On the Acoustics of the Central Rooms in Sans Souci Palace in Potsdam

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Introduction and Motivation

King Friedrich II of Prussia was an educated representative of enlightened absolutism. Furthermore, he was taught to play the traverse flute by J.J. Quantz and composed for this instrument. In the spring of 1756, Friedrich was daily accompanied by C.P.E. Bach, J.S. Bach's son, alternating every month with his young colleague C. F. Chr. Fasch [1].

Friedrich the Great's private summer retreat and UNESCO World Heritage Site Sanssouci Palace in Potsdam was completed in May 1747 and is a building of outstanding cultural and historical significance. The architect was Georg Wenzelslaus von Knobelsdorff. This palace is of particular musicological interest, especially the king's concert room.

However, little can be found in literature about the objective room acoustics of Sanssouci, although similar objects have lately been measured and analysed [2],[3].

Thanks to the kind support of the Prussian Palaces and Gardens Foundation Berlin-Brandenburg, the author was allowed to perform room acoustic measurements in central rooms of Sanssouci on 5 February 2024. Within four hours, the central rooms vestibule/entrance hall, domed marble hall, audience room and Friedrich the Great's concert room were measured and evaluated according to EN ISO 3382-1 in almost original state and with low occupancy. The evaluation of the measurements exhibits astonishing results regarding audibility and acoustic suitability for the respective use.

The acoustic measurements performed, their evaluation, results and interpretation are presented in this contribution. In addition, the room acoustic properties of these rooms were made audible by auralisations with characteristic audio stimuli during the oral presentation.

Description of the four measured central rooms

Four central rooms of Sanssouci Palace were measured as followed, see table 1, fig. 1 and 2 [4]: Entrance hall / Vestibule; marble Hall; audience room and concert room.

The central domed marble hall has a complex basic geometry with an oval floor plan, see fig. 1, and an ellipsoidal dome upwards from approx. 6 metres above the floor, in the apex of which an oval light opening is enthroned in the manner of the Pantheon in Rome, approx. 11.5 metres high.

Carrara marble is the favoured material for the columns, walls, reveals and floor inlays. The globally concave form is broken up by eight pairs of Corinthian columns with niches between them; the ceiling is made of partly gilded stucco.

The other three rooms exhibit cuboid geometries of varying dimensions, see Table 1.

Similar to the central marble hall, the walls of the vestibule are structured by ten pairs of Corinthian columns. The boundary surfaces of this hall are made of stucco marble.

The audience (small reception) room has upholstered textile wall coverings and rich decoration with paintings, see fig. 2.

The King's concert room, one of the most beautiful rooms of the German Rococo period [4], is richly ornamented with mirrors opposite the façade, panelling, paintings embedded in the walls, gilded details, decorations and a chandelier hanging from the ceiling, designed as a lattice arbour.

These central interior rooms of Sanssouci Palace have been largely preserved in their original historical state and furnishings. Only a 2.2 m wide sisal-like protective carpet is laid out on the walking paths in the rooms, see fig. 1 (shaded areas) and fig. 2, adding some high-frequent absorption comparable to one to two persons extra in the room(s).

Table 1 exhibits the dimensions and data of the analysed rooms, fig. 1 the ground plan of the central part of the palace with the 4 rooms examined and the measurement positions.

Table 1: Approximate dimensions of the examined palace rooms

Room	Parameter				
	Length L [m]	Width W [m]	Height H [m]	Floor area S [m^2]	Volume V [m^3]
Entrance Hall	13,5	8,7	7,5	117	875
Marble Hall	4,3	10,9	6,2… 11,6	113	1.150
Concert Room	10,1	8,2	6,12	84	515
Audience Room	10,1	5,4	6,16	53	315

The measured reverberation times, see table 2 and fig. 3, indicate in combination with the volumes, that the Schröder-frequency F_s is below 100 Hz for audience and concert room, 91 Hz for the marble Hall, and 127 Hz for the entrance Hall; thus modal sound fields can be neglected here.

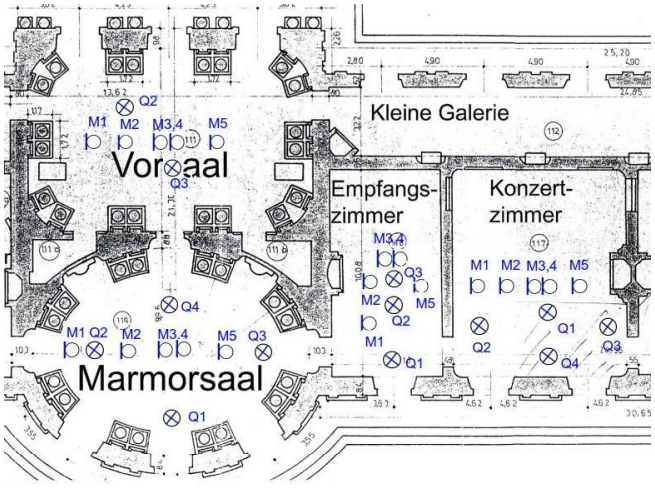

Figure 1: Floor plan of the central rooms of Sans Souci Palace, 1744, with the rooms: entrance hall (Vestibül, upper left), marble hall (down left), audience room (centre) and concert room (right) with measurement positions (**blue**)

Vestibule, Entrance Hall

Domed Marble hall

Audience / Reception Room

Concert Room

Figure 2: Views of the four measured central rooms in Sanssouci Palace on Monday, february 5th, 2024

Performance of the Measurements

Measurement conditions

The room acoustic measurements took place on Monday, 5th of February 2024 while Sanssouci palace was closed to the public. The measurements were carried out with two persons present in the measured rooms. During the measurements, the ambient conditions in the concert room were approx. 15°C temperature and 55 % relative humidity.

Measuring devices used

The following measuring and evaluation devices were used:

- Class 1 calibrated sound calibrator, type Norsonic 1251
- Class 1 measuring microphones, type Esper K4 with Sennheiser KE 4-211-2 microphone capsules
- 6-channel digital recorder, type Tascam DR-680
- Thermo- and hygrometer, type Testo 608H1
- Impulse sound sources: bursting balloons
- Computerised evaluation unit Peutz Spectralyzer 3.7.1
- MATLAB™ programme script Peutz Raci116 [2],[3]

Measurement positions and measurement paths

Figure 1 shows the measurement positions and paths.

Performance

The performance and evaluation of results were done in close accordance to EN ISO 3382-1 and EN IEC 60268-16. Popping balloons as impulse sound sources were used at, depending on the room, two to four source positions at a height of approx. 1.5 m above floor level. The directivity of these sources is approx. Q ~ 1.5. Using the omnidirectional class 1 measuring microphones, the resulting room impulse responses were recorded digitally on 6 channels at the receiver positions shown in figure 1. The impulse response measurements were carried out at two to four sender and ≥ 5 receiver positions per room with three decay processes digitally recorded per measurement path, in total 35 decays in the case of audience room, entrance hall and marble hall and 50 decays in the case of the King's concert room.

Evaluation

In order to evaluate the reflection structure of the impulse responses, they were analysed in both broadband and octave bands and displayed in energy-time curves. Typical examples of the impulse responses are shown in fig. 5.

The values of the room acoustic parameters clarity C_{80}, Deutlichkeit D_{50}, centre time T_C, early decay time EDT and the speech intelligibility indicator AL_{cons} were calculated from the measured room impulse responses by means of a Peutz MATLAB™ computer script [2],[3], the reverberation times were analysed with Peutz software Spectralyzer 3.7.1.

The results were averaged arithmetically to determine a room mean value for the average of the octave band values for octave bands with centre frequencies 500 to 2,000 Hz.

Measurement Results

Table 2 shows the room average values of the parameters. In brackets are the expectation values conform the diffuse field theory given (quoted after Möser [5]). The recommendations

of DIN 18041 "speech" and "concert" are square bracketed, curly brackets mark the expected values according to Peutz.

Table 2: Parameter room average values (all without 1 m-path)

Room	Average of octave bands 500…2.000 Hz					
	$T_{30,3}$ [s]	$G_{theo,3}$ [dB]	$D_{50,3}$ [%]	$C_{80,3}$ [dB]	EDT_3 [s]	AL_{cons} [%]
Entrance Hall	3,5	21	29 (24)	-2,5 (-3,1)	3,5	15,0 {16}
Marble Hall	2,4	18	37 (36)	-0,5 (-0,7)	2,35	10,8 {12}
Concert Room	1,25 [1,3]	19	49 (50)	+2,4 (2,5)	1,3	5,8 {6,6}
Audience Room	0,75 [0,8]	19	70 (68)	+7,4 (6,4)	0,75	3,3 {2,5}

The theoretical values of strength G turn out to be quite high.

Fig. 3 shows the frequency dependent reverberation times, fig. 4 the background noise floors during the measurements, and fig. 5 typical examples of the measured ETCs per room.

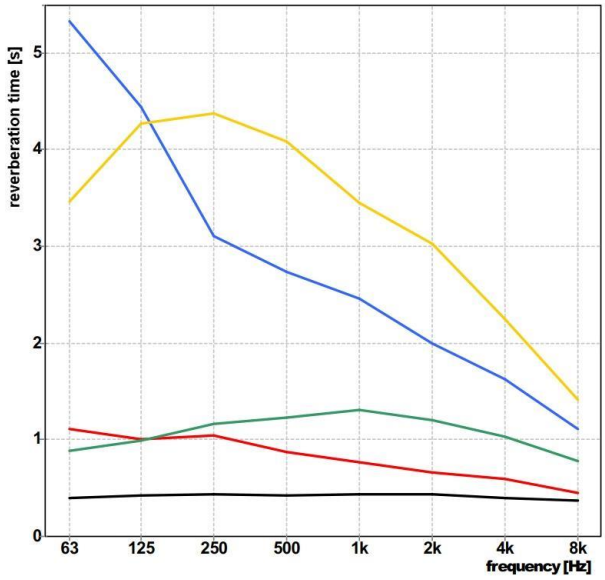

Figure 3: Frequency dependent reverberation times: **entrance hall**, **marble hall**, **concert room**, **audience room**

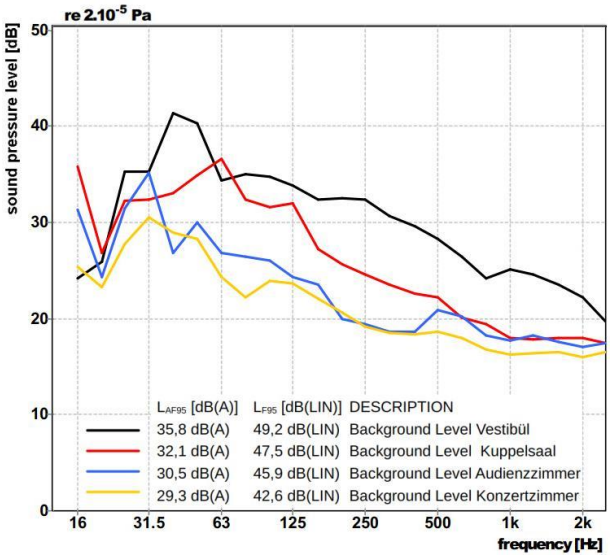

Figure 4: Background noise levels L_{95} during measurements: **entrance hall**, **marble hall**, **audience** and **concert room**

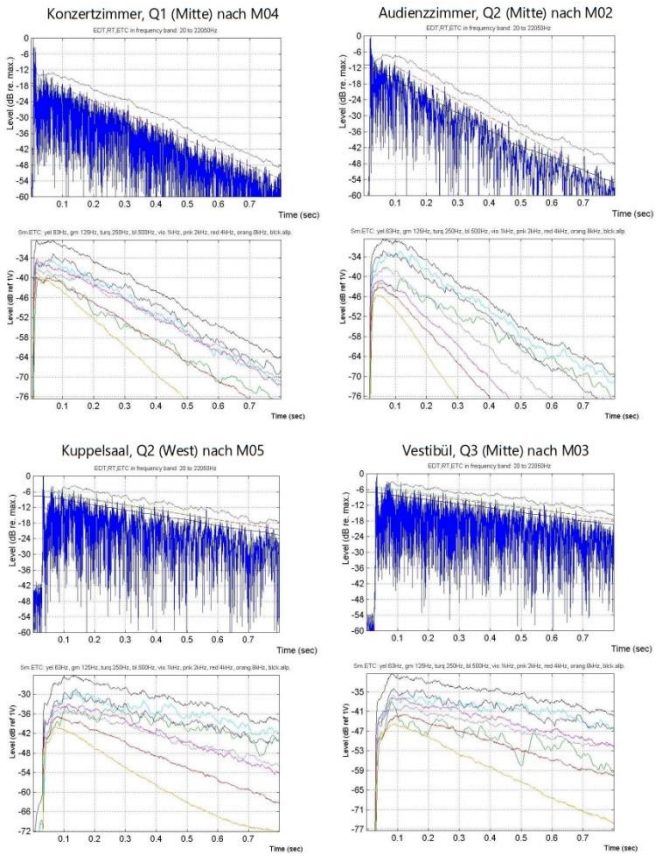

Figure 5: Typical impulse responses in ETC view: upper left: concert room, upper right: audience room, bottom left: marble hall; bottom right: entrance hall/vestibule

Assessment of the Measurement Results

Reverberation times

The reverberation times measured in the existing, largely historically original and sparsely occupied state of the rooms show *characteristic values for the respective usages*.

The frequency dependency of the reverberation times for the entrance hall and the marble hall as well as in the audience room exhibits higher values in the low frequencies, see fig. 3, indicating an impressive (entrance hall) resp. festive atmosphere (in the marble hall).

In the concert room, the reverberation times show highest values in the mid octave bands with a flat maximum in the octave band with centre frequency 1 kHz, indicating a brilliant timbre of musical performances therein.

The average reverberation times measured in the audience room and the concert room correspond almost exactly to the values of the actual recommendations of DIN 18041 for (unamplified) speech and music/concert performances.

Background noise

The background noise level L_{AF95} measured in the rooms in the measurement situation without public in the palace were between approx. 28 and 30.5 dB(A) for the concert and audience room, and approx. 32 dB(A) in the marble hall resp. 35 dB(A) in the entrance hall, see fig. 4, including wind noise from outside. The first values are low enough for understandable speech and qualitative musical performances.

Room impulse response reflection structures

The reflection structures of the room impulse responses measured in the rooms are fairly regular from medium

frequencies upwards for most of the measurement paths, and comparatively low in echoes, see typical examples in fig. 5. Flutter echoes are rather vague and, apart from lower frequency bands in the vestibule, negligible; even in the domed hall they are prevented by the scattering wall substructures, except low-frequent ones in the focal points.
In the case of the three other rooms, the diffusely scattering secondary structures of the room boundary surfaces succeed quite well in dispersing room acoustic defects from medium frequencies upwards. All rooms show plateaus in the ETCs.

Values of the Indicators of speech intelligibility

In the measurements of the indicator of speech intelligibility AL_{cons} and for the parameter Deutlichkeit D_{50} resulted values indicating an intelligibility which can be rated:

- in the entrance hall as 'just fair',
- in the marble hall as 'fair',
- in the concert / music room as 'good',
- in the audience room as 'excellent'.

Measured vs. expected room acoustical parameter values

The measured average room values for the parameters Deutlichkeit D_{50} and clarity C_{80} correspond well to the revised diffuse field theory expectation values (after [5]):

$$C_{80,E} = 10\log_{10}\frac{\left(\frac{r_H}{r_x}^2\right)^2 + 1 - e^{-\frac{13{,}8*0{,}08}{T}}}{e^{-\frac{13{,}8*0{,}08}{T}}} \quad \text{[dB]} \qquad (1)$$

within 1 JND, at limited distances 2…5 m, as were measured here, see bracketed values in table 2. This indicates the sound fields in the rooms to be quite diffuse due to their secondary structures, ornaments and details. The measured AL_{cons} values also correspond well to the expected values.
The C_{80} values in the concert room and in the marble hall indicate quite advantageous temporal binding of musical sounds, which is underlined by the auralisations, see below.

Summarised assessment of the measurement results

The measured parameter room averages are characteristic of the respective rooms and usages and can also be assessed in terms of their use according to actual recommendations, in particular audience and concert room. They are very suitable for their usage even by current standards, exhibiting:

- reverberation times in accordance with the recommendations of DIN 18041:2016 for the usage for ‘speech’ (A2) in the audience, and ‘music concert’ (A1), in the concert room, see [squared bracketed values] in table 2,
- appropriate values for the other room acoustic parameters, including the clarity C_{80}, particularly in the case of the concert room, and the indicators for speech intelligibility Deutlichkeit D_{50} and AL_{cons},
- no major acoustic defects such as strong echoes nor flutter echoes occur due to detailed structures;
- The room impulse responses generally sound fairly regular from medium frequencies upwards.

Overall, based on the results of the measurements carried out, it can be concluded that the four central rooms in Sanssouci palace analysed were and are very well suited to their usages and purposes from room acoustical perspective.

Especially in the case of the audience and the concert room the room acoustic conditions can be assessed as excellent:

The rooms exhibit reverberation times in accordance to the recommendations in DIN 18041:2016 as well as appropriate values of the other room acoustical parameters.

Auralisations

In order to make the sound of the four measured rooms of Sansscouci palace accessible and audibly perceptible to a wider audience, auralisations were created using the room impulse responses recorded in the Palace rooms (microphones 3 and 4 were placed as A-B-time-delay stereophony main microphone pair for this purpose).
Suitable stimuli with little reverberation were used: As musical stimulus, the first bars of the "Thema Regium" of Friedrich II., on which J. S. Bach wrote his 'Musical Offering', were played by a professional flute player in a rather dry living room of a cottage with an open wooden beamed ceiling in August 2024 and recorded with two omnidirectional pressure receiver microphones MTG M93, 0,4 m spaced apart in a distance of < 1 m of the instrument and in the height of ca. 2 m above floor level. The reverberation time of the room was below 0,45 s in all octave bands, see black curve bottom in fig. 3. As speech stimulus an excerpt from a rather dry recorded speech of an well known actor was taken. These stimuli were convolved with the impulse responses of the rooms, in which the direct sound was muted and replaced by the direct sound of the stimulus recordings.
Based also on these auralisations it can be concluded, that the four rooms of Sanssouci were and are appropriate for baroque chamber music to a certain degree, with focus on the King's concert room and the marble hall, whereas the vestibule is auditive very reverberant and thus not particularly suitable for rapid chord changes, while the audience room is quite dry and rather suited for practising rhythmic structures and of course, speech and audiences of the King.

Acknowledgements

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