The stage is wide and covers an important part of the open-air central patio (Figure 4). The particular geometry of the stage makes the stage acoustics of the Palace quite singular. Some performers can be quite near, while others can be more than 20 m away from a given musician in the orchestra.



Figure 4. The stage during the measurement campaign.

The long distance from closer walls can exacerbate this problem as the direct sound path will predominate over the first reflections among near performers. A quick estimation would predict an attenuation of more than 25 dB, comparing a musician 20 m away to another one at a 1 m distance (under free-field conditions). The high reverberation is expected to reduce this issue by enhancing the strength (G) between distant positions.

Gade [38–40] recommends measuring ST (see Section 2.2.4) with chairs on stage. In addition, Dammerud [41] deepens into the different results obtained in real-condition experiments (with musicians). Sadly, this set of measurements was made without musicians or chairs on stage, as was explained previously. Uncertainty of stage measurements can be higher than expected for other descriptors according to Giovannini and Astolfi [42].

2. Materials and Methods

A measurement campaign was carried out on the 2nd and 6th of July 2021. The measurements followed the recommendations of the ISO 3382-1 standard [9]. It took place between 10 PM and 1 AM without the presence of the public. The late hours allowed for low noise levels as the Palace was closed for visits. Wind speeds were negligible (less than 0.5 m/s) and the temperature was lower than during hot summer afternoons. All the tests were taken without musicians or an audience. Only the chairs in the audience and the platform of the stage were mounted. The Palace does not have those elements unless a performance is programmed. Giving reliable and enlightening results has therefore been a concern. The recommendations of Pompoli-Prodi [29] and Astolfi et al. [10] were interpreted and followed as far as possible and some of the descriptors were not averaged to provide more information. Measuring with an audience was not possible. Performing the measurements in the Palace required permission from Patronato de la Alhambra and Festival de Granada, but performing them with an audience and orchestra would have

required extra permissions from the visiting orchestras and would have been disturbing for the audience.

2.1. Measurement Setup and Methodology

Three source positions were selected on the stage. They were kept for both the audience and the stage measurements. Furthermore, sixteen microphone positions on the stage and ten in the audience (see Figure 5) were selected following the guidelines of the ISO 3382-1 standard [9]. All the source–receiver combinations were measured.

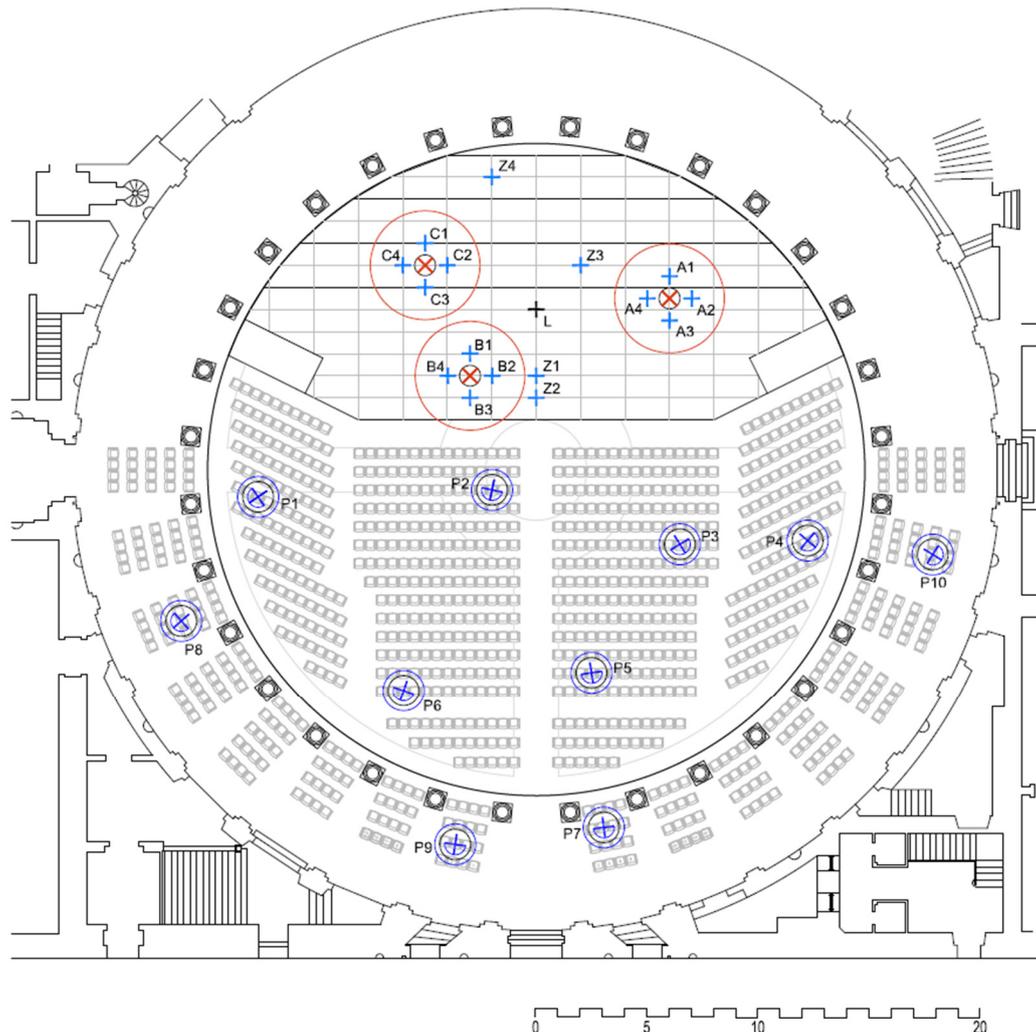


Figure 5. Layout of the concerts and the measurement campaign with source and receiver positions. (Red crosses indicate source positions; blue crosses indicate microphone positions).

Measurements in selected audience seats took place during the second night. A Lookline DL-203 dodecahedral source was used. Calibration of the source in an anechoic chamber enabled the calculation of G (strength) and other energetic parameters. A Genelec 8040 studio monitor was used for half of the seats to improve the frequency and phase response of the computed RIR in addition to the omnidirectional source. The sweeps were recorded using one of the omnidirectional microphones together with a Rode NT-SF1 first-order Ambisonic array.

The measurements of the stage were carried out on the first night using the dodecahedral source. The signals were recorded using four 378B02 PCB half-inch microphones. The air conditions are stated in Table 2.

Table 2. Air conditions during the measurement campaign.

	Audience		Stage	
	Beginning	End	Beginning	End
Temperature, °C	28.1	24.9	30.5	24.7
Humidity, %	33	49	29	31
Barometric Pressure, mB	929.0	928.8	931.4	929.7

Exponential sine sweeps were used because of their segregation of harmonic distortion, documented by Farina [43], and their higher impulse-to-noise ratio under usual test circumstances. Recorded signals were deconvolved by post-processing using Aurora plugins [44] to obtain the RIR. Extracting room acoustic indices from the RIR was easy and convenient.

2.2. Acoustic Indices

Unless otherwise specified, all indices have been calculated according to ISO 3382-1 [9].

2.2.1. Level Parameters

The impulse-to-noise ratio (INR) describes the quality of the RIR measured, as it gives the range of the usable decay. Therefore, the minimum values of each measurement are more interesting to know than the average values.

Strength (G) is the logarithmic ratio of the squared pressure of the measured impulse response to that of the response measured in a free field at a distance of 10 m. A graphical plot of G_m as a function of the source–receiver distance can be useful, as it varies with distance. Moreover, a comparison with the theoretical free field and the summation of it with the room constant (R) helps to visualise the contribution of the reverberation to the acoustic level.

All of the strength values displayed are the average values of the octave bands of 500 and 1000 Hz (noted as G_m).

2.2.2. Reverberation and Energy Ratios

The T20 and T30 reverberation times (RTs) and the EDT (early decay time) have been calculated together with their standard deviations ($\sigma(T20)$ and $\sigma(T30)$). T20 and T30 are normalised reverberation times, calculated from linear regression of different sections of the Schröder curve, while EDT is calculated using the first 10 dB drop when the signal is not yet diffuse.

Definition (D_{50}) is the 50 ms-to-total arriving sound energy ratio. D_{50} relates to the perceived definition or speech intelligibility. Clarity (C_{80}) is the logarithmic early-to-late arriving sound energy ratio, being 80 ms, the time limit between “early” and “late”. C_{80} relates to the perceived musical clarity. According to Adelman-Larsen [45], the reverberation time of the 63 Hz octave is important for rock music.

2.2.3. Speech Transmission

This paper covers the use of the Palace for music but the voice is usually part of the music. The speech transmission index (STI) is based on modulation transfer functions as defined by the IEC 60268-16 standard [34]. The values were calculated for female and male voices using the impulse responses without any corrections due to background noise, meaning the SNR is assumed to be infinite.

2.2.4. Stage Parameters

Stage conditions are important for the performers to hear themselves and each other. Early support (ST_{Early}) describes the ensemble conditions while late support (ST_{Late}) describes the reverberance. The results are averaged from 200 to 2000 Hz.

2.2.5. Spatial Impression Parameters

Inter-aural cross-correlation coefficients (IACC), correlate well with the subjective quality of “spatial impression” in a concert hall. IACCE stands for the early (<80 ms) IACC, while L stands for late (>80 ms). The results averaged in the octave bands of 500, 1000 and 2000 Hz are noted as “3”.

The binaural quality index (BQI), calculated as (1-IACCE3) and introduced by Beranek [46], has the highest correlation of all the physical measures with the subjective judgments of acoustic quality in opera houses by the conductors, and it is related to the apparent width of the sound source (AWS) sensation. Listener envelopment (LEV) was calculated as (1-IACCL3). Binaural RIRs were processed from Ambisonic RIR using Ambi Head HD [47] with a Neumann KU 100 SOFA (Spatially Oriented Format for Acoustics) and then calculated using ARTA software [48].

3. Results and Discussion

The results included in this section were calculated from the RIR obtained from the omnidirectional and first-order Ambisonic microphones.

3.1. Level Parameters

Table 3 shows the INR results of the measurements in the audience and stage areas, with both the average and minimum of each band. Some stage measurements showed low INR values. Therefore, T20 will be used to calculate the stage reverberation time instead of T30. Measurements on the stage were recorded with lower input levels to avoid clipping at the positions at a 1 m distance. That explains the lower INR values.

Table 3. Average and minimum INR values.

f, Hz	Audience		Stage	
	Average, dB	Minimum, dB	Average, dB	Minimum, dB
125	49	42	50	43
250	53	48	54	47
500	57	53	53	45
1000	58	54	49	42
2000	62	58	49	43
4000	64	60	44	36

Strength (G) was averaged in the 500 and 1000 Hz octaves (Gm). Higher values were expected near the source. The spatial average of Gm does not provide meaningful information. Table 4 displays the 30 individual values for the selected positions in the audience.

Table 4. Gm values of each source–receiver pair in the audience.

Gm (dB)	Rec. 1	Rec. 2	Rec. 3	Rec. 4	Rec. 5	Rec. 6	Rec. 7	Rec. 8	Rec. 9	Rec. 10
Source A	−0.7	−1.3	0.3	1.3	0.4	−0.1	−1.7	−1.5	−1.7	−1.6
Source B	0.4	5.0	−1.3	−1.1	0.3	−0.5	−1.4	−0.7	−2.0	−1.4
Source C	0.4	−0.3	−0.6	−0.2	0.8	1.0	−0.1	−0.2	−1.1	−1.2

Under free-field conditions, the pressure level from an omnidirectional source only depends on its sound power and distance. Reverberant noise must be added to this free-field level. The easiest way is to consider perfect diffuse conditions, represented by a room constant (R), see (1).

$$L_p = L_w + 10 \cdot \lg \left(\frac{1}{4\pi r^2} + \frac{4}{R} \right) \quad (1)$$

Figure 6 shows the measured strength versus the distance to the source of the measurements in the audience area.

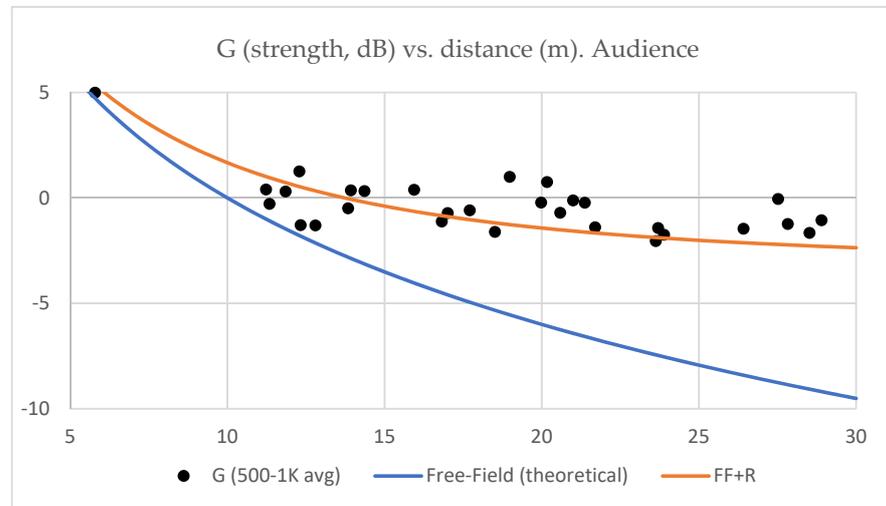


Figure 6. Gm in the audience versus source–receiver distance (m). Free-field values for comparison.

Figure 6 also shows the curves of the free-field behaviour and the free field plus the averaged reverberant noise for comparison (called FF + R). The contribution of the reverberation was calculated by subtracting the free-field contribution of each measurement and averaging the level excess. Positions near to walls, such as those around 20 m and 28 m, are over the curve, while the positions far from reflective areas, around 12 m, are below the curve. This Equation (1), known as the “classical theory”, only accounts for free field and diffuse field. A revised theory for concert spaces was formulated by Barron and Lee [49], including the contribution of the early reflections. This topic will be explained in Section 15.6.

Figure 7 shows the same calculated values for the stage positions. Similar behaviour was observed on stage, but the highest distance was 12 m. The 12 measurements at a 1 m distance showed deviations from the expected value of 19.9 dB under free-field conditions. The average was 19.8 dB and the standard deviation was 0.90. Using 1 m distance measurements on stage to calibrate G instead of an average in an anechoic chamber is common practice. Averaging some of them can help to minimise systematic errors.

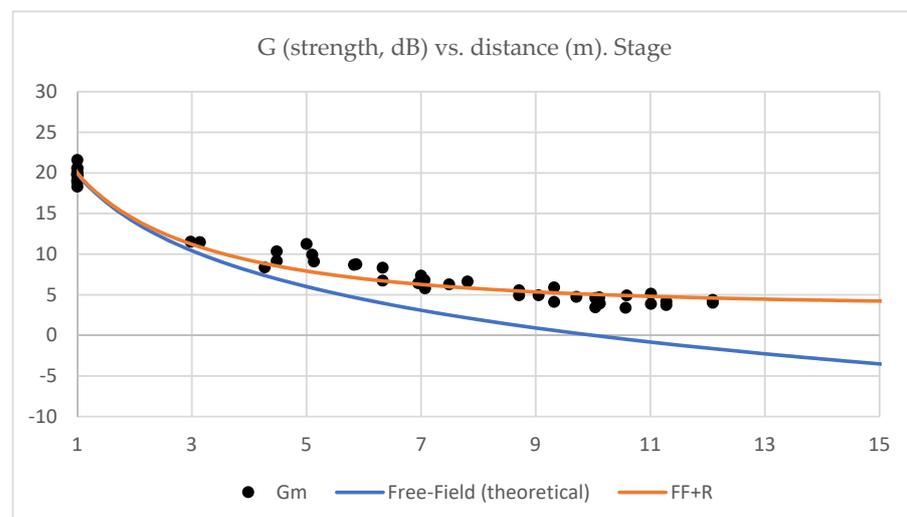


Figure 7. Gm on stage versus source–receiver distance (m). Free-field values for comparison.

3.2. Reverberation and Energy Ratios

Reverberation times averaged from audience points under unoccupied conditions (RT^U): (T_{20} and T_{30}) are quite similar. T_{30} and C (which is $T_{30}/T_{20}-1$) are shown in Table 5. The reverberation time of each measurement is little dependent on the location, as previously reported by Thomas et al. [7]. Table 6 shows the values for the stage measurements.

Table 5. Reverberation times and energy ratios (audience).

f, (Hz)	T_{30} , (s)	σ (T_{30})	EDT, (s)	σ (EDT)	C, %	D_{50}	C_{80} , (dB)
63	2.78	0.309	2.50	0.69	−0.04%	0.34	−0.68
125	2.43	0.101	2.20	0.43	0.04%	0.33	−0.63
250	2.40	0.083	2.10	0.29	−0.04%	0.25	−1.71
500	2.25	0.055	2.08	0.31	1.12%	0.28	−1.26
1000	2.24	0.038	2.08	0.24	0.09%	0.35	−0.1
2000	2.09	0.031	1.93	0.22	0.58%	0.41	0.77
4000	1.81	0.04	1.61	0.24	1.40%	0.46	1.98

Table 6. Reverberation times and energy ratios (stage).

f, (Hz)	T_{20} , (s)	σ (T_{20})	EDT, (s)	σ (EDT)	D_{50}	C_{80} , (dB)
63	2.47	0.416	1.62	1.094	0.76	7.61
125	1.83	0.627	1.60	0.952	0.7	7.83
250	2.06	0.138	1.67	1.015	0.65	6.41
500	1.91	0.152	1.55	0.924	0.69	7.47
1000	1.95	0.14	1.50	0.902	0.74	7.98
2000	1.81	0.081	1.45	0.882	0.74	7.71
4000	1.47	0.176	1.13	0.692	0.78	9.27

The energy–time curves are quite diffuse; more so than expected in an open-air place. In fact, the echo criterion by Dietsch and Kraak [50] EC (1,14) of every measurement was 0.70 averaged, with a maximum of 0.89. For 10% of the audience to perceiving an echo with the music, a value of 1.5 would be needed.

ITDG measured at the central points of the audience was around 60 ms, if we take the first reflection arriving from the parapet, and up to 90 ms with the more energetic reflection from the wall. This can be expected from the geometry and is too much to be a great hall, according to Beranek’s research [46]. Figure 8 shows the energy–time curve of the source in B and the microphone in P2, the most central positions of those measured. The top right of the figure shows a closer look at the first 200 ms. Early energy ($t < 80$ ms) is in dark grey, late energy ($t > 80$ ms) in light grey, and there are several detection thresholds for single reflections with different signals (clicks in green, pink noise in blue, speech in orange from the work of Olive and Toole [51], and classical music from Barron [52] in red). Thresholds are included as a reference, as reflections are as important as they are audible. The most energetic reflections arrive in the “late” fraction of the impulse response contributing to a high T_{30} , but a particularly low C_{80} , and every other parameter that segregates early-to-late energy. The main effect on subjective judgements is the lack of intimacy. The downward slope of thresholds means that the later a reflection arrives, the more audible it will be.

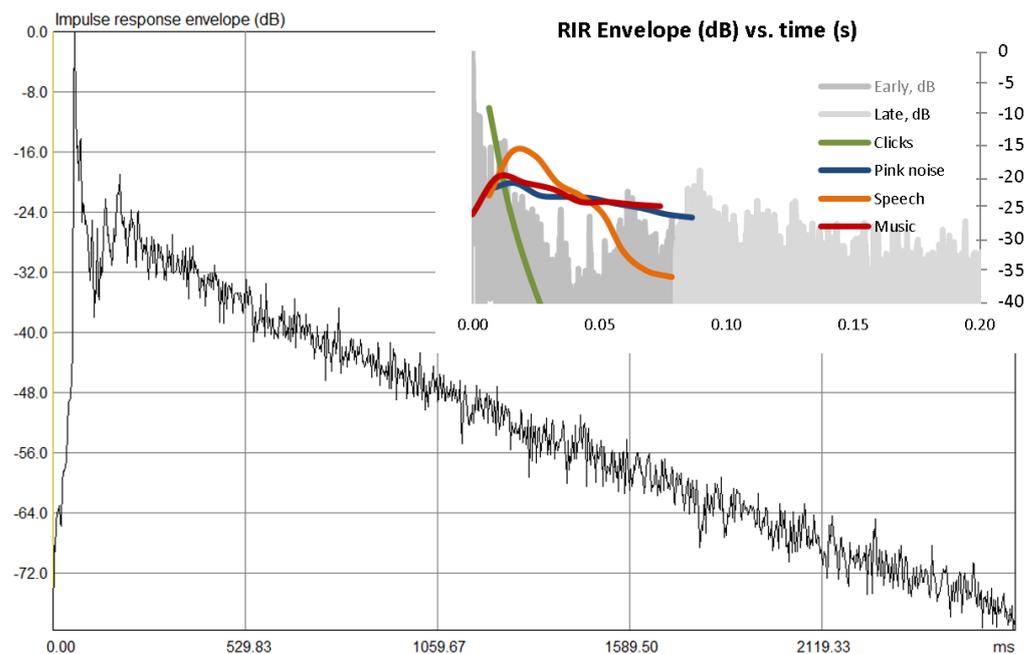


Figure 8. Impulse response envelope. The source in B and microphone in P2.

Figure 9 shows the values of C_{80} versus the source-to-receiver distance. Clarity tends to decrease with distance, with the exception of the farthest positions and the measurement with the source in the C position and the microphone at P6, which is red-coloured (see Figure 5 for the positioning layout)

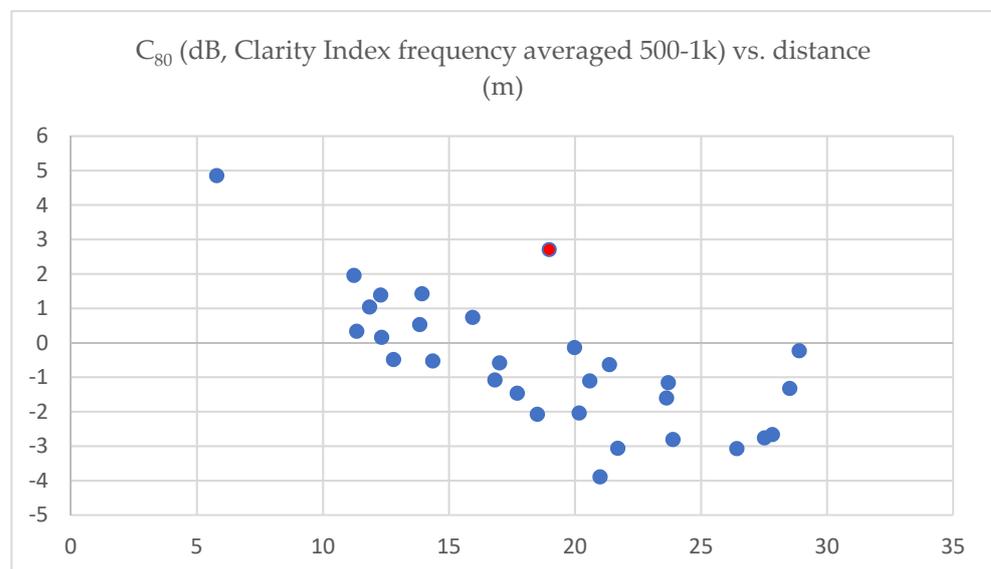


Figure 9. Clarity index (C_{80}) vs. source–receiver distance (m).

A quick estimation of the reverberation time with an audience (RT^0) can be calculated using Sabine's equation [53]. The results will have high levels of uncertainty, as the field is not diffuse and the audience areas are not flat surfaces. Iannace et al. used the audience absorption coefficients of Table 7 to estimate the absorption of the audience in the Roman theatre of Beneventum [54].

Table 7. Audience absorption coefficients (mid frequencies).

Frequency, Hz	500	1000
Minimum values	0.56	0.69
Maximum values	0.88	0.98

The estimation of T_m with Sabine's equation led to a result of 1.28 to 1.49 s. That result does not match the sensation during the concerts. Using data from Table 8, another way to estimate the RT^O is by calculating the equivalent absorption per occupant and using the average from the 25 halls that have data for RT^O , RT^U , number of seats (S) and volume (V). That average was 0.14 m² (metric Sabins) and the resulting RT^O was 1.98 s. This result is expected to be higher than the real value as the Palace has chairs, and concert hall seats have some absorption when unoccupied. Table 8 shows the reference values for concert halls with volumes between 15,000 and 20,000 m³. There are 29 cases from the 100 presented by Beranek [55] in that volume range. It is noteworthy that 28 of the 29 concert venues have a volume per occupant much lower than the Palace's.

Table 8. Technical details of the 29 halls between 15,000 and 20,000 m³ from Beranek [55].

Concert Hall	V [m ³]	Seats	RT^O [s]	RT^U [s]	RT^U/RT^O	V/S [m ³]
Palace of Charles V	17,907	1208	-	2.25	-	14.80
Benedict Music Tent, Aspen, Colorado, USA	19,830	2050	-	3.40	-	9.67
Kleinhans Music Hall, Buffalo, USA	18,240	2839	1.60	1.94	1.21	6.24
Severance Hall, Cleveland, USA	16,290	2101	1.65	2.10	1.27	7.75
Orchestra Hall, Minneapolis, USA	18,970	2450	1.90	2.35	1.23	7.74
Academy of Music, Philadelphia, USA	15,700	2921	1.20	1.40	1.17	5.38
Abravanel Symphony Hall, Salt Lake City, USA	19,500	2812	1.80	2.03	1.13	6.93
Beranoya Hall, Seattle, USA	19,263	2500	1.80	2.23	1.24	7.70
Festspielhaus, Salzburg, Austria	15,500	2158	1.50	1.96	1.31	7.18
Grosser Musikvereinssaal, Vienna, Austria	15,000	1680	2.56	3.60	1.41	8.93
Konzerthaus, Vienna, Austria	16,600	1865	1.96	2.30	1.17	8.90
Sala Sao Paulo, Sao Paulo, Brazil	20,000	1620	2.00	-	-	12.40
Barbican Concert Hall, London, England	17,000	1924	1.40	1.70	1.21	8.84
Sibelius, Talo Lahti, Finland	15,500	1250	2.30	-	-	12.40
Salle Pleyel, Paris, France	15,500	2386	1.55	2.12	1.37	6.50
Shauspielhaus, Berlin, Germany	15,000	1677	2.00	2.30	1.15	9.53
Beethovenhalle, Bonn, Germany	15,728	1407	1.65	1.80	1.09	11.18
Liederhalle, Stuttgart, Germany	16,000	2000	1.60	2.03	1.27	8.00
Megaron, Athens, Greece	19,100	1992	1.90	2.30	1.21	9.73
Concert Hall, Kyoto, Japan	20,000	1840	2.00	2.20	1.10	10.90
Symphony Hall, Osaka, Japan	17,800	1702	1.80	2.20	1.22	10.45
Bunka Kaikan, Tokyo, Japan	17,300	2327	1.50	1.89	1.26	7.42
Opera City Concert Hall, Tokyo, Japan	15,300	1636	1.99	2.72	1.37	9.40
Filharmonik Petronas, Kuala Lumpur, Malaysia	17,860	850	2.05	2.30	1.12	21.00
Concertgebouw, Amsterdam, Netherlands	18,780	2037	2.05	2.59	1.26	9.20
Usher Hall, Edinburgh, Scotland	15,700	2502	1.80	2.55	1.42	6.27
Auditorio Nacional de Música, Madrid, Spain	20,000	2293	1.85	2.07	1.12	8.72
Palau de la Música, Valencia, Spain	15,400	1790	2.10	3.35	1.60	8.60
CCC Concert Hall, Lucerne, Switzerland	17,823	1892	1.6–2.2	-	-	9.42
Cultural Centre Concert Hall, Taipei, Taiwan	16,700	2074	2.00	2.46	1.23	8.05

The recommended reverberation times for halls of 17,900 m³, according to Arau [56], range from 1.88–2.20 s for concert music, 1.38–1.86 s for opera and 1.03–1.61 s for speech. Although Adelman-Larsen [45] has a recommendation for rock-pop music, all the halls are smaller and cannot be extrapolated to the size of the Palace.

3.3. Speech Transmission

STI values were found to be quite constant, given the size of the Palace. It makes sense to provide single measurement values of every point instead of averaging. Table 9 also displays the measurement distance and Figure 10 shows that the STI decreases with distance until around 20 m, and rises a little when the distance is higher than 28 m because of the contribution of strong early reflections.

Table 9. STI values for source/receiver combinations.

	Source A			Source B			Source C		
	Female	Male	d, m	Female	Male	d, m	Female	Male	d, m
P1	0.50	0.50	20.59	0.59	0.58	11.23	0.56	0.55	13.93
P2	0.53	0.52	12.80	0.73	0.71	5.79	0.54	0.53	11.34
P3	0.55	0.54	11.85	0.55	0.54	12.33	0.48	0.48	17.71
P4	0.56	0.55	12.29	0.50	0.49	16.82	0.53	0.52	21.37
P5	0.51	0.51	15.94	0.52	0.51	14.36	0.53	0.53	20.17
P6	0.52	0.52	21.00	0.54	0.53	13.84	0.59	0.59	18.98
P7	0.45	0.45	23.89	0.46	0.46	21.70	0.52	0.51	27.52
P8	0.46	0.45	26.42	0.49	0.49	17.01	0.51	0.51	19.98
P9	0.50	0.49	28.52	0.46	0.45	23.63	0.51	0.50	28.90
P10	0.45	0.45	18.51	0.48	0.47	23.70	0.47	0.46	27.83

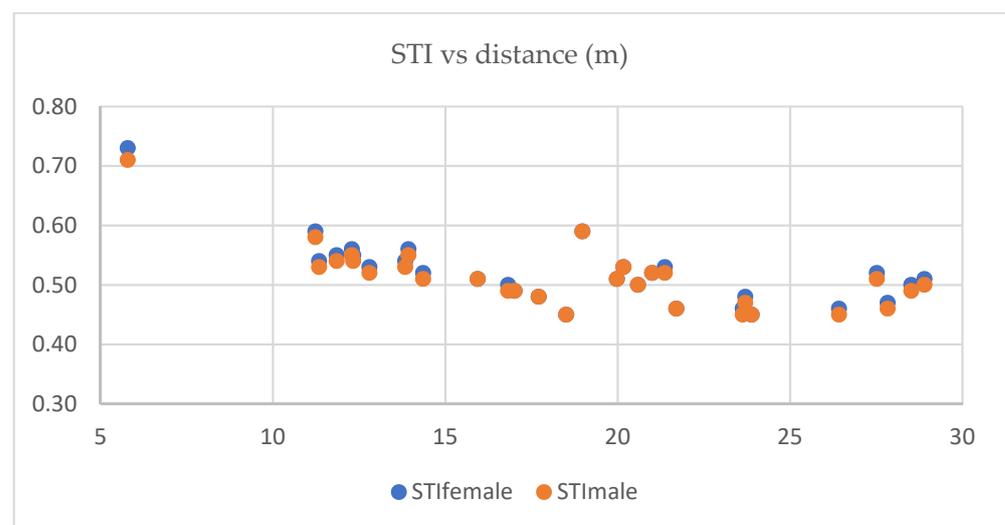


Figure 10. Speech transmission index vs. source–receiver distance (m).

3.4. Stage Parameters

As an open-air auditorium, a lack of overhead reflections is expected. Those reflections are important for the musicians to hear each other. Reflections coming from the sides can be easily affected by the presence of the performers. Early and total support has been averaged in frequency (250–2000 Hz octave bands) but single values of every source–mic combination are displayed in Tables 10 and 11. The 1 m distance positions are marked in grey.

Table 10. Early support ST_{Early} (250–2000 Hz frequency averaged).

ST_{Early}	Microphones in A				Microphones in B			
	mic 1	mic 2	mic 3	mic 4	mic 1	mic 2	mic 3	mic 4
Source A	−17.3	−17.1	−18.3	−16.9	−3.0	−3.1	−2.2	−1.9
Source B	−2.9	−1.6	−4.2	−2.9	−18.5	−18.1	−18.7	−17.0
Source C	−1.4	0.3	−0.5	−0.9	−6.2	−6.3	−4.9	−7.0
	Microphones in C				Microphones in Z			
	mic 1	mic 2	mic 3	mic 4	mic 1	mic 2	mic 3	mic 4
Source A	−0.7	0.1	0.4	1.0	−2.6	−3.4	−4.0	−1.4
Source B	−3.6	−7.8	−8.0	−5.5	−11.6	−12.6	−3.7	−0.5
Source C	−15.9	−17.3	−17.9	−17.2	−4.1	−4.2	−1.9	−7.0

Table 11. Total support ST_{Total} (frequency averaged).

AVG	Microphones in A				Microphones in B			
	mic 1	mic 2	mic 3	mic 4	mic 1	mic 2	mic 3	mic 4
Source A	−15.0	−14.8	−15.4	−14.8	0.6	0.4	1.5	1.5
Source B	1.2	2.2	0.1	1.0	−14.8	−14.8	−14.8	−14.1
Source C	2.3	3.6	3.1	2.3	−3.2	−2.2	−1.3	−3.4
	Microphones in C				Microphones in Z			
	mic 1	mic 2	mic 3	mic 4	mic 1	mic 2	mic 3	mic 4
Source A	3.0	3.2	3.9	4.3	0.6	−0.2	−1.5	1.9
Source B	−0.1	−4.1	−4.1	−1.9	−7.3	−8.5	−0.1	2.8
Source C	−13.7	−13.7	−15.0	−14.5	−0.2	−0.7	0.8	−4.3

Support is also averaged from the 12 positions in which the source is a 1 m distance from the microphones. The results are ST_{Early} : −17.5 dB, ST_{Late} : −18.1 dB and ST_{Total} : −14.7 dB. Information in octave bands for late support shows little influence on the frequency (see Table 12). These two tables contain a lot of information about the stage at every point. The overall view shows a big stage with a lack of strong reflections. In consequence, the musicians will have a balance of the orchestra, in which the closer instruments will prevail.

Table 12. Late support, ST_{Late} .

f, Hz	ST_{Late} , dB
125	−20.4
250	−18.4
500	−18.6
1000	−18.3
2000	−17.3
4000	−19.5
Avg (250–2000)	−18.1

3.5. Spatial Impression Parameters

The IACC results were averaged from all of the 30 source–receiver combinations in the audience. The BQI average was 0.53 and its standard deviation was 0.11. This is a good to excellent result according to Beranek. The LEV average was 0.72 with a standard deviation of 0.03. The existence of strong reflections after 80 ms can explain this low value. It must be noted that the uncertainties of these two results can be high as they have been calculated with a non-standard method.

3.6. Spatial Distribution of the Reflections

Reverberation times show very little dependency on the source–receiver combination (see Table 5). Previous figures show interesting trends in the behaviour of several parameters with distance (G , STI and C_{80}) that suggest a deeper sight on reflections should

be carried out. Barron and Lee [49] observed a deficiency in the reflected sound level at distant seats. These local differences are caused by strong reflections, which in turn are caused by geometry. The circular geometry of the Palace creates the opposite effect: an excess of sound level at distant seats.

The computation of first-order Ambisonic room impulse responses (FOA-RIR) with IRIS [20] enabled the estimation of the direction of arrival (DOA) of the reflections. A few measurements were chosen (Figure 11).

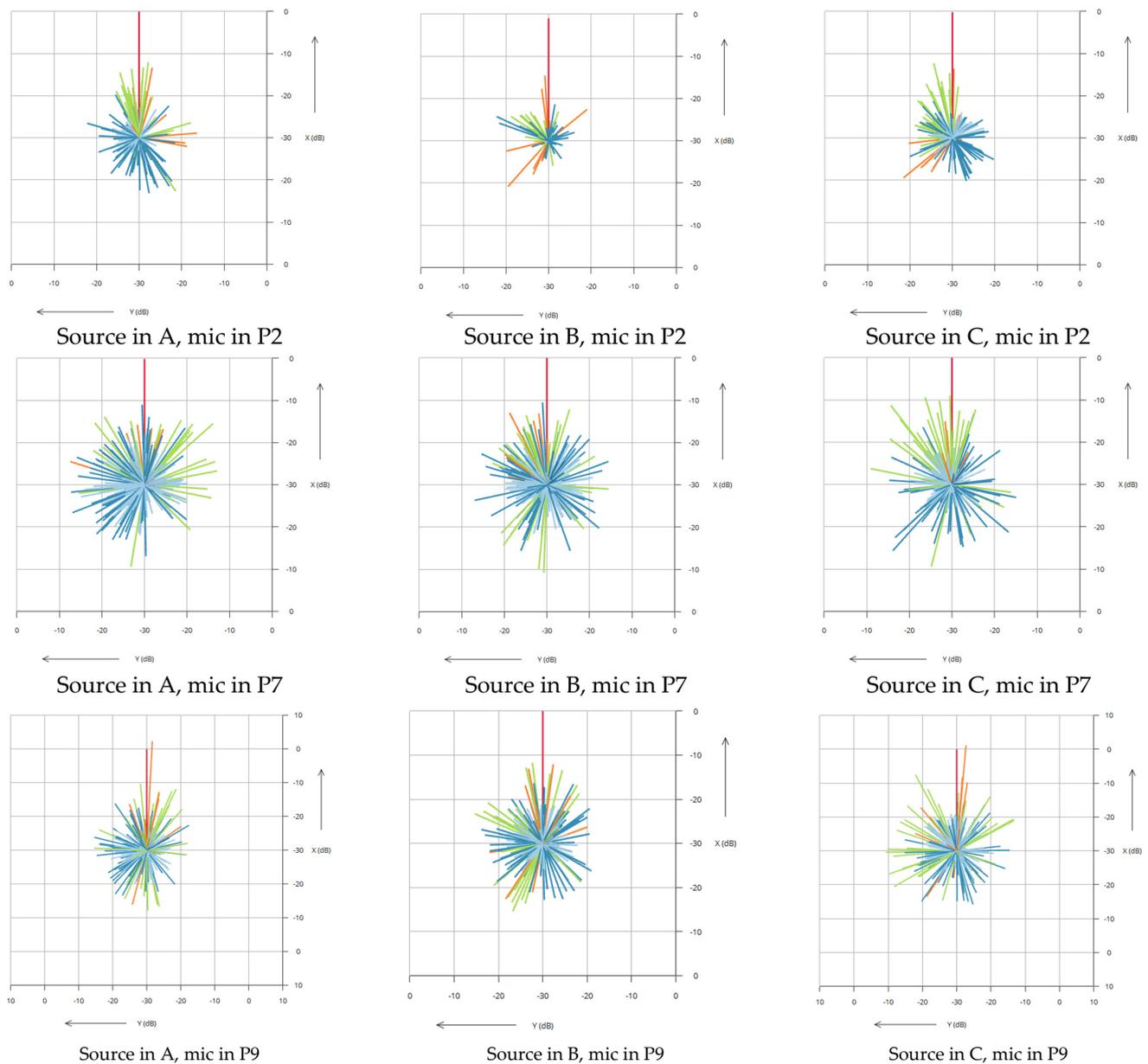


Figure 11. Directions of arrival of reflections. 30 dB range.

P2 is near the centre of the patio, very near to B (see Figure 5). That increased G and C_{80} from B, but not so from A or C, due to the dimensions of the stage ($C_{80,A-P2} = -0.5$ dB, $C_{80,B-P2} = -4.8$ dB, $C_{80,C-P2} = 0.3$ dB). Those close musicians will stand out from the rest of the orchestra. P7 is in the corridor on the main floor, under the toroid vault. C_{80} was low ($C_{80,A-P7} = -2.8$ dB, $C_{80,B-P7} = -3.1$ dB, $C_{80,C-P7} = -2.8$ dB). The blend of the musicians seems more adequate and the DOA of the first reflections is highly dependent on the position of the source on stage. That may improve the spaciousness sensation. P9 on

the grandstands of the first floor (see Figure 12). C_{80} was higher ($C_{80,A-P9} = -1.3$ dB, $C_{80,B-P9} = -1.6$ dB, $C_{80,C-P9} = -0.2$ dB) and the blend level of the three sources was quite similar. However, reflections do not tend to come from the sides as in P7. Some returning spectators show a preference for seats in this area.

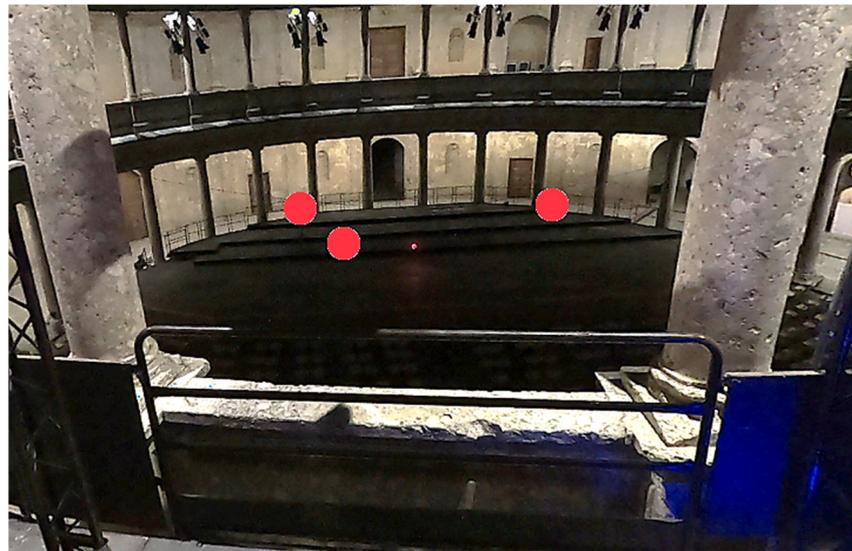


Figure 12. View from P9 featuring A, B and C positions.

Figure 9 shows a remarkably high C_{80} value for the C-P6 combination that deserves some explanation. The energy–time curve (Figure 13) shows two groups of strong reflections arriving in the first 80 ms (yellow and red lines) causing a C_{80} and STI rise. Figure 14 shows the directions of arrival for the same combination.

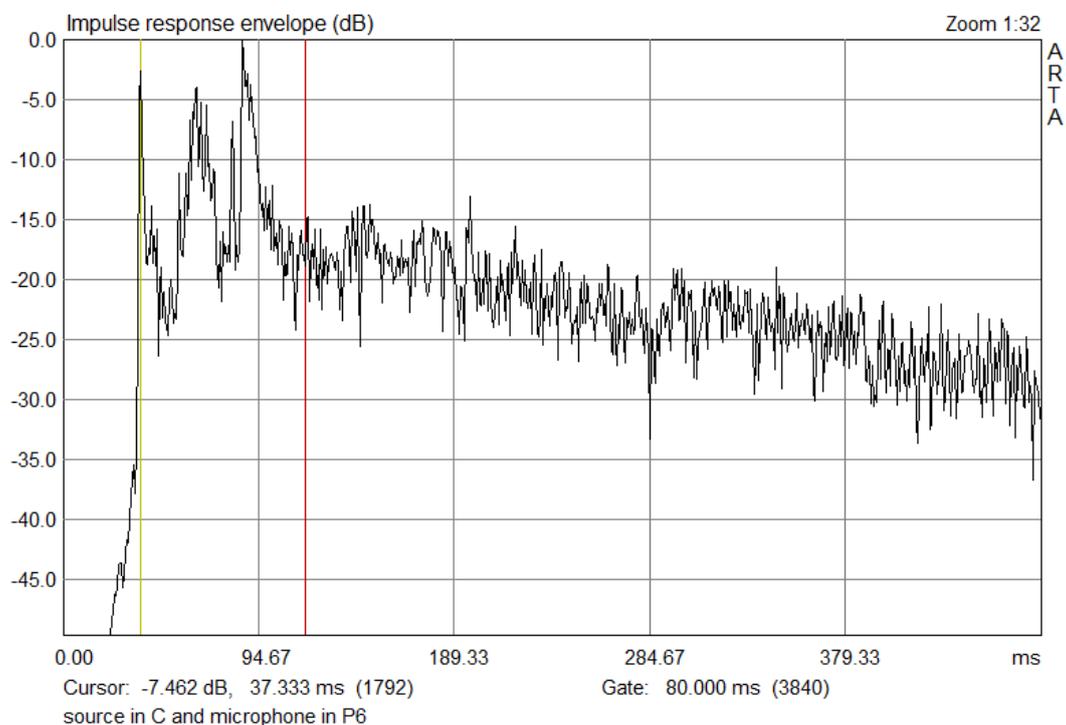


Figure 13. Energy–time curve (source in C, microphone in P6).

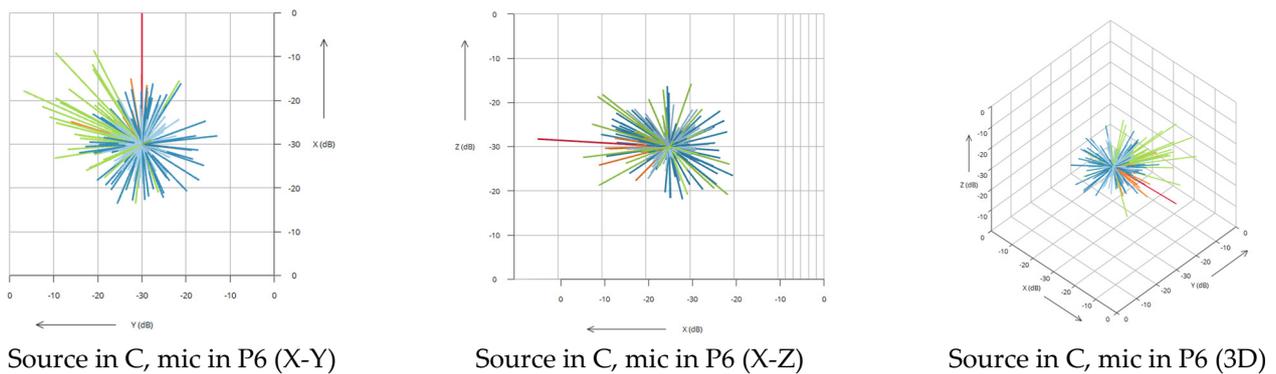


Figure 14. DOA of reflections. Source in C, microphone in P6. 30 dB range.

There are two groups of strong reflections with delays around 30 and 50 ms. IRIS shows they both come from the left side (Figure 15). The source was positioned in C (red dot and line), while the first group came from the parapet (green lines and dot, 15–50 ms delayed) and the second from the outer ring (blue lines and dot, >50 ms delay). The delays match the length of the geometrical paths.

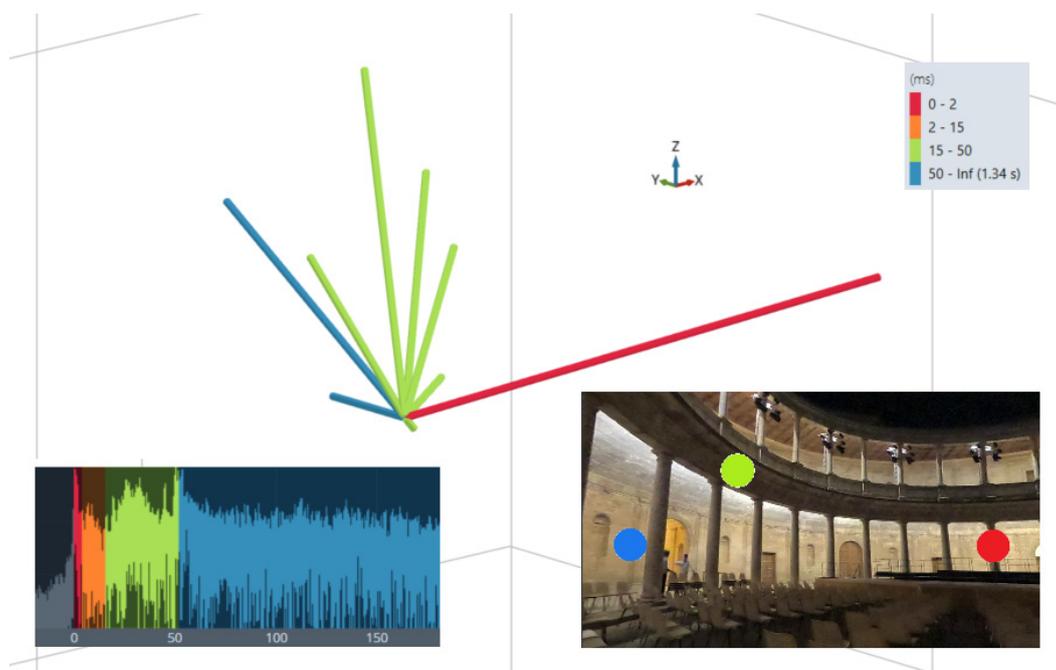


Figure 15. Directions of arrival of reflections. Time regions and 360° photograph included. 10 dB range.

3.7. Overall Attributes Discussion

The auditorium is quite reverberant. Taking into account it is open-air, a lot of the reflections come from the sides. This has been found by Pätynen and Lokki [57] to increase the emotional impact. The Palace is also wide, so the ITDG is very high as well. Taking a look at Figure 8, it is not straightforward to decide which reflection should be considered the first for the calculation of ITDG, especially if we think about the implications of psychoacoustical pre-masking and post-masking [58]. The balance of frequencies in the reverberation time is adequate: the bass ratio (BR) was 1.08 and brightness (Br) was 0.87. Only Br is too low for pop and rock according to Adelman-Larsen [45], but BR and Br are optimum for different kinds of music according to Arau [56]. The differences between T30 and EDT are not significant when averaged (see Table 5), but they are high in the centre of the hall due to the high ITDG. Of note, the standard deviation of EDT was much

higher than that for T30. No echoes or strong reflections that could cause artefacts were detected in any of the points measured, other than the first-order high-energy reflections already mentioned.

Previous research by Paini et al. [59] claims reverberation time (T30) and clarity index (C_{80}) not to be accurate for unroofed auditoriums and suggests strength (G) together with auralisations to be satisfactory for finding possible echoes. Moreover, Mo and Wang [60] support this claim. Cabrera and Martens [61] proposed using loudness models to predict reverberance (the subjective perception of reverberation). In the particular case of this palace, T30 was high and diffuse; the dimensions are not big compared to typical squares, and the circular shape avoids flutter echoes due to parallel walls. The only exception is when the source and receiver are close to the centre. Only then, a huge echo is audible and it makes sense to neglect the T30 values.

One of the particularities of the Palace is the high ITDG in every seat. This is caused by the long distance from the side walls. Some first reflections are strong and surpass the 80 ms limit of the early ones, affecting parameters such as clarity (C_{80}) or envelopment (LEV). LEV has a low value and it is paradoxical, given that the room is circular and open-air. This low ITDG is expected to be judged as a lack of intimacy and a defect. The best-liked halls in the world have an ITDG around or below 25 ms in the centre of the main floor, according to Beranek [46]. At over 35 ms, halls are considered lower grade, and over 60 ms, lower results are expected. However, the Palace is an imposing and monumental venue. Furthermore, clarity (C_{80}) in the mid frequencies had a negative value (Table 5), meaning that energy arriving late to the receiver was higher than early energy.

This blend of characteristics makes the orchestra sound big and not intimate. Good acoustics involve definition and intimacy but also reverberation, loudness and spatial impression. This multidimensional nature of the preference approach is not new; Hawkes and Douglas [62], and others such as Beranek [46] have researched in that direction. All these attributes should be blended to some extent, but some of them are opposed to others. Blauert [25] divides the quality of the acoustics into functional adequacy, typicality, listening tradition and aesthetics. The concept of ‘eignung’, named in the introduction, makes sense here. Good halls sound intimate but “should the palace of the emperor who ruled territories on which the Sun never set sound intimate?” We believe that a place with those visual characteristics should have monumental, not intimate acoustics.

4. Conclusions

This paper tries to answer the question of whether the Palace of Charles V has good acoustics, and if not, why the audience thinks it sounds so good. It is a heritage building where musical performances are held. Concerts include different genres such as classical music, opera, flamenco or rock, with different acoustic needs. Several acoustic parameters were measured without the public or musicians in the audience and stage areas. The most remarkable findings are related to the high energy and delayed reflections due to the circular shape of the inner patio.

The $RTU_{500-1000}$ was 2.24 s, while the RTO was expected to be between 1.28 and 1.98 s, which is not excessive given the size of the building. The high RT is due to the massive stone building. The absence of a ceiling leads to a predominance of reflections in the horizontal plane. This non-diffuse field affects the calculations of reverberation times under different conditions (occupied or adding treatment).

Clarity is very low due to the delay of the first strong reflections after 80 ms. Intimacy is supposed to be very important for concert halls. This palace is the opposite of intimate. Furthermore, the LEV was very low but the BQI was quite good. The lack of earlier reflections from the sides, compared to a similar shoebox-style concert hall, causes all these issues.

Using standard descriptors has been found useful in open-air spaces and heritage buildings but it is still not clear if the recommendations regarding their value should be applied. The emotional response to historical architecture or suitability of the place

and the music must be taken into account. This research includes an extensive set of descriptors and also Ambisonic RIR that can be used for auralisation, documentation and safeguarding. Further research can use these data to assess specific recommendations for heritage buildings. Which acoustic indices are important for music in heritage places deserve further research.

Auralisations with visual content can be an effective tool for checking whether the sound of the Palace can be improved with the use of absorbers or by reconsidering the design of the stage to give earlier reflections. There is no doubt that the acoustic indices would improve, but it would be interesting to know if the audience would find it appropriate as the architecture of the Palace is monumental, not intimate.

Programmers need to understand the acoustics of singular heritage halls such as this. A search for appropriately sized and aesthetically pleasing heritage sites can result in possible high-quality venues. Further research is needed, including semiology and audio-visual interactions, to understand why halls that were not designed as auditoria and are far from perfect in terms of hall acoustic recommendations sound so good.

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