A COMPARISON BETWEEN SOME MEASUREMENT TECHNIQUES IN THE FOLIGNO AUDITORIUM

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1 INTRODUCTION

The town of Foligno, central Italy, has an ancient dismissed church that was restored about 20 years ago and transformed into Auditorium. Due to dimensions of the main nave, the sound quality resulted not fully satisfying. Therefore, and acoustical design was carried out in order to improve intelligibility, sound distribution and spaciousness. A set of panels, accomplished with acoustic plaster and some tissues were designed and inserted in the stage and in the nave with the aim to redirect sound energy, decrease reverberation field and increase clarity. Since the main nave of the church is narrow and long, the side walls produce a lot of strong lateral early reflections, so the spatial impression resulted good when a reflector was added over the orchestra scene, to avoid echoes and focalisations from the apse, and to redirect the reflected sound energy towards the rear part of the main nave, where the direct wave arrives attenuated by the grazing incidence over the long seating area.

Measurements were conducted in different times, in 1990, 1994 and 2001, aiming to verify acoustical parameters during the prosecution of works. In this paper the different measurement campaigns are considered, starting with the analysis of the techniques and the instrumentation. The different measurement techniques of IRs utilised in the three different campaigns are critically compared, and the acoustical data calculated from the IRs are compared and analysed. Improvements in definition and spaciousness were found during the years. Finally, the actual acoustical behaviour of the nave wis fully analysed and commented.

2 THE AUDITORIUM OF FOLIGNO: HISTORICAL BACKGROUND

The church of San Domenico, located in the homonymous square with its annexe cloister, is one of the most significant architectural monuments of the city of Foligno. For centuries it has changed its functional correspondence but it has kept its own architectural identity. The frontage has a beautiful gothic portal; the saddleback roof, typical of the churches of the Mendicant Order, keeps the gothic structure. In the 1799 the Black Friars, after their eviction, returned in the convent while in the 1806, during the second suppression of the Convent, it has been changed in “Spedale de’ Francesi” (“Hospital for Frenchmen”).

In 1848, during third suppression of the convent, the church has been used as dormitory for the troops going to Rome; in 1861 the Church of San Domenico has been adapted to stable for the horses of the Army and then, in 1904, it has been used as gymnasium until the local government in 1980 decided to restore it and to finally designate the main room to Auditorium. The structural shape is particularly suitable for concerts, theatrical works and congresses and now the site can hosts 662 spectators in the main hall and it’s provided of a meeting-hall, foyer, breakfast room and a video room with 96 places.

3 ACOUSTICAL LIMITATIONS

Due to dimensions of the nave, the acoustical behaviour of the renewed auditorium appeared soon not fully satisfying. Therefore, an acoustical project was planned. A set of panels was designed in the stage area, in order to redirect early reflections in the audience. The panels were equipped with an engine and orientation, height and curving were all possible. Absorbing plaster and tissues were put on walls, close to the ceiling. Also the seats were designed, with care of their absorption and shape. The first acoustical measurements were conducted in the hall in 1986 and repeated in 1990. The impulse responses were measured, by using a pistol shot and recording the pressure, with binaural microphones. Four years later, in 1994, acoustical measurements were repeated, by means of a dummy head and an omni-directional sound source fed by MLS signal. Finally, in 2001 acoustical measurements were performed by means of a frequency equalised omni-directional sound source and two different dummy heads and the Soundfield probe. Furthermore, many musical pieces by piano and orchestra were recorded by means of a multi-channel sound board and the Soundfield microphone. The three measurements of acoustical parameters were done at different times and different architectural conditions, and the results pointed out the improvement of sound field during the progress of works.
Since the measuring campaign lasted 15 years, the instrumentation and the techniques greatly improved during this time. Therefore, in order to properly evaluate the results, the different techniques should be firstly analysed

4 ACOUSTICAL MEASUREMENTS

Acoustical measurements were made mainly in accordance with the ISO 3382 code, which describes the measurement techniques that can be used for the determination of the impulse response and the main characteristics that should be fulfilled by the equipment.

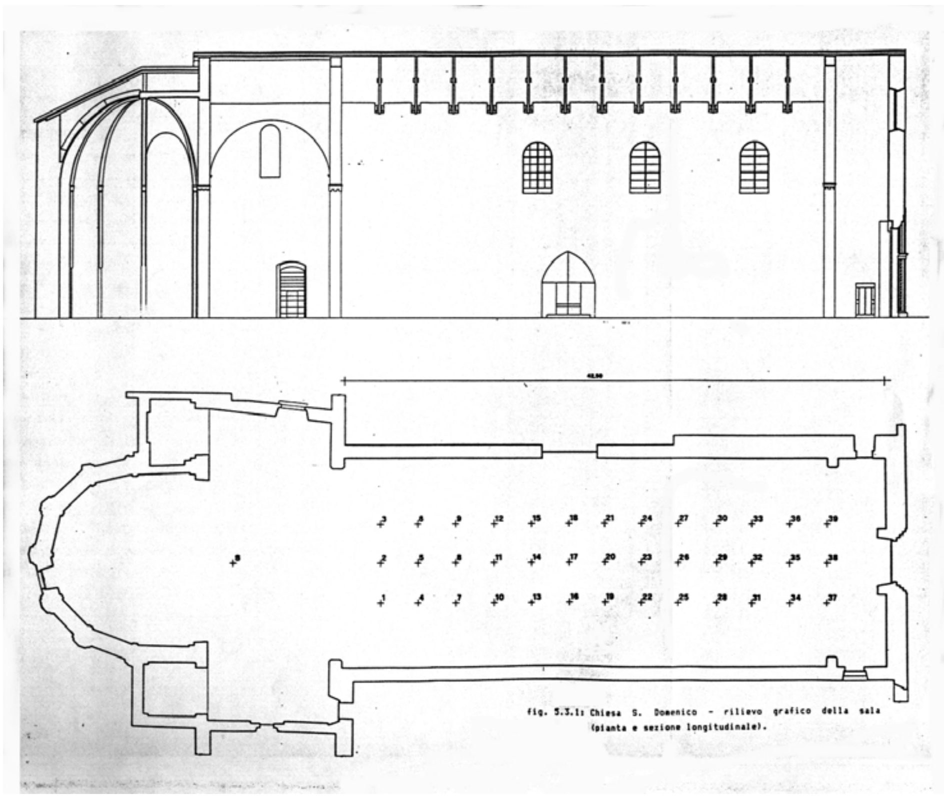


Figure 1 Measuring point in the Auditorium S. Domenico, Foligno

The measurement techniques used in this research were the following:

- Digital recording of the impulse response generated by impulsive sources (pistol shots) and its subsequent analysis (1986-1990);
- Calculation of the impulse response based on the deconvolution of a steady pseudo-random test signal (MLS) (1994);
- Calculation of the impulse response based on the deconvolution of an exponentially-sweeping sine wave test signal (2001).

From all measurements the main acoustical parameters described in the ISO 3382 were calculated, including spatial parameters (IACC).

5 THE FIRST ACOUSTICAL MEASUREMENTS, 1986-1990

The procedures based on the recording of the impulse response generated by impulsive sources (pistol shots) and its subsequent analysis could be carried out by using a small portable digital recorder (DAT) or directly a personal computer equipped with a sound-board. Since the sound source is not stable and repeatable and does not have a normalized spectrum, it is not possible to obtain information neither about the absolute sound spectrum produced by a room, nor about the absolute value of the sound pressure level. Nevertheless, acoustical parameters could be obtained after transferring wave-forms of IRs into PC.

During the measurements (preliminary measurements were done in 1986), a pistol shot was used. A Digital Audio Tape was used and in a second step the wave-forms were transferred and analyzed with a dedicated software (MLS). The measurements were conducted in 39 receiving points.

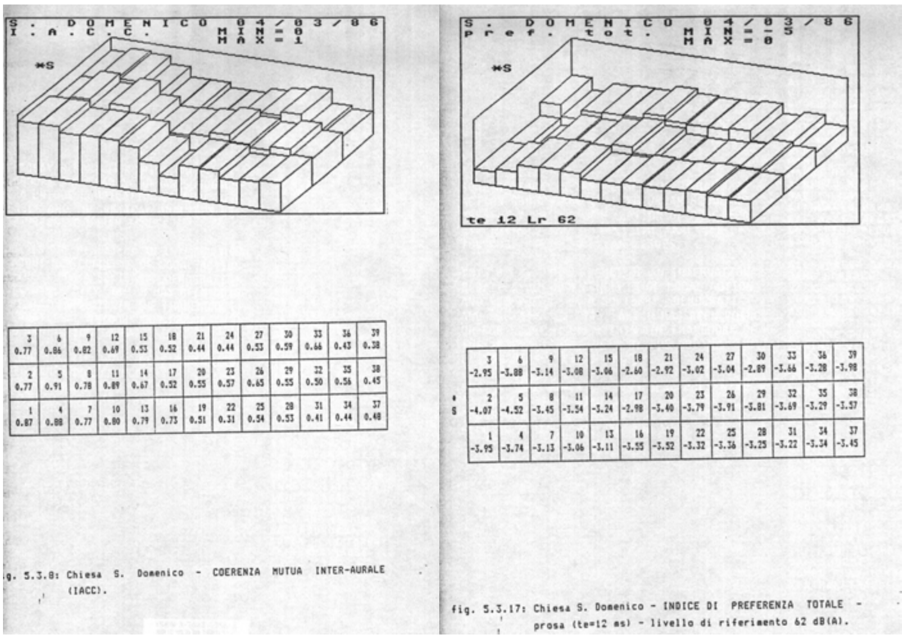
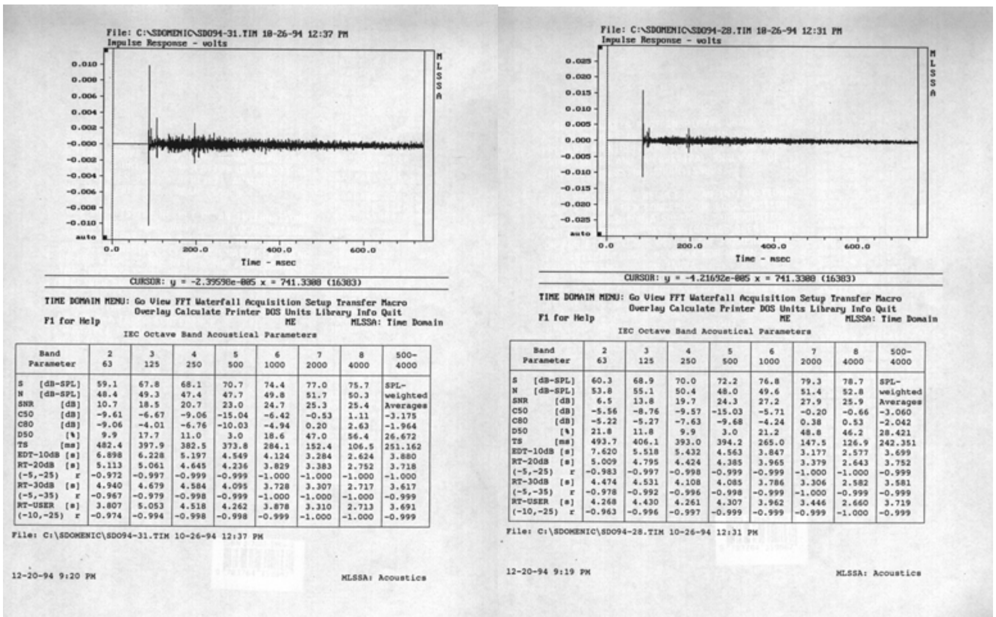


Figure 2 IACC and total preference index (τ_e=42) measured in 1986

6 THE SECOND ACOUSTICAL MEASUREMENTS, 1994

The impulsive technique called MLS (Maximum Length Sequence) is based on the deconvolution of the response of the hall to a deterministic pseudo-random test signal. Using Hadamard's fast transformation it is possible to obtain the correlation function between the test signal and the room's response, which gives the impulse response directly in the time domain. As the MLS technique is based on a deconvolution of deterministic sequences, it is useful only for a time-invariant system. The signal to noise ratio can be improved by averaging many sequence repetitions.

The measuring system has been used basically to obtain the binaural impulse responses in each listening point. For this, an omnidirectional loudspeaker was used, being fed with the Maximum Length Signal produced by a MLSSA board (A2D160), installed in a portable 286 PC. The signal period was 65535 samples, and the sampling rate varied between 22.05 kHz and 44.1 kHz. The acoustic signal was sampled through a dummy head (Sennheiser MKE2002set), connected with the MLSSA board through a wireless system (NADY VF-701). The measure was performed in the same time for both ears, thus enabling the computation of the Inter Aural Cross Correlation (IACC) through a dedicated post-processing program, in addition to the wide range of other acoustical parameters computed by the MLSSA software.



Band Parameter	2 63	3 125	4 250	5 500	6 1000	7 2000	8 4000	500-4000
S [dB-SPL]	59.1	67.8	68.1	70.7	74.4	77.0	75.7	SPL-
N [dB-SPL]	48.4	49.3	47.4	47.7	49.8	51.7	50.3	weighted
SNR [dB]	10.7	18.5	20.7	23.0	24.7	25.3	25.4	Averages
C50 [dB]	-9.61	-6.67	-9.06	-15.04	-6.42	-0.53	1.11	-3.175
C80 [dB]	-9.06	-4.01	-6.76	-10.03	-4.94	0.20	2.63	-1.964
D50 [%]	9.9	17.7	11.0	3.0	18.6	47.0	56.4	26.672
TS [ms]	482.4	397.9	382.5	373.8	284.1	152.4	106.5	251.162
EDT-10dB [s]	6.898	6.228	5.197	4.549	4.124	3.284	2.624	3.880
RT-20dB [s]	5.113	5.061	4.645	4.236	3.829	3.383	2.752	3.718
(-5,-25) r	-0.972	-0.997	-0.999	-0.999	-1.000	-1.000	-1.000	-1.000
RT-30dB [s]	4.940	4.679	4.584	4.095	3.728	3.307	2.717	3.617
(-5,-35) r	-0.967	-0.979	-0.998	-0.999	-1.000	-1.000	-1.000	-0.999
RT-USER [s]	3.807	5.053	4.518	4.262	3.878	3.310	2.713	3.691
(-10,-25) r	-0.974	-0.994	-0.998	-0.998	-0.999	-1.000	-1.000	-0.999

Band Parameter	2 63	3 125	4 250	5 500	6 1000	7 2000	8 4000	500-4000
S [dB-SPL]	60.3	68.9	70.0	72.2	76.8	79.3	78.7	SPL-
N [dB-SPL]	53.8	55.1	50.4	48.0	49.6	51.4	52.8	weighted
SNR [dB]	6.5	13.8	19.7	24.3	27.2	27.9	25.9	Averages
C50 [dB]	-5.56	-8.76	-9.57	-15.03	-5.71	-0.20	-0.66	-3.060
C80 [dB]	-5.22	-5.27	-7.63	-9.68	-4.24	0.38	0.53	-2.042
D50 [%]	21.8	11.8	9.9	3.0	21.2	48.8	46.2	28.421
TS [ms]	493.7	406.1	393.0	394.2	265.0	147.5	126.9	242.351
EDT-10dB [s]	7.620	5.518	5.432	4.563	3.847	3.177	2.577	3.699
RT-20dB [s]	5.009	4.795	4.424	4.385	3.965	3.379	2.643	3.752
(-5,-25) r	-0.983	-0.997	-0.998	-0.999	-0.999	-1.000	-1.000	-0.999
RT-30dB [s]	4.474	4.531	4.108	4.085	3.786	3.306	2.582	3.581
(-5,-35) r	-0.978	-0.992	-0.996	-0.998	-0.999	-1.000	-0.999	-0.999
RT-USER [s]	4.268	4.430	4.261	4.307	3.962	3.446	2.660	3.719
(-10,-25) r	-0.963	-0.996	-0.997	-0.999	-0.999	-0.999	-1.000	-0.999

Figure 3 Impulse responses and table of parameters measured in 1994

The hardware generation ensured tight matching between generation of the signal and recording. This enabled the system to calculate a decay of the sound field over 1.5 seconds with a sampling rate of 44.1 kHz. The acquisition board used gave the system a good signal to noise ratio and the dedicated software allowed the direct calculation of all of the above-mentioned acoustical parameters.

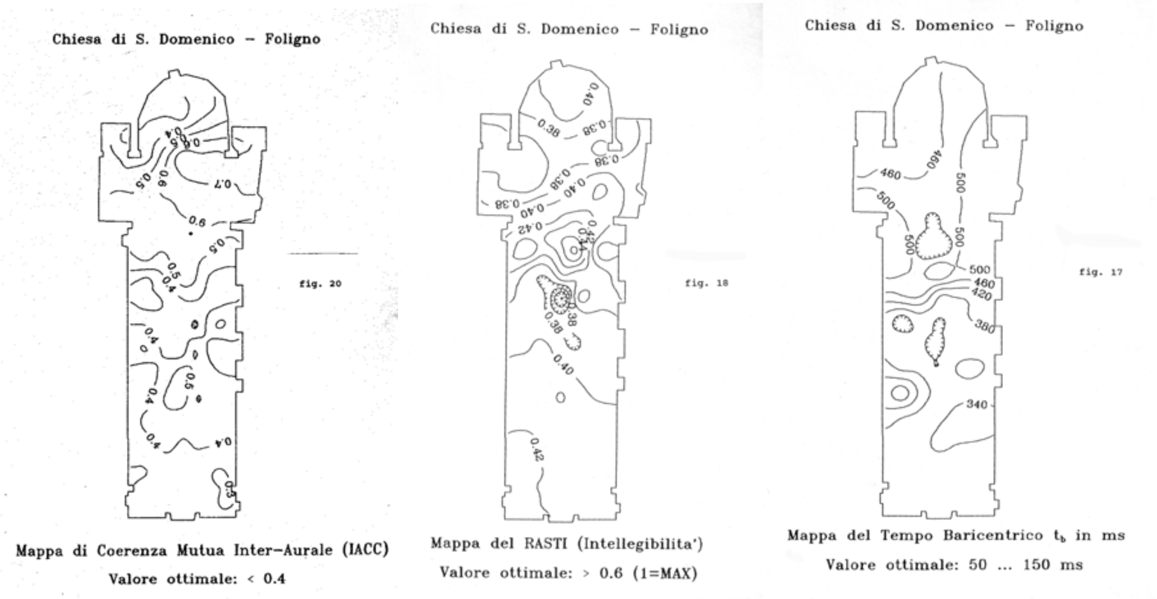


Figure 4 Maps of IACC, RASTI and Centre Time measured in 1994

After the second measuring campaign of 1994, it appeared quite impossible to perform music in that hall, therefore a set of acoustical panels was proposed to the architect for the conservation of monument and cultural heritage. Moreover, a mechanical apparatus was requested in order to eventually remove the panels from the apse. The panels were designed to send the reflected sound energy towards the rear part of the main nave, where the direct waves arrived attenuated by the grazing incidence over the long seating area. Finally, some sound absorbing plaster on the walls was added.

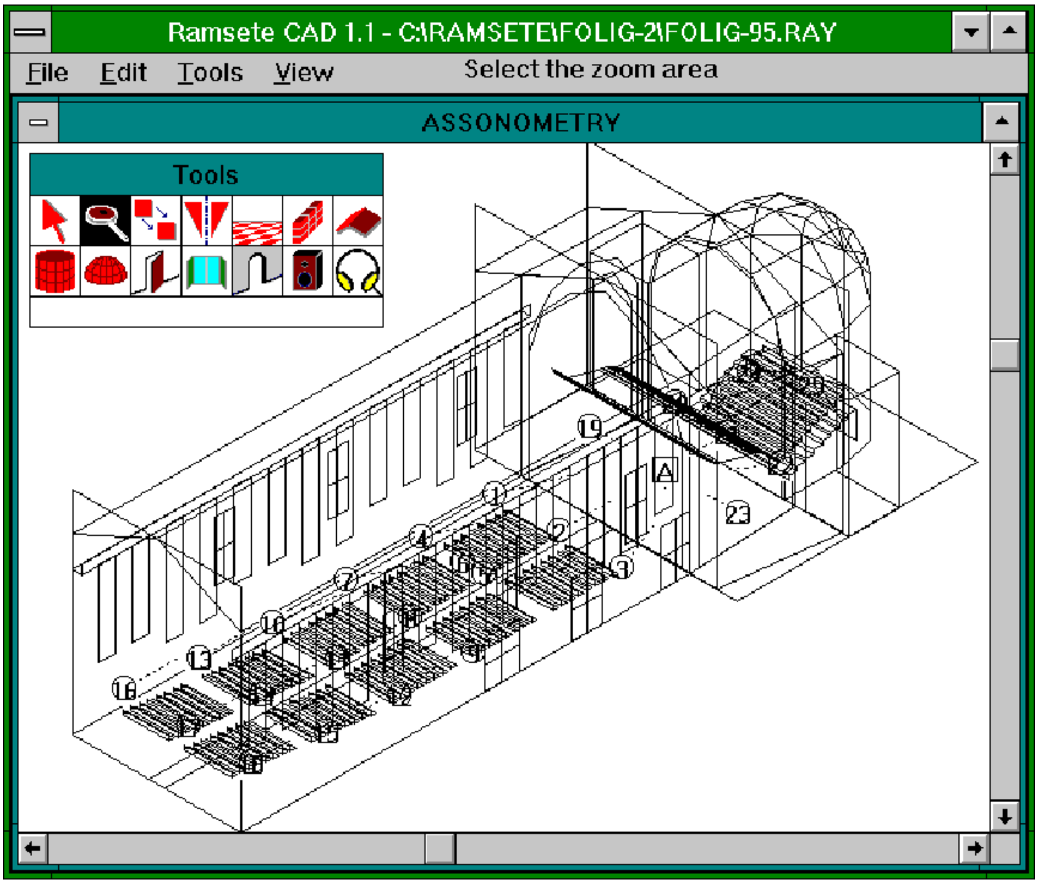


Figure 5 numerical model utilised in 1995

To check the acoustical results achievable with different orientations, acoustical simulations were carried out by means of a pyramidal tracing code (Ramsete). It must be noted that the effective solutions proposed (installation of sound absorbing plaster on the walls of the apse and transepts, large velvet panels suspended from the top of the laterals walls and realisation of an acoustic reflector over the orchestra area) seemed to be effective only at medium and high frequency, whilst in order to reduce reverberation time at low frequencies it would probably be necessary to add some vibrating panels on the back wall, to control the low end of the spectrum.

7 THE THIRD ACOUSTICAL MEASUREMENTS, 2001

The third technique is based on an exponentially-sweeping sine wave test signal used for the determination of the impulse response. The technique was recently developed by one of the authors [5]. Although this technique is apparently similar to the previously-employed linear-sweeping sine wave methods, such as TDS and Stretched Pulse, the exponential-sweeping technique is quite new.

Using a multi-channel wave editor program, the test signal is emitted. In the meantime, the proper shaped inverse filter (simply the time reversal of the excitation signal) was generated.
Thanks to the synchronous Rec/Play capabilities of the sound board, the response of the system can be sampled simultaneously with the emission of the test signals: some repetitions are made, in order to ensure that the system has reached the steady state, and usually the response to the second or third repetition is analysed.

To recover the system's impulse response, the inverse filter is simply convolved with the recorded system's response. This method proved to be substantially superior to the Maximum Length Sequence (MLS) method previously employed: the S/N ratio is better, particularly at low frequencies, thanks to the "pink" shape of the excitation spectrum, and the measurement is almost free from non-linearity and time variance. Close matching between the clocks of the signal generation and sampling is no more an issue (two different machines can be used without any problem). Furthermore, by properly setting the frequency limits for the sine sweep, it is possible to avoid damaging the transducers by applying too much signal outside their rated frequency response limits.

These last measurements were performed only in few positions in the nave, since B-format recordings were added to the measures. Furthermore, the IRs were utilised in the new listening room, called *Arlecchino,* at the laboratory of University of Bologna, in order to virtually reproduce sound quality of the Auditorium, for psycho-acoustical evaluating tests.

Figure 6 measurements performed in 2001

8 DISCUSSION

The comparison between the three different acoustical measurements campaigns is not easy, as the techniques utilised have changed, even if the measurements have allowed the calculation of the same acoustical parameters. Furthermore, in the 1986/1990 the church was almost completely empty, without any furniture and seats. The side walls were not treated, and the proscenium completely empty. The acoustical quality was poor, strong reflections came from the ceiling and the walls.

8.1 Comparison between the three different measurement techniques

During the second measurement campaign, some acoustical treatments were completed. The acoustic plaster in the rear wall, and some tissues were inserted. The analysis of IRs revealed an improvement in sound quality, even if not yet fully satisfactory.

Parameter		First	Second	Third	Goal
Early Decay Time	EDT	5.5 s	3.6 s	2.6 s	1.5 to 2.0 s
Reverberation Time	RT	5.8 s	3.9 s	2.7 s	1.8 s
Clarity	C80	-4.2 dB	-2.2 dB	-1.9 dB	-2 to +3 dB
Clarity	C50	-5.5 dB	-2.7 dB	-2.1 dB	-2 to +3 dB
Definition	D50	0.40	0.51	0.51	0.34 to 0.60
Central Time	Ts	570 ms	310 ms	220 ms	< 140 ms
Strength	G	- 1 to + 4 dB	- 2 to + 4 dB	- 2 to - 3 dB	- 2 to + 4 dB
Inter-Aural Cross-Correlation	IACC	0.39 to 0.71	0.33 to 0.59	0.25 to 0.50	0.12 to 0.70
Initial Time Delay Gap	ITDG	40 ms	38 ms	36 ms	30 ms

The third acoustical campaign was especially directed to measure B-format IRs. However, the measurements pointed out ad additional improvement of spatialisation and a reduction of reverberation time, thanks to the realisation of the reflectors above the orchestra stage.

Figure 7 live-recordings performed in 2001

9 CONCLUSIONS AND REMARKS

Nowadays the restoration of ancient musical environments is strictly accomplished with the aid of an acoustical design. The restoration of the church of S. Domenico, Foligno has been carried out paying attention to improve the acoustical quality in the audience that resulted not fully satisfying. Preliminary acoustical measurements were done since 1986, and repeated in 1990. A set of wood-panels was planned in the apse to redirect early reflections to the rear seats. Furthermore, acoustic plaster, combined with tissues, were applied in the side and rear walls. The analysis of acoustical measurements, both in 1994 and especially in 2001, highlighted an improvement especially in spatialisation and a reduction of reverberant field. Even if the comparison between the acoustical data is hardly feasible, as methodologies changed during last two decades, it seems interesting to point out that the analysis of IRs has allowed to calculate monoaural and binaural and 3D acoustical parameters that are still essential in the characterisation of sound quality in concert halls and opera houses.

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11 INTERNET REFERENCES

Many pictures of last measurements, accomplished with 3D recordings with Soundfield probe in the Auditorium, could be found at: http://www.ciarm.ing.unibo.it/ambisonics