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Acoustics of Notre-Dame cathedral de Paris

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Abstract

Notre-Dame de Paris is amongst the most well-known worship spaces in the world. Its large volume, in combination with a relatively bare stone construction and marble floor, leads to rather long reverberation times. Despite the notoriety of this space, there are few examples of published data on the acoustical parameters of this space, and these data are often not in agreement. Archived measurement recordings from 1987 were recovered and found to include several balloon bursts. In 2015, a measurement session was carried out which included similar source-receiver pairs using both balloon bursts and swept sine stimuli. Comparisons between results from these two sessions show a significant decrease in reverberation time in the modern state. This change is attributed to the addition of carpet in several areas of the cathedral. A geometrical acoustics model of the cathedral was constructed and calibrated from the 2015 measurements. The effect of carpeting was investigated through simulations. Comparison of the 2015 room impulse responses measured over the course of the 1-hour measurement session also indicated a potential slowly time-variant system. This was attributed to small temperature changes within the cathedral. Correction of this variance using a recently developed method allowed for the averaging of repeated measurements, providing the correct value for the reverberation time estimation, an improved signal-to-noise ratio, and a quantification of the temperature changes. This paper presents the results of these measurements, providing a modern documentation of the acoustical parameters of this historic worship space.

Keywords: Room-acoustic Measurement, time-variant system, Notre-Dame de Paris.

1 Introduction

The Cathédrale Notre-Dame de Paris is amongst the most well-known worship spaces in the world. This medieval cathedral is widely considered to be one of the finest examples of French Gothic architecture. It is approximately 130 m long, 48 m wide, and 35 m high. The large volume in combination with its vast exposed limestone and marble surfaces lead to long reverberation times.

Despite the notoriety of this space, there are few examples of published data on the acoustical parameters of this space. Hamayon [1] presented reverberation time estimations as a function of octave bands [125–4000 Hz: 8.5, 8.0, 7.5, 6.0, 4.5, 2.7 s]. Mercier [2] presented slightly different reverberation time values [125–4000 Hz: 8.5, 8.2, 6.5, 6.2, 4.7, 2.5 s]. Both studies presented simply the reverberation times without any measurement protocol information, nor with information about other room-acoustical parameters.

Therefore, this study carried out an acoustical measurement (2015) employing sine-sweeps and balloon bursts as excitation signals. Additionally, archival recordings (1987) were recovered which included balloon bursts [3] (Sec. 2). Parameter results of these two measurements are presented (Sec. 3).

The presented parameter results showed a decreased reverberation time between the 2 series. To explore the possible causes of these differences, a geometrical acoustics (GA) model was created and calibrated according to a methodical procedure [4] employing the 2015 sine sweeps as a reference (Sec 4).

During the 2015 measurements, 4 S(ource) × 8 R(eceiver) combinations recorded 4 sets of 2 sine sweeps. It was identified from the resulting room impulse responses (RIRs) that they were measured under time-variant conditions, resulting in reverberation time underestimations of the averaged RIRs. Sec. 5 summarizes a recently established correction method for slowly time variant systems caused by minor temperature changes.

2 Measurements setup

2.1 1987 measurement

Measurement protocol – Fig. 1a shows the measurement plan for the 1987 measurements with S-R positions. While a variety of techniques using different stimuli were employed, only balloon burst sources were exploitable due to lack of anechoic stimuli details. 3 balloon bursts from source position 1 were recorded as well as 1 balloon burst from source position 2.

Measurement equipment input – The sound was recorded with 13 omnidirectional microphones which were connected to a multitrack recorder (Tascam).

2.2 2015 measurement

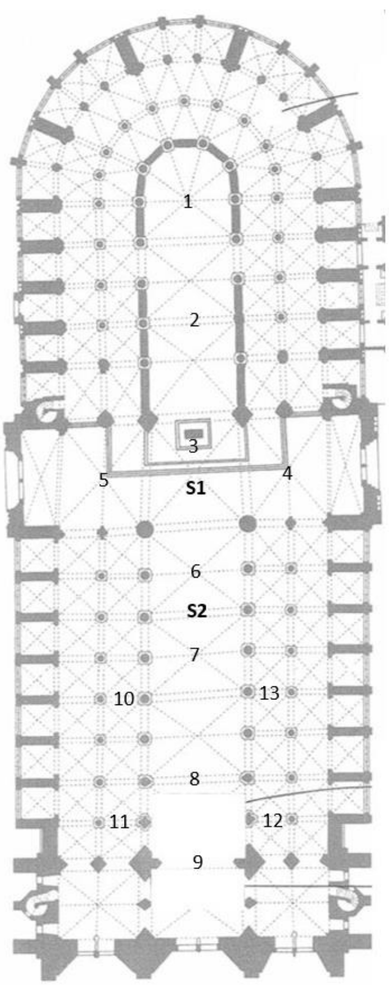
Measurement protocol – Fig. 1b shows the measurement plan highlighting S-R positions for the 2015 measurement. 3 measurement sets of 2 sine-sweeps during which microphones 1–8 changed positions were carried out (the changing positions of these microphones are represented by the letters behind the measurement position). Due to excessive exterior noise, the first measurement repetition was carried out twice, resulting in 4 measurement sets. Microphones 9–16 hang from the ceiling (7 m above floor level), thus remained at the same position and consequently recorded eight similar RIRs. After the last sweep measurement, a balloon burst at every source position was recorded with the receivers at the final position to provide comparable stimuli to the 1987 measurements.

Measurement equipment output – The audio output was sent to an amplifier (SAMSOM, model Servo 120a) and sequentially to four miniature dodecahedral sound sources (Dr-Three model 3D-032).

Signal – The excitation signal was based on the Swept Sine method. The sweep frequency rose exponentially over 20 s from 20 Hz to 20 kHz. The sweep was played at a sample rate of 44.1 kHz using the DAW software Reaper and sound card (RME Fireface 800).

Measurement equipment input – The input signal was recorded by two measurement chains as the measured session was carried out in conjunction with a concert recording installation. 1.) The sweep was recorded at a sample rate of 44.1 kHz by 5 omni-directional microphones (4 DPA model 4006 (1–4) and 1 Schoeps model MK5 omni, (5) and transferred to a sound card (RME Fireface 800). 2.) The sweep was recorded at a sample rate of 48 kHz by the other 11 omni-directional microphones (6 DPA model 4006 (11–16), 5 Schoeps model MK5 omni, (6–10)) and using a sound card (RME Micstacy).

(a)



(b)

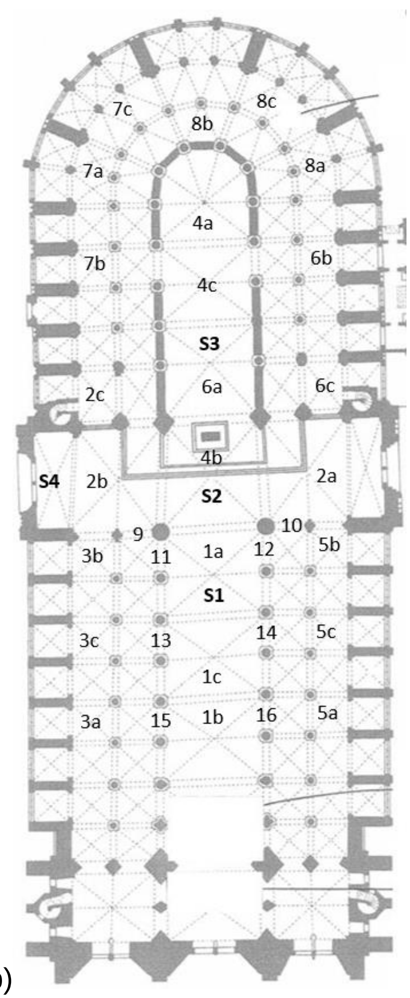


Figure 1 –Measurement plans (a) 1987 and (b) 2015 of the Notre-Dame cathedral.

2.3 General

Post-processing – Subsequent deconvolution, sample rate conversion, and post-processing steps were performed in MATLAB. RIRs were analyzed using LIMSI's in-house MATLAB IR analysis (IRA) toolkit in accordance with the ISO 3382 standard [5]. T20, the reverberation time evaluated by a linear fit of the Schroeder decay curve between –5 and –25 dB, and EDT, similarly evaluated from the decay between 0 and –10 dB, were determined. C50 and C80 are logarithmic ratios between early and late arriving energy, which vary as a function of frequency, calculated respectively for a time division of 50 (for speech) and 80 ms (for music).

3 Comparison of parameter results

Table 1 and Fig. 3 present the T20, EDT, C50, and C80 results of these measurements. Additionally, Fig. 3 presents the T20 results from previous Notre-Dame reverberation time studies. As expected, reverberation parameters were within one Just Noticeable Difference (JND_{EDT} = 5% [5]) between 2015 sine-sweeps and balloon burst. Subsequently, 1987 and 2015 balloon bursts were compared under two assumptions: 1) parameter averaging over multiple S-R combinations located throughout the space provides sufficiently comparable results, and 2) averaging over repeated balloon bursts compensates for variations in individual burst emissions [6]. Results show a decrease of 1–3 JND in T20 for the octave bands 250–2000 Hz (limited data for the 125 Hz octave band due to poor SNR). Additionally, the 2015 T20 measurements show better resemblance to values presented in the previous 1996 and 2002 studies [1,2] than the 1987 measurements. EDT showed similar differences, decreasing for octave bands 125–1000 Hz by 1–3 JND.

Table 1 – Mean and SD of the EDT, T20, C50, and C80 of all measured S-R combinations for the 1987 balloon burst, 2015 balloon burst, and 2015 sine-sweeps.

Frequency band (Hz)	Mean T20 (s) and SD						Mean EDT (s) and SD					
	Balloon burst 1987		Balloon burst 2015		Sine-sweep 2015		Balloon burst 1987		Balloon burst 2015		Sine-sweep 2015	
125	9.93	0.39	-	-	-	-	9.20	0.89	8.34	1.11	8.57	1.17
250	9.62	0.30	8.22	0.18	8.41	0.32	8.75	1.03	7.95	0.93	8.20	1.01
500	7.93	0.23	7.58	0.20	7.38	0.18	7.59	0.93	7.19	1.07	7.42	0.94
1000	6.56	0.29	5.89	0.21	6.08	0.24	6.25	0.85	5.86	0.75	6.14	0.83
2000	5.04	0.21	4.69	0.16	4.61	0.18	4.86	0.69	4.73	0.63	4.67	0.70
4000	3.25	0.22	3.13	0.19	3.04	0.20	3.06	0.46	3.07	0.51	3.20	0.64
	Mean C50 (dB) and SD						Mean C80 (dB) and SD					
125	-5.12	2.48	-6.98	2.84	-3.75	5.08	-4.26	2.53	-5.95	2.97	-2.44	4.74
250	-6.22	4.38	-8.28	2.81	-7.60	3.46	-4.95	4.02	-6.97	2.71	-6.32	3.27
500	-7.40	3.09	-8.08	2.81	-8.03	3.41	-6.17	2.90	-6.64	2.69	-6.56	3.18
1000	-6.33	2.94	-7.23	3.05	-7.18	3.81	-5.02	2.75	-5.64	2.86	-5.67	3.57
2000	-6.07	3.00	-6.27	3.31	-7.04	4.16	-4.68	2.95	-4.67	3.14	-5.38	3.89
4000	-3.90	2.55	-4.09	3.11	-4.21	4.55	-2.25	2.51	-2.36	2.95	-2.46	4.40

As expected, clarity parameters between 2015 sine sweeps and balloon bursts showed good resemblance, except in the 125 Hz octave band where the sine sweeps were more than 3 JND (JND_{C80} = 1 dB [5]) higher, though the meaning of clarity and the validity of the ISO JND values in such a low frequency octave band may be questionable. As clarity parameters are dependent on S-R distance, these parameters were compared for similar S-R combinations between 1987 and

2015 balloon bursts (1987: S1R2, S1R7, S2R2, and S2R7; and 2015: S2R4c, S2R1c, S1R4c, and S1R1c respectively). The mean clarity parameter (500-1000 Hz) for these position slightly decreased (C50 - 1987: -6.3, 2015: -6.9. C80 – 1987: -5.1, 2015: -5.2.). This is in contrast to what one would expect; decrease in reverberation time typically results in an increase in clarity.

4 GA model

The difference in reverberation between configurations was explored using a GA model. The room acoustic model of the Notre-Dame cathedral (see Fig. 2) was created using the GA software CATT-Acoustic (v.9.0.c, TUCT v1.1a) [7]. Calibration was performed according to the 7-step procedure presented in [4]. Details regarding the creation and calibration of the Notre-Dame model can be found in [8].

The Notre-Dame cathedral is a space with a fairly even absorption distribution. As such, simulations were run with CATT Algorithm 1: *Short calculation, basic auralization* using *transition order* 1, with 250,000 rays. S-R positions were simulated corresponding to the 2015 sine sweep measurements.

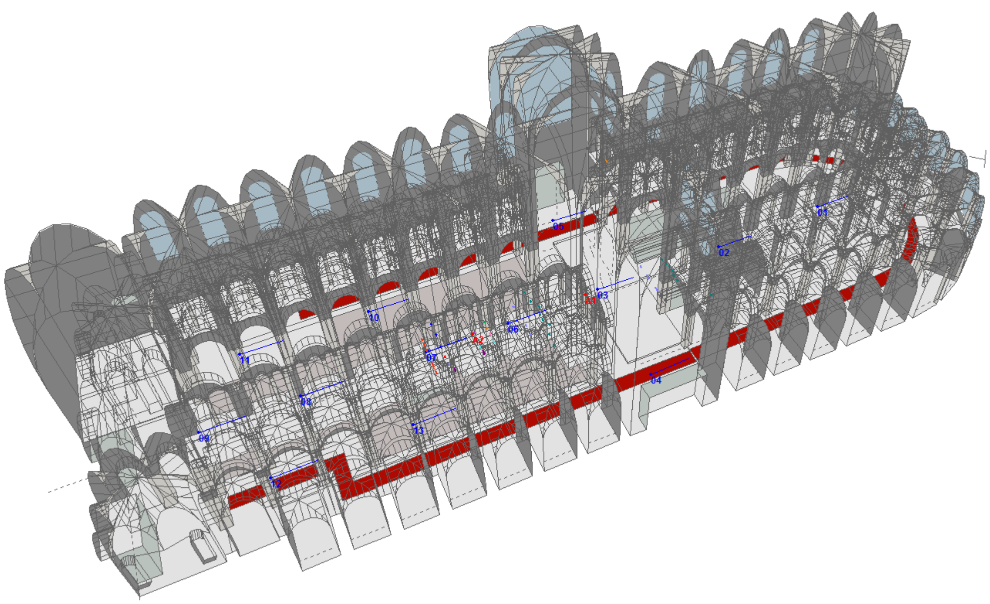


Figure 2 – GA model of the Notre-Dame de Paris cathedral (~14,700 surfaces). The red surfaces highlight the positions of the carpeting.

Fig. 3 shows the distribution of the T20, EDT, C50, and C80 for the 2015 sine sweep and balloon burst measurements, as well as the calibrated GA model. Mean simulated reverberation parameters EDT and T20 were within one JND of the measured values across all frequency bands. Mean simulated clarity parameters slightly overestimated measurements by more than 1 JND in the 500 and 2000-4000 Hz octave bands. The overestimation of clarity parameters could not be corrected while both maintaining reverberation parameter calibration and keeping scattering properties within physically viable values.

As data from [1,2] (published in 1996 and 2002) was comparable to the 2015 measurements, it can be concluded that changes leading to the shorter reverberation time estimations were carried out between 1987 and 1996. As the volume of the Notre-Dame cathedral is rather large the reverberation time difference has to be the result of substantial changes. In a telephone conversation with the

Notre-Dame cathedral it was confirmed that carpeting was installed in several areas and two confirmation booths were added in the two alcoves adjacent to the first two bays of the south naves during this time period. As the effect of the confirmation booths was considered marginal, simulations were performed only replacing the carpet by marble flooring. The possibility of the atmospheric conditions influencing the reverberation time results was considered. As temperature and relative humidity mainly effect reverberation estimations above 1000 Hz [9], this can be excluded as the cause for the decrease in reverberation time.

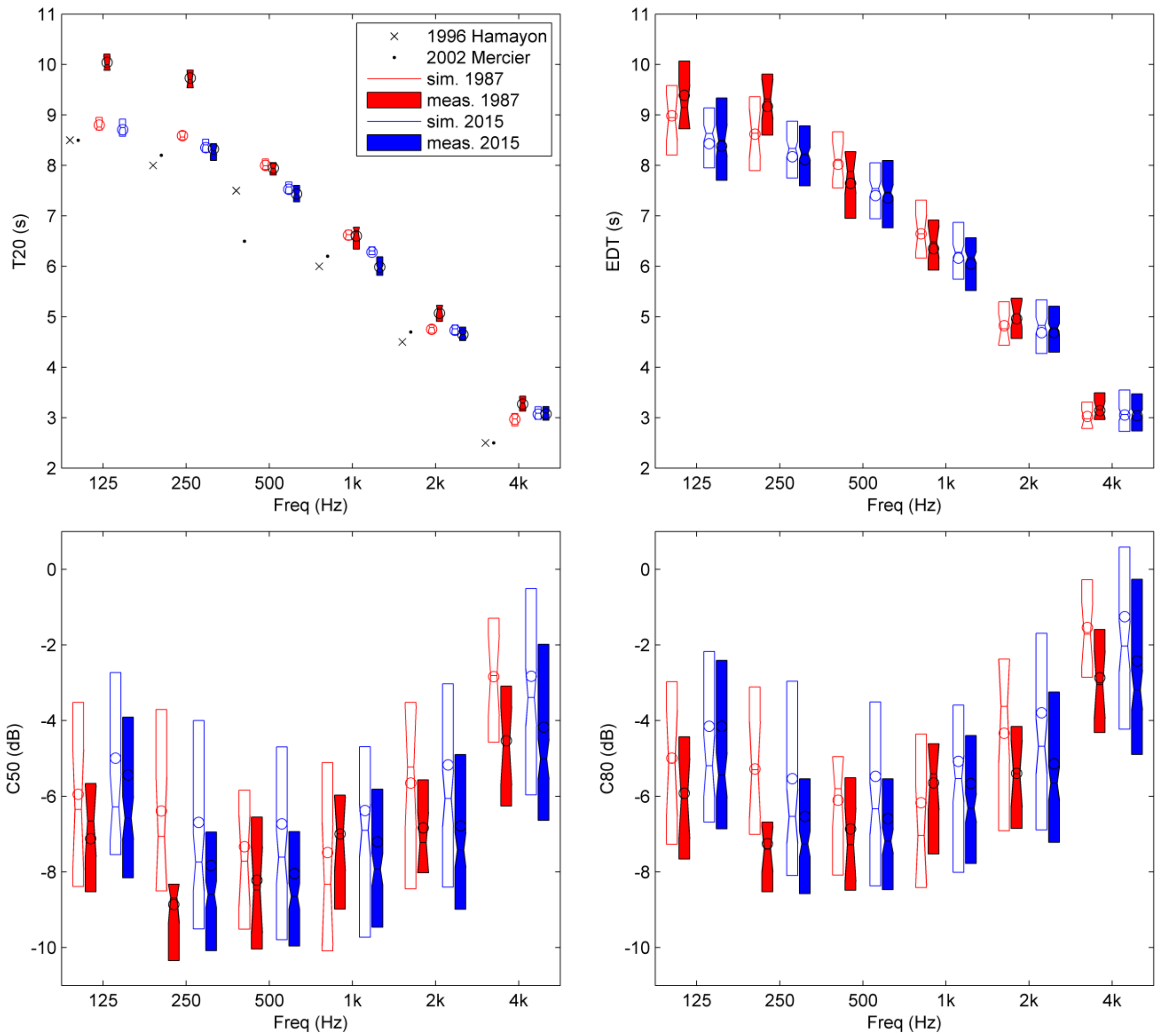


Figure 3 – Distribution of T20, EDT, C50, and C80 results of the 1987 balloon burst and GA model, as well as 2015 measurements (combination of sine sweeps and balloon bursts), and its GA model. Additionally, results from previous Notre-Dame reverberation studies [1,2] are included for T20. Box limits represent 25% and 75% quartiles, (|) median, and (o) mean values.

Fig. 3 shows the distribution of the T20, EDT, C50, and C80 for the 1987 GA model and corresponding measurements. It shows that the reverberation changes can only be partly explained by the addition of the carpet. As no other refurbishments or renovations were carried out, one can only contemplate about other causes for the decreased reverberation time.

5 Correction for the time-variant system

As the Notre-Dame cathedral has a large volume (~84,000 m^3), obtaining a sufficiently high Signal-to-Noise-Ratio (SNR) was more troublesome than in smaller volumes, such as theatres or concert halls. A sufficiently high SNR is necessary in order to obtain reliable room acoustical parameter. Under the assumption of a time-invariant acoustic system, it is possible to perform post-measurement averaging of repeated RIRs in order to improve the SNR. The assumption of time-invariant acoustic systems can be invalidated by factors such as air turbulence or temperature variations between repetitions resulting in a time-variant acoustic system. RIRs averaged under time-variant conditions exhibit shorter reverberation time estimations, especially in higher octave bands.

The sources and 8 receivers (9-16 in Fig. 1b) remained at the same position during the 2015 measurements and consequently these S-R combinations measured 8 RIRs over the course of one hour. As the SNR of the S-R combination including source 3 and 4 was rather low, subsequent analysis employs only the S-R combinations including source 1 and 2. Fig. 4a shows the T20 of the numerical average of the 8 individual sweeps and their averaged RIR before and after correction. Table 2 shows that the mean *error ratio* (percentage difference between the reverberation time estimation of the averaged RIR and the numerical average of the reverberation time determined from the separate RIRs) for T20 rose from 4.5% to 25.9% (octave bands 250-8000 Hz), with a mean SD of 2.3%. These error ratios rendered the averaged RIRs unreliable for parameter analysis and auralizations, as well as showing that the measurements were subject to a time-variant system.

A recently proposed correction method [10] was employed to average the 8 similar RIRs with considerably less energy loss. Cross correlations were calculated between a reference and considered RIR pair at 10 ms intervals. The argument of the maximum versus time (time lag or Ƭ) was examined. Fig. 4b depicts Ƭ determined between the first and last sweep (×10 up-sampled) for S1R8 as well as the least-squares linear-fit between $t_0 + 0.2\ s$ and $t_0 + 2.5\ s$, chosen as a function of RIR SNR performance. As this followed a linear slope, temperature changes were deemed to be the cause of the time-variant acoustic system. Since it fluctuates somewhat around the linear fit, some air turbulence was also considered as contributing.

When one qualitatively regards two repeated RIRs measured at different temperatures, one can observe that, due to the changed speed of sound, RIRs become progressively more out of sync. Fig. 4c shows that the measured RIRs of S1R8 mirror this effect. This translates to the averaged RIR as a steeper and concave Schroeder Decay Curve, resulting in shorter reverberation time estimations.

To correct for the observed energy loss, a time-stretching based on interpolation of the considered RIRs to a reference was performed (the first measured RIR was used as the reference). First, the RIRs were up-sampled ×10. Second, the slope m of Ƭ's linear least-squares best-fit function, over the range $t = [t0 + 0.2 : t0 + 2.5\ s]$, calculated in 10 ms steps, with a 10 ms window, was determined. Subsequently, a re-sampling of each RIR was performed using the re-sample factor ratio: $f_{s,ref} / (f_{s,ref} + m)$. Finally, an anti-aliasing filter (Butterworth filter, 10^{th} order, f_c = 20 kHz) was applied.

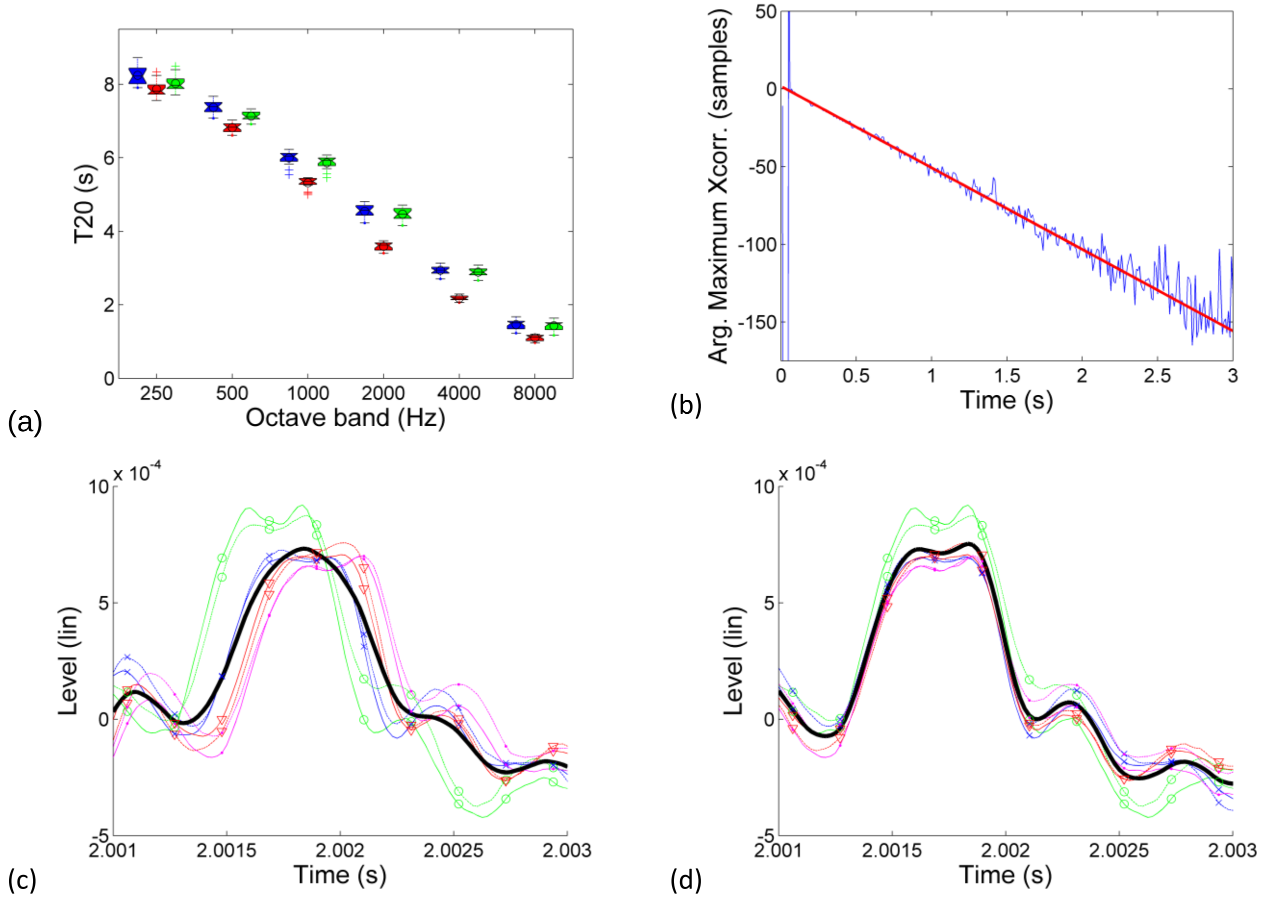


Figure 4 – (a) Summary of results for T20 of the 2 S × 8 R considered configurations. (Blue): Numerical average of parameters calculated individually on the 8 measured RIRs. Parameters calculated on averaged RIR before (red) and after (green) time-stretching correction. (b) (—-) Time lag (T) between the first and last RIRs and (—-) linear fit, before correction for S1R8 (f_s = 480 kHz). (c) Extract of 8 measured RIRs of S1R8 (1st (o), 2nd (×), 3rd (◊), and 4th (●) repetition; first (—) and second (– –) sweep) and their average (thick line). (d) Extract of 8 corrected measured RIRs of S1R8 and their average (from [10]).

Fig. 4d shows that the resulting eight RIRs of S1R8 and their average became more coherent. Additionally, from T, it is possible to estimate the associated temperature change between measurements according to the formula C = 331 + 0.6 Tc under the assumption of dry air. Differences between consecutive sweeps within each of the four sets varied minimally (0.001-0.002 °C), while the temperature difference clearly increased over the four sets, separated by 10-20 min (0.01-0.04 °C). However, it is noted that such variations in temperature are practically impossible to measure without a high sensitivity specialized thermometer.

After applying this method, Table 2 shows the mean T20 error ratios improved from approx. 15.8%, mean SD of 2.3%, to 2.3% with a mean SD of 0.7%. These values are well within 1 JND. This validates the corrected averaged RIRs as being suitable for room acoustical parameter analysis, and auralizations, while providing a clearly improved SNR.

Table 2 – Mean T20 (sec) and SNR (dB) results of the 16 S-R combinations. Numerical average of the 8 individual sweeps and their averaged RIR before and after correction and their associated error ratios.

	250	500	1000	2000	4000	8000
$\overline{T20(RIR)}$	8.24	7.37	6.00	4.55	2.94	1.46
$T20(\overline{RIR})$	7.87	6.82	5.32	3.59	2.18	1.10
Error ratio	4.5%	7.5%	11.3%	21.1%	25.9%	24.7%
$T20(\overline{RIR_{corr}})$	8.02	7.13	5.87	4.47	2.89	1.43
Error ratio	2.7%	3.3%	2.2%	1.8%	1.7%	2.1%
$\overline{SNR(RIR)}$	35.4	36.5	40.7	43.8	49.5	53.7
$SNR(\overline{RIR})$	43.8	46.5	49.2	50.6	55.9	62.2
$SNR(\overline{RIR_{corr}})$	43.8	45.2	48.7	50.9	56.4	62.2

6 Conclusions

The acoustical parameter results of two measurements (dated 1987 and 2015) carried out in the Cathédrale Notre-Dame de Paris were presented. These provide a modern documentation of the acoustical parameters of this historic worship space. It was found that the reverberation time has slightly decreased over the course of the last 30 years. The cause of this acoustical difference was explored using a calibrated GA model. It can be concluded that this decrease can be partly explained by the placement of a carpet in several areas of the cathedral.

Additionally, a newly established correction method was presented which enabled the averaging of RIRs subject to a time-variant system. This method rendered the averaged RIRs as being suitable for room acoustical parameter analysis and auralizations while providing a clearly improved SNR.

Acknowledgments

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