Study of Acoustical Properties in Santa Cecilia Concert Hall in Rome

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A detailed acoustical study of the 2,800-seat Santa Cecilia Concert Hall in the recently-built Auditorium "Parco della Musica" in Rome has been made. The study consists of a series of spatially resolved measurements of the basic objective acoustical parameters of a theater designed for large orchestra musical performance. From impulse responses measured by deconvolving frequency-swept test signals, emitted from an omnidirectional source located on the stage, it has been possible to determine octave-band values of reverberation time, early decay time, clarity, center time, strength, and parameters related to spaciousness and envelopment, such as IACC and LF. The experimental findings suggest that, considered the remarkably large volume of the hall, its general characteristics can be considered satisfactory, with possibilities of further improvement in future times.

I. INTRODUCTION

Purpose of this work is a detailed technical investigation of the Santa Cecilia Hall, the largest of the three concert halls in the recently built Auditorium "Parco della Musica" in Rome, designed by architect Renzo Piano with the assistance of the acoustic engineering firm Müller BBM of Munich. Spatially resolved basic qualification parameters, as internationally defined, have been measured by means of electro-acoustic instrumentation. The paper is divided into three parts. In the first part, we recall the fundamental parameters of architectural acoustics specified in the ISO standard 3382 (1997), namely, those relating to reverberation phenomena (short- and long-term reverberation times, T20 and EDT), those defining clarity and intelligibility of the signals at the listener site (Clarity Index C_{80} and Center Time t_s), those concerning envelopment and spaciousness (LF, IACC, etc.), and the one providing a quantitative estimate of the sound pressure level relative to the sound power emitted from the source (Strength G).[1] In the second part, we discuss the techniques, the procedures and the equipment employed in experimental acoustical characterization of music halls. The third part illustrates and discusses the main experimental results of our work. A number of color-coded maps are shown to permit a rather immediate judgment of the various sites and compartments in the hall. Finally, some conclusions are drawn about the general merits and possible minor flaws of the Santa Cecilia Hall and some suggestions are given about possible future improvements.

Before we proceed further, it is important to give some figures about the shape and the size of the Santa Cecilia Hall. A picture is given in Fig. 1. The hall boasts 2800 seats, distributed over an area of 3,400 square meters, for a volume of about 33,000 cubic meters. This makes it one of the biggest concert halls in the world. As opposed to the other two halls in the "Parco della Musica", i.e., Sinopoli Hall (1,200 seats) and Petrassi Hall (700 seats, variable acoustics), which have rectangular shape – *shoe box* – Santa Cecilia Hall is shaped like a "vineyard" (i.e., shorter on the stage side, far more extended on the audience side, which surrounds completely the stage) with slightly curved lateral walls. About 1000 seats occupy the parterre; the rest is distributed among a number of terraced galleries. Most of the internal coating material – walls, floor, 26 sound-diffusing coffers forming the ceiling, movable reflector panels above the orchestra – is polished American cherry wood. The remaining surface is constituted of sound absorbing upholstered seats, so that the difference in measured parameters with or without audience is not too large. Excellent acoustic

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[1] An excellent treatise giving full account of all the major parameters characterizing a concert hall is: S. Cingolani and R. Spagnolo, *Acustica musicale e architettonica*, UTET, 2005.

insulation from the outside is insured by the structure of the coverage, which is made of wood, steel and concrete, and is enclosed in a lead envelope. Internally generated noise – such as the one from air conditioning equipment - is below 25 dB(A), thanks to acoustic filters at the doors and in the corridors and along the air ducts. Our measurements have all been performed at night time, in order to minimize all kind of disturbances, the hall being virtually empty.

Fig. 1. The Santa Cecilia Hall as seen from the front rows of the main rear gallery (courtesy Photo Maggi). Note coffered ceiling designed to reflect the sound diffusively, with no privileged direction; the curved reflector panels above the orchestra that can be oriented in different ways; lateral cavities created by the presence of the side galleries; curvature of the upper parts of the walls and tilted panels coating the lower parts: all these elements contribute to minimizing specular reflections, and to create a diffuse sound field.

Old-school orchestra conductors would bemoan the fact that the Santa Cecilia Hall is exaggeratedly large, so large in fact that the performers might almost have the feeling of playing out in the open, where the sound gets lost. But, as we shall demonstrate, this objection does not hold on a technical level, and it is at odds with the circumstance, as composer Ennio Morricone has observed, that even the softest sounds are heard very well in all parts of the room, even the most remote ones from the stage. If anything, it is the violin sections that might lament the fact that they are overwhelmed by the sound of the brass and percussion sections. Among the various conductors who have taken the podium up to now, there have been some who have used the variable elements of the hall in ways that are diametrically opposed (for example, the reflecting panels that are above the orchestra have been at times raised near the ceiling, at other times lowered closer to the instrumentalists). Some well-known soloists have said they were dissatisfied, in spite of the addition of extra reflecting movable walls placed right behind them, intended to reinforce the sound at its source. But this is inevitable for a hall designed for a large orchestra and, as such, characterized by long reverberations times (and therefore little suited to small ensembles or single instruments). Our data will show that, in most parts of the hall, these complaints do not find adequate justification. The performance of the Santa Cecilia Hall is probably as good as it can be obtained for an enclosure of so large a size.

II. FUNDAMENTAL PARAMETERS

In free space, the intensity of the sound emitted from a source is attenuated by the square of the distance from the source (6 dB for doubling the distance). The source-receiver distance in the Santa Cecilia Hall ranges between 5 and 50 m: the corresponding attenuation would be about 100 times, equivalent to 20 dB. This means that the fortissimo *ff* produced on the first row should be reduced to a pianissimo *pp* at the back row. This is the problem with open-air performances. In concert halls, however, reverberated sound adds to direct sound. This clearly appears in a recording of the response to an impulsive sound: one sees the direct wave, followed by some individually separate early reflections, and later the subsequent reverberation forming a continuum. Such reflected waves are absolutely essential for keeping the sound level almost uniform throughout the whole audience area. They critically depend, of course, on the dimensions of the hall, its shape, the inclination of its walls, whether reflective elements are present, the materials used in the construction, and many other factors, not the least of which is the presence of an audience.

Conventionally, 80 ms is the delay time that permits a reflection to be received as a distinct sound. Early reflections, arriving with a delay lower than 80 ms after the direct sound, have the effect of perceptually reinforcing the direct sound, in particular by increasing *clarity* (or intelligibility). Early reverberations that come from the sides have the effect of enlarging the source, giving the sound a great *spaciousness*. Late reflections, arriving later than 80 ms, provide a follow-up that guarantees *liveliness* and *fullness* to the sound. If these come from the sides, they give the spectators the impression of *envelopment*, that is, of finding themselves enveloped by sound. To this end, the shape of the hall, the structure and the inclination of the walls, and whether or not proper reflective elements are present, are of great importance.

II.1 Reverberation time
A measure of the duration of the long-term reverberation is given by the *reverberation time T_r*, defined as the time needed for the sound intensity to decay to a millionth of its value at emission (that is, 60 dB). The reverberation time should be rather different depending on the use for which the hall is intended. A long T_r guarantees *liveliness* and *fullness* of sound; in contrast, a short T_r is required for *clarity*. Current recommendation is that reverberation time should not exceed 1 second for drama; it should be around 1.5 s for opera, while it should be of the order of 2 seconds for a symphony orchestra, these being the values that characterize the best opera houses and concert halls in the world.[2] A high value of the reverberation time in the low-frequency range is recommended for giving *warmth* to the hall, even at some expense of sound brilliance. Oppositely, if the reverberation time is maximum at medium frequencies, and falls down at low frequencies, the sound becomes dull and cold.

The measurement of the reverberation time is never made in the interval between 0 and -60 dB, as per definition. This is in order to prevent local effects of the spatially-variable direct sound and strong early reflections from affecting the measurements, and considered that some background noise level is inevitably present. According to ISO-3382, the measurements are made between -5

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[2] Some satisfactory concert halls well suited for symphony orchestra performance are:

Concert hall	Year of fabrication	Volume	Long-term reverberation time
Musikvereinsaal, Vienna	1870	14,600	2.1
Concertgebouw, Amsterdam	1887	18,700	2.0
Carnegie Hall, New York	1891	24,250	1.8
Symphony Hall, Boston	1900	18,740	1.8
Teatro Colon, Buenos Aires	1906	20,000	1.8
Neue Philarmonie, Berlin	1963	26,000	2.0
Kennedy Center, Washington	1971	19,800	2.2

and -35 dB or between -5 e -25 dB,: the reverberation time T_r is then obtained by mathematical extrapolation, having assumed a purely linear decay. T_r is respectively called T_{30} and T_{20}, if deduced from either the first or the second approach.

According to private communication from Müller BBM expert Jürgen Reinhold, the Santa Cecilia Hall was designed on the computer and optimized thanks to a scale model. Tests with a range of sounds whose frequencies were proportionally scaled-up were performed on the model. The use of the model proved to be more valuable than the use of the computer. The average reverberation time in the central frequency range 500-1000 Hz, measured by the firm in the finished hall with no audience turned out to be around 2.4 s, i.e., very close to the *a priori* predicted value. A reduction by 10%, due to increased absorption of reverberated sound waves can be expected in presence of audience, which leads to a reverberation time only slightly larger than what would be considered ideal.

Early reflections, as explained above, are received superposed to the direct sound and have the effect of energizing and enlivening it. It has been proposed[3] to characterize their strength by referring to an early decay time (*EDT*), obtained by extrapolation of the data recorded in the time interval corresponding the first 10 dB decay of sound (0 to -10 dB). However, we could not retrieve any reliable information about the optimal value of this parameter for symphonic concert halls.

II.2 Other basic parameters
We illustrate in detail only those parameters that will be presented and discussed in this paper. Internationally accepted parameters for quantitative definitions of the sonic quality of a concert hall are Clarity Index C_{80}, Strength G, and Inter-Aural Cross-Correlation *IACC* (a measure of the spaciousness of sound). They are defined as follows:

(a) *Clarity Index C_{80}*, initially proposed by the Dresden school[4], is defined at each point of the hall on the basis of the ratio between the acoustic energy received in the first 80 ms and that which follows (p = sound pressure measured with a pulsive sound source, energy is supposed to be proportional to the square of pressure):

$$C_{80} = 10 \log \frac{\int_0^{80} p^2(t) \, dt}{\int_{80}^{\infty} p^2(t) \, dt} \quad \text{(in dB)}$$

The value considered to be optimal for this index, based on experience with the best concert halls, is 0 dB, but it can be considered satisfactory if it falls between -4 dB and +2 dB in the entire room, at medium frequencies (500-1000 Hz). The average value reported by Müller BBM in the same frequency range was -1 dB, i.e., right at the center of the "optimal" interval. An alternative definition of the clarity index is often encountered, namely, C_{50}, where reference is made to 50 ms *in lieu* of 80. However, C_{50} is more significant for speech intelligibility, and C_{80} is usually preferred for assessing music perception.

b) *Strength G*: this parameter gives a measure of the effect of reinforcement of sound produced by the hall enclosure with respect to free space. There are different ways to define this parameter: according to ISO 3382 standard, the sound level in the hall is compared with the sound level in open space at a conventional distance of 10 m from an omnidirectional point source:

[3] V.L.Jordan, "Einige Bemerkungen uber Anhall und Anfangsnachhall in Musikraumen", *Applied Acoustics*, 1:29-36, 1968.

[4] W.Reichardt, O.Abdelalim, and W.Schmidt. "Definition und meßgrundlage eines objiectiven maßes zur ermittlung der grenze zwischen brauchbarer und unbrauchbarer urchsichtigkeit bei musik-darbietung". *Acustica*, 3:291-302, 1975.

$$G = 10 \log \frac{\int_0^\infty p^2(t)\,dt}{\int_0^{\Delta t} p_{10}^2(t)\,dt} \quad \text{(in dB)}$$

where Δt is the duration of the emission, usually very short for a pulsive sound source. Wherever in the hall is $G>0$, the sound is enhanced with respect to the hypothetical level at 10 m from the source in open space. The G parameter is considered satisfactory if it is close to zero and uniform throughout the whole room. The average value measured by Müller BBM in the usual 500-1000 Hz frequency range was -1 dB. No information about spatial uniformity or frequency dependence was made available to us.

c) *Inter-Aural Cross Correlation* (*IACC*), which provides an index for the spaciousness of sound. The sensation of spaciousness depends on various factors,[5] though it has been demonstrated that the two major ones are the *apparent source width* (*ASW*),[6] larger than the real one but still with appreciable directionality, and the *listener envelopment* (*LEV*),[7] i.e., the sensation by the listener of being "immersed" in the sound field.[8] For a marked sensation of spaciousness one requires strong lateral reflections and a relatively low correlation between the sounds reaching the left and right ears of the listener.[9] The normalized cross-correlation function gives a measure of the similarity between two signals when shifted each other by a time interval τ:

$$\kappa(\tau) = \frac{\int_0^t p_l(t) \cdot p_r(t+\tau)\,dt}{\sqrt{\int_0^t p_l^2(t)\,dt \cdot \int_0^t p_r^2(t)\,dt}}$$

where p_l and p_r are the sound pressures at microphones placed respectively at the left and right ear. The integration time t is usually set to 80 ms (early IACC, or $IACC_E$), but it is also possible to measure with t tending to infinite (processing the whole impulse response); in some cases, a "late" IACC is measured, having the integral ranging between 80ms and the end of the impulse response. The largest value attained by κ when the delay τ is made to vary between -1 and +1 ms is the *IACC*.[10] This is considered to be very good if its value is comprised between 0.4 and 0.6 throughout the entire hall. Values larger than 0.6 would correspond to poor spaciousness of sound, values less than 0.4 would be indicative of an exceedingly large "expansion" of the source or even no localizability of the source.

As to the average values measured by Müller BBM which were made available to us, they can only be taken as indicative, providing no information about uniformity of the hall, sound levels at great distance from stage, and possible spurious effects such as dominant echoes or focusing of sound waves at particular points of the room. This is why a spatially resolved experimental analysis of all major characterizing parameters was needed.

[5] A. H. Marshall and M. Barron, "Spatial responsiveness in concert halls and the origins of spatial impression", *Applied Acoustics*, 62:213-219, 2001.

[6] T. Okano, L. L. Beranek, and T. Hidaka, "Relations among interaural cross-correlation coefficient (*IACC*), lateral fraction (*LF*) and apparent source width (*ASW*) in concert halls", *J. Acoust. Soc. Am.*, 104, 1998.

[7] J. S. Bradley and G. A. Soulodre, "Objective measures of listener envelopment", *J. Acoust. Soc. Am.*, 98, 1995.

[8] M. Morimoto and Z. Maekawa, "Auditory spaciousness and envelopment", *Proc. 13th ICA (Belgrade)*, 1989.

[9] C. Ianniello, in S. Cingolani and R. Spagnolo, *op. cit.*, p. 674.

[10] Y. Ando, *Concert Hall Acoustics*. Springer series in Electrophysics, 1985.

III. EXPERIMENTAL APPARATUS

III.1. Sound sources

We have used two types of sound generators. First, a system combining a dodecahedral speaker system with a subwoofer; second, a directional acoustic box. The first item (by Omnisonic) was meant to obtain an emission as uniform as possible over the entire solid angle: each individual speaker was placed in a shallow cavity so as to minimize mutual interference (see Fig. 2). The bass range, which can be considered omnidirectional, was reinforced by coupling the dodecahedral emitter to a subwoofer SIPE AB 300. The system includes a digital processor for crossover and equalization, resulting in an output signal which was essentially flat in the investigated frequency range, with a moderate attenuation at frequencies of little musical significance (31.5 Hz and 16 kHz). The second sound source was used to simulate voice directionality. It was a low-noise Genelec S30D acoustic box, with a frequency response that was flat within 3 dB from 35 Hz to 50 kHz. For this reason, equalization was not needed.

Figura 2: Dodecahedral source by Omnisonic.

III.2. Sound detectors

The following sound detectors have been used:

(1) Microphone type Soundfield ST-250, consisting of four tetrahedral-mounted sub-cardioid capsules. Through sum and subtraction of signals and proper equalization, this yields a signal W corresponding to acoustic pressure (i.e., like an omnidirectional microphone) and three signals X, Y, Z representing particle-velocity components along the three Cartesian axes, with figure-of-8 directional patterns. The ensemble of these 4 signal represents the so-called B-format signal. By knowing the signals along the three axes it is possible to deduce the responses in all directions through vectorial operations, thus realizing a virtual microphone with any desired directionality and aiming.

(2) A pair of cardioid microphones Neumann KM-140, placed at a distance of 170 mm and forming an angle of 110° (ORTF configuration).

(3) An artificial binaural head Neumann KU-100, equipped with ear ducts containing two high-quality, medium-diaphragm pressure microphones: built with material that has the same acoustic impedance as a real head, its purpose is to simulate the transfer function of the head. The artificial head, surmounted by the two ORTF microphones and rigidly connected by a 1 m long arm to the Soundfield microphone, was put on a rotating platform. The latter, placed at chosen locations in the hall, was made to take a full 360° turn in steps of 15°. Measurements combined with computer

simulation lead to a description of the spatial characteristics of the hall.[11]

The equipment described above is not very transportable and consequently it was possible to employ it just in a little number of locations in the hall.
For quick measurement of a large number of positions, a readily transportable, battery-operated system was employed. It consists of a Sony TCD-D100 DAT recorder, equipped with Sony DRW70C mini-microphones placed in the ear ducts of the experimenter (this method, of course, does not allow spatial the detailed spatial description of the sound field made available by the Soundfield microphone). The experimenter, wearing the microphones as an headset, did move throughout the audience area, collecting the recording of one test signal at every seat.

III.3. Other details
The large number of channels to be contemporarily handled by the main microphone array requires the usage of a multichannel sound carde of an audio card: we used an Aadvark Pro Q10. The software adopted for the measurements was Adobe Audition, capable of handling a number of tracks limited only by the computer hardware, sampling at 96 kHz, and working at 32 bit. The program has been enriched by a packet of plug-ins, called *Aurora*, especially developed by one of the authors for architectural acoustic purposes.[12] This has allowed also to perform "auralization" of the sound in the different seats of the hall, i.e., to recreate through headsets or speakers the sound sensation that one would have at each point in the hall during a real performance. This is achieved by convolving a piece of music recorded in an anechoic room with the impulse responses measured during our experimental analysis of the Santa Cecilia Hall.

III.5. Measured parameters
The experimental apparatus described above enabled us to measure a large variety of basic parameters, among which some appear redundant, and will not be presented here:
1. Reverberation time, in particular long-term T_{20}, T_{30}, and short-term EDT;
2. Center Time t_s;
3. Definition Index D_{50} and Clarity Indexes C_{50} e C_{80};
4. Strenght G;
5. Signal to noise ratio;
6. Speech Transmission Index STI[13] and Rapid Speech Transmission Index $RASTI$[14];
7. Spatial parameters such as LE, LF, LFC, $IACC$.[15]
All parameters have been determined in 10 octave frequency bands from 31.5 to 16000 Hz, and also through wide-band filters of type A and Lin (unfiltered).

IV. MEASUREMENTS, RESULTS AND DISCUSSION

Measurements were made feeding the directional Genelec box and the dodecahedral/subwoofer sound generators with an exponential sine sweep signal varying between 22 Hz e 22 kHz, generated at a sampling frequency of 96 kHz, with an amplitude resolution of 32 bits (but the effective resolution of the AD and DA converters was 24 bits). Fig. 3 shows the positions of the emitters on the stage (full circles): all positions were used for the Genelec acoustic box, just position C for the

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[11] A. Farina and A. Avanzino, "Registrazione della risposta acustica delle sale da concerto per i posteri", *Seminario AES-Italia, Workshop sulle tecniche di ripresa stereofoniche multicanale per le orchestre sinfoniche*, 2003.
[12] A. Farina, http://www.aurora-plugins.com.
[13] T. Houtgast and H. J. M. Steeneken, "A physical method for measuring speech-transmission quality, *J. Acoust. Soc. Am.*, 61:318-326, 1980; T. Houtgast, H. J. M. Steeneken, and R. Plomp, "Predicting speech intelligibility in rooms from the modulation transfer function", *Acoustica*, 16:60-72, 1980.
[14] M. Schroeder, "Modulation transfer function: definition and measurement", *Acoustica*, 49:179-182, 1981.
[15] A. Farina and L. Tronchin, in S. Cingolani and R. Spagnolo, *op. cit.*, p. 818.

other system. Recordings have been divided into two sessions: in the first session we have used the rotating microphone system constituted – as earlier described - by two ORTF microphones, the head with binaural microphones and the Soundfield microphone. This system allows a very accurate analysis of the spatial parameters at the points explored, but because of its high time-consuming operation it was placed at only three locations in the hall, as shown by full squares in Fig. 3.

In the second session we have measured the response in 28 strategic points along the central line of the hall and in its left side (as seen from the stage) by means of the binaural microphones and the Sony DAT. In all cases measurements were more precise in the central frequency range, i.e., between 125 Hz and 4 kHz. The amount of data is so large, that we shall present only the most significant ones. More extended information can be found in the thesis dissertation of one of the authors.[16]
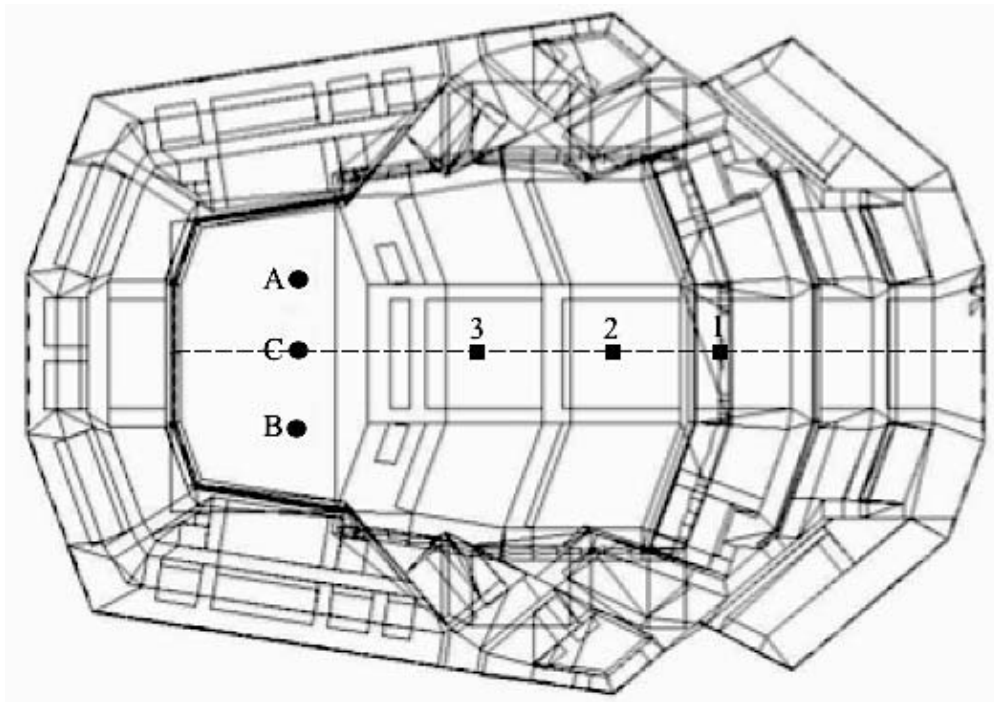
Fig. 3. A, B, C are the three positions for the sound emitters on the stage. 1, 2, 3 are the positions for the head and sensors on the rotating platform.

IV.1. Reverberation time

Fig. 4 reports reverberation time T_{30} in the W channel of the Soundfield microphone, at points 1, 2 and 3 in the hall. The source was the dodecahedral speaker system in central position C on stage (the results of T_{20} are nearly identical). Fig. 5 shows early decay time EDT in the same measurement conditions. Fig. 6 gives again T_{30} in points 1, 2, 3, using the Genelec box: in this case the data come from an averaging over the three speaker location A, B, C on stage. Fig. 7 gives EDT in the same conditions. In all figures, the shaded areas correspond to the region where the accuracy of the measurement system is appreciably lower than in the central frequency range.

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[16] G. Araneo, "Caratterizzazione acustica in risoluzione spaziale della sala Santa Cecilia dell'Auditorium Parco della Musica in Roma" (Physics Department, Università di Roma "La Sapienza", 2005).
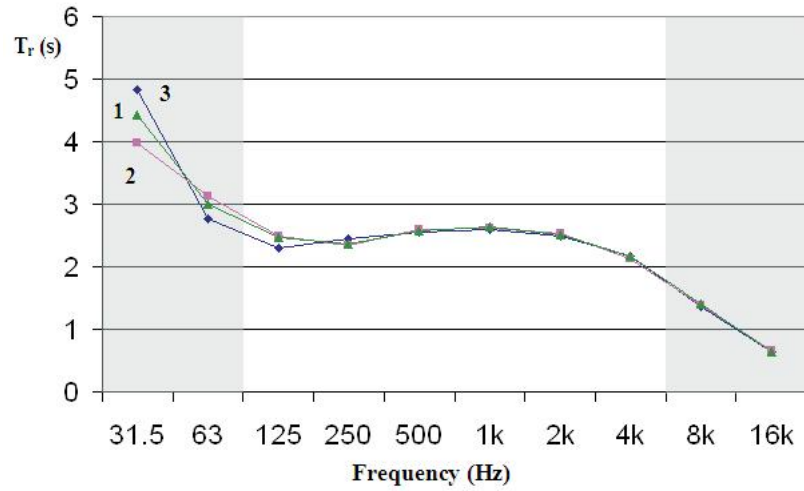
Fig. 4. T_{30} reverberation time as a function of frequency using the dodecahedral source in position C on stage (data taken at points 1, 2, 3 in the hall).
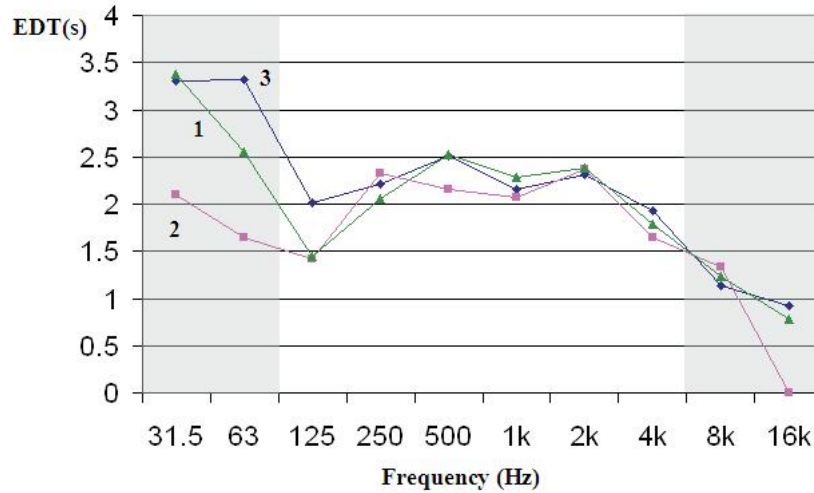

Fig. 5. *EDT* as a function of frequency using the dodecahedral source in position C on stage (data taken at points 1, 2, 3 in the hall).
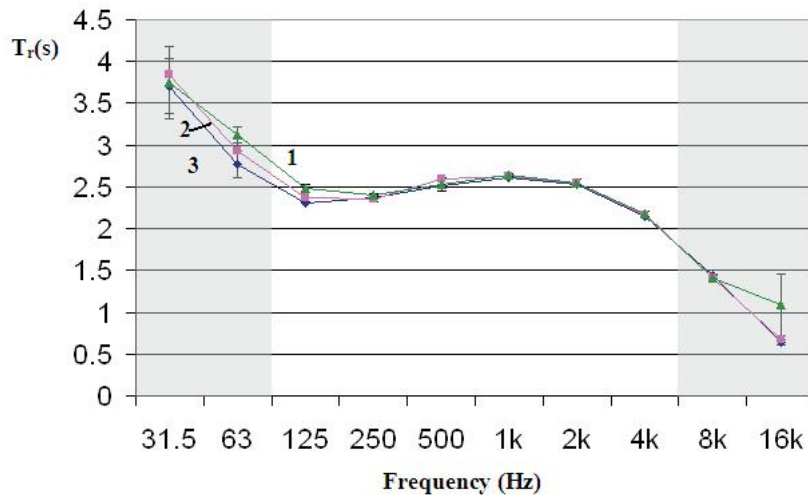

Fig. 6. T_{30} reverberation time as a function of frequency using the Genelec source, average data of positions A, B, C on stage (data taken at points 1, 2, 3 in the hall).
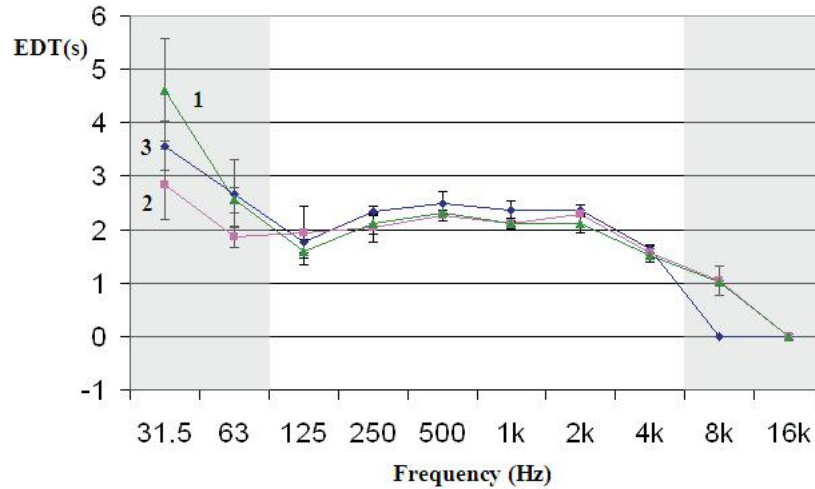
Fig. 7. *EDT* as a function of frequency using the Genelec source, average data of positions
A, B, C on stage (data taken at points 1, 2, 3 in the hall).

Fig. 4 indicates a remarkable uniformity over the three points of measurement in the hall, with values for the reverberation time ranging between 2.2 and 2.6 s, slightly larger than the average figure reported by the project maker Müller BBM.

T_r in the bass region is not high enough compared to the value at medium frequencies (the values at 125 Hz are systematically lower than at 1000 Hz, whilst it is recommended that they should be at least equal, or even greater by some 10%). Of consequence, the hall cannot be said to be warm, but this occurrence plays in favor of limpidity and brilliancy.

The reverberation time extrapolated from the early decay (*EDT*) in Fig. 5 shows values slightly lower than T_{30} in the central frequency zone and rather non-uniform values in the low range. One merit of a lower reverberation at the beginning of emission, when the sound is stronger, is that one gains in clarity. The difference, however, is small enough that the decay can be regarded as virtually linear. The data in Figs. 6 and 7, taken with the Genelec box, lead essentially to the same conclusions. This substantial "invariance" of the results is typical of rooms where the reverberant field is well diffuse, and there are no single echoes or focalizations causing variations.

IV.2. Clarity parameters
Among the many parameters measured, we choose to present here only C_{50} and C_{80}, measured with the omnidirectional dodecahedral source, because the definition coefficient D_{50} and the Center Time T_s (see for instance Ianniello[17]) are strongly correlated and bring to similar conclusions. Also data taken using the Genelec source are not dissimilar. The data shown in Fig. 8 are suggestive of a good distribution of the sound tail in time, as the two curves behave very similarly as a function of frequency. The values move from slightly below 0 in the bass range to slightly above 0 in the treble range, which have therefore higher clarity. In any case, they keep rather close to the optimal value of zero, with position 3 appearing a little better than the other two.

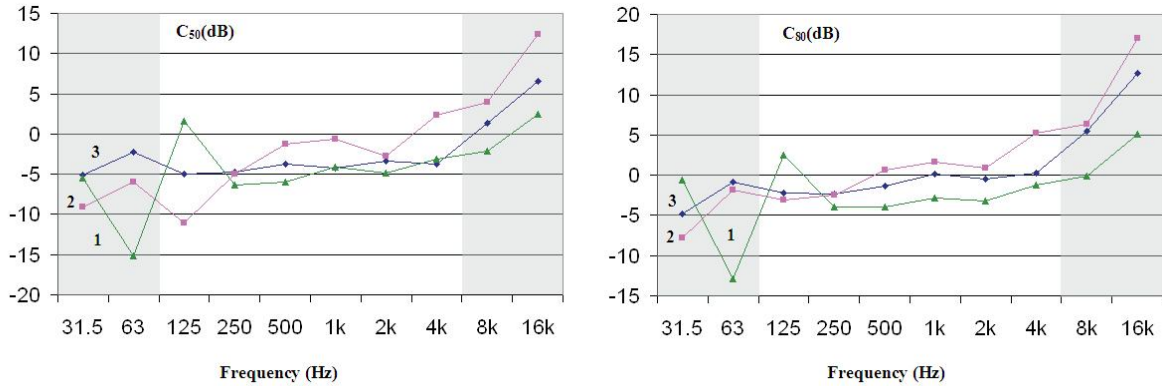[17] C. Ianniello, in S. Cingolani and R. Spagnolo, *op. cit.*, p. 670.

Fig. 8. Clarity coefficients C_{50} and C_{80} as measured with the dodecahedral microphone source in position C on stage.

IV.3. Strenght G

In Fig. 9 we show the values of strength G in the usual three positions in the hall, as determined for both the Genelec loudspeaker and the dodecahedral lodspeaker on stage. It should be mentioned that no true calibration of the direct sound in free space was made: these G values should therefore be used only to draw comparative conclusions as to frequency and position dependance. It appears very clearly that the hall has the effect of boosting the medium-high range – 1 to 8 kHz, in particular bands at 2 and 4 kHz - more efficiently than the bass, in particular for the omnidirectional emitter. For this source, moreover, there is an appreciable non-uniformity, G in positions 1 (front rows of main gallery) and 3 (fore parterre) being no less than 5 dB lower than the more central position 2.
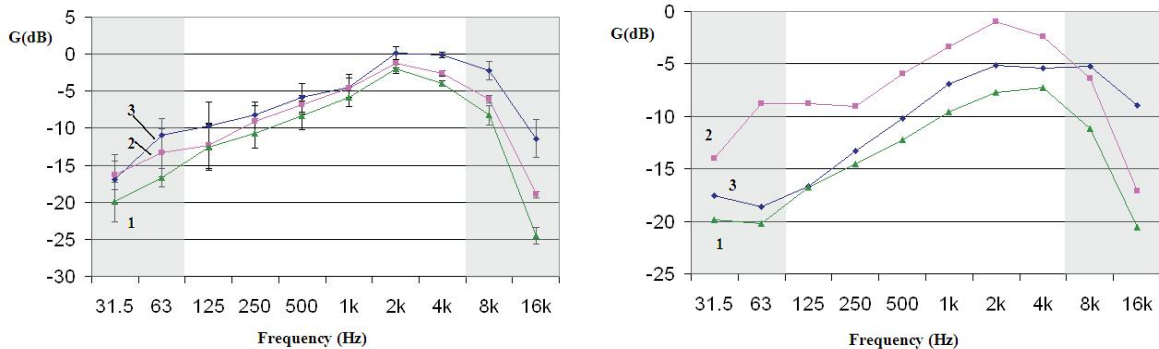

Fig. 9. Left, Strength G as determined by the Genelec box (average of three positions on stage) and, right, same by the dodecahedral omnidirectional emitter in C position.

IV.4. Inter-Aural Cross Correlation (IACC)

In Fig. 10 we report the *IACC* parameter as measured in points 1, 2, 3 in the hall by using the Genelec source in central position. Data refer to three fixed frequencies, 500 (blue curve), 1000 (green curve) and 2000 Hz (red curve). The data show rather curious behaviors: at 500 Hz the *IACC* parameter is rather uniform and close to the good value 0.5 in position 3, but shows pronounced lateral lobes in positions 1 and 2. At 1 kHz, and even more at 2 kHz, the curves present a number of peaks and valleys, which are indicative of a polarized sound field. The *IACC* values are often remote from the ideally expected value, being in general smaller. A reasonable interpretation of these figures is not easy to advance at the present moment.
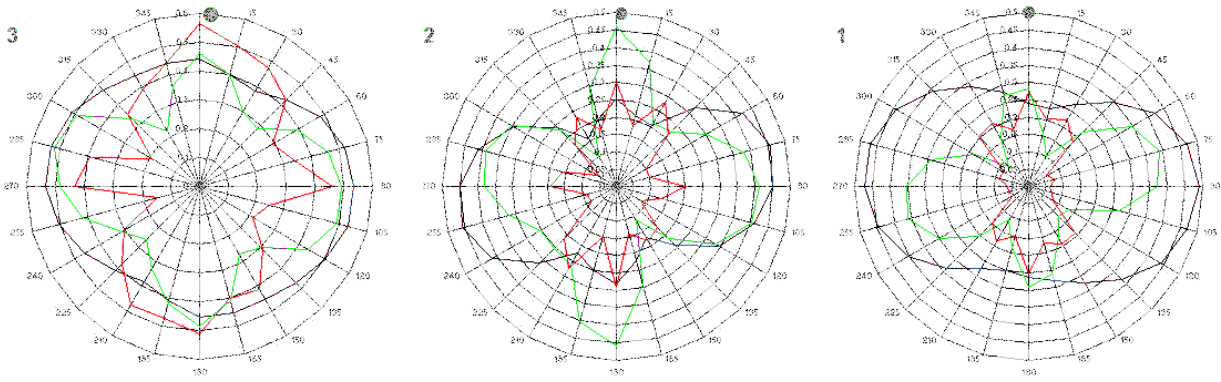
Fig. 10. Left to right: polar diagrams of *IACC* as determined with the Genelec source in central position C on stage respectively at the points 3, 2, 1 in the hall. The black dot shows the angular position of the source.

IV.5. DAT recorder measurements

We should first of all underline the important fact that the measurements of T_{20} and T_{30} done with the rapidly transportable DAT Sony TCD-D100 recorder, as taken in the positions 1, 2, 3 where the rotating platform had been placed, were quite consistent with the values obtained with that equipment. The same cannot be said of *EDT*, which shows a somewhat more pronounced variation with frequency. The most significant spatially resolved results of the DAT experiment are shown in Figs. 11 through 14 as color-coded maps of the hall. The maps have been dobtained using the
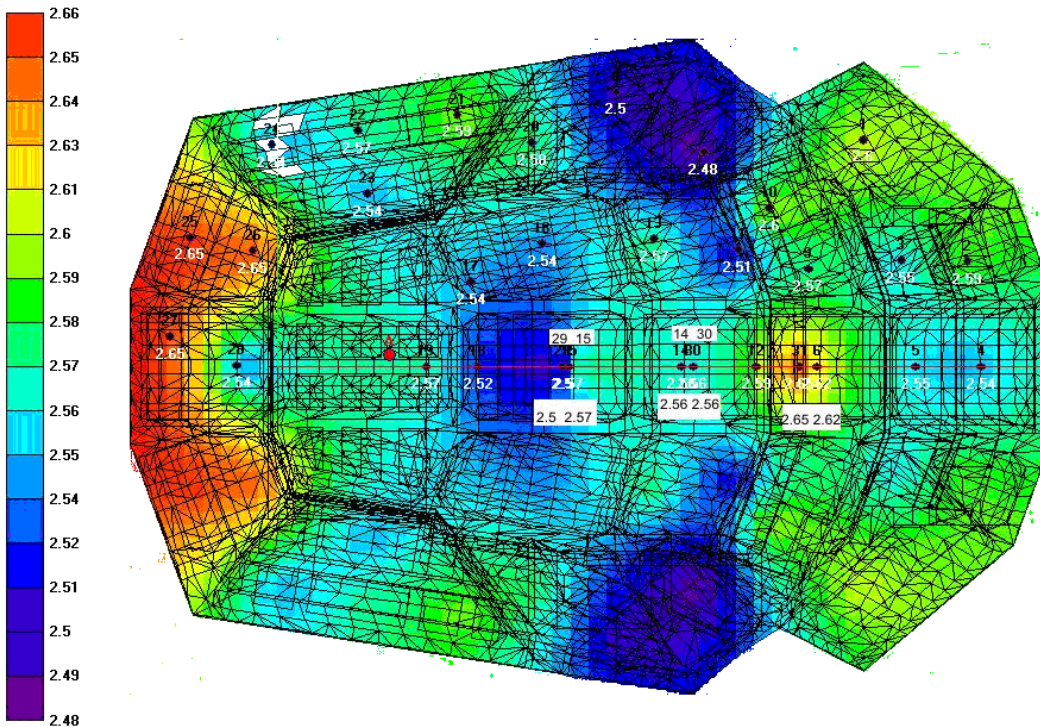

Fig.11. Map of reverberation time T_{30} at 500 Hz. The time ranges from 2.48 (purple) to 2.66 (red).

Fig. 12. Early decay time *EDT* at 500 Hz. The time ranges from 1.80 (purple) to 3.20 (red).

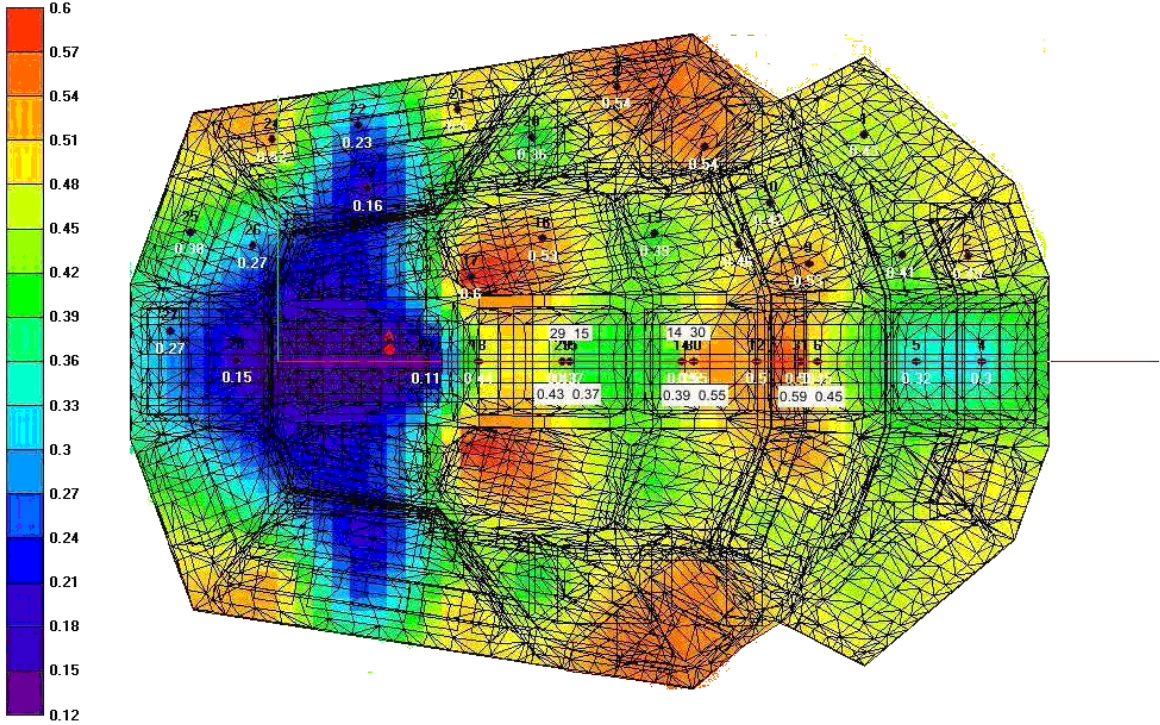Fig.13. Map of clarity index C_{80} at 500 Hz. Values range from -5.0 (purple) to 3.0 (red).

Fig. 14. Map of interaural intercorrelation coefficient 1-*IACC*_{E3}. Values range from 0.12 (purple) to 0.60 (red).

program *Surfer*, and have been obtained by the least-curvature interpolation algorithm. Due to the remarkable spatial variability of some parameters, to facilitate the discussion it seems appropriate to divide the hall in a number of sectors, as illustrated in Fig. 15 (sectors 1 and 2 constitute the parterre; 3 an 4 are, respectively, the galleries behind the stage and at its sides; 5 are the galleries siding the parterre; 6 and 7 represent the main galleries behind the parterre).

Fig. 15. Major sector identification.

The reverberation time map in Fig. 11, as deduced from T_{30} measurements, does not present important differences from the T_{20} map (not shown). Note that colors have been chosen to give maximum evidence even to small differences in reverberation time. The whole range actually spans from a minimum of 2.48 s in the back of sector 5 to a maximum of 2.66 s in sector 3. Though the values are somewhat high, one can definitely talk about an excellent uniformity, which implies an equal sense of fullness and liveliness of sound throughout the hall. If a slight preference should be given to certain sectors, it seems as sector 1 of the parterre and galleries 5 offer the shortest long-

term reverberation. On the contrary, the central part of the main gallery 6 boasts a reverberation a little in excess of average.

A different story applies to the early decay time *EDT* in Fig. 12. We should consider as bad parts of galleries 3 and 4, which are affected by a large value of *EDT*, and also the stage, which of course goes to the other extreme (EDT too short, indicating a direct sound too loud for proper music listening – but, of course, this is good for musicians while playing…). *EDT* spans over a relatively wide interval, having its minimum of 2.2 s in gallery sector 6 and its maximum of 2.8 s in gallery sector 5. This behavior appears to be quite complementary to the one we have seen for T_r. It is not a tremendous difference, but it is one that can be perceived by many listeners, and in fact the reported user's preference is not the same for all the areas where the audience seats.

We come now to clarity, Fig. 13. The behavior is rather satisfactory for most of the hall, if we exclude the stage and its surroundings. Most of the parterre and galleries have a C_{80} index falling in the interval from -4 to 0 dB, namely, well within the one held as fully adequate. The sound is clearest in the farthest gallery (sector 7) and in sector 1 of the parterre, while turning out to be close to the lowest level for good clarity in sector 2 of the parterre and in galleries 5. Such low values are probably attributable to strong reflections occurring just after 80 ms. For instance, as we show in Fig. 16, the data taken with the artificial head in position 2 (see Fig. 3) present a sharp echo about 120 ms after receiving the direct sound. Center Time t_s – which we do not report for the sake of brevity - gives similar general indications. Of course one would expect some correlation between high clarity and low reverberation, but this does not seem to be brought out by our data in a plain way.
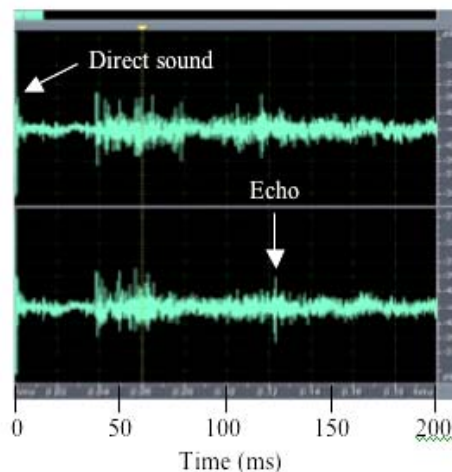

Fig. 16. Response to binaural impulse in a particolar position of the parterre showing a distinct echo 120 ms after the direct sound.

Finally, in Fig. 14 we show 1-$IACC_{E3}$ results (this is actually an average of measurements at 500, 1000, 2000 Hz).[18] If we ignore, as usual, the critical spots - stage and surrounding space - the index ranges from 0.4 to 0.6. This is the interval considered to be best for adequate sound spaciousness; however, the spatial distribution of *IACC* appears definitely curious, looking like a patchwork where numerous zones in the parterre and in galleries 5 come very close to the upper boundary value 0.6 (where spaciousness begins to be insufficient), being separated by others where the *IACC* drops to the lower boundary, where localizability of the sound source tends to be lost. This behavior is probably consistent with the bizarre observations made with the rotating platform and discussed in relation with Fig. 10. We do not have an explanation for this occurrence, but the

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[18] See for instance L. L. Beranek. *Concert Hall and Opera Houses*. Springer, 2004.

effect might be related to the very rich and complex morphology of the enclosure, compared to a shoe-box shaped hall.

V. SUMMARY AND CONCLUSIONS

To summarize, the results obtained with our two methods of measurement are quite consistent with each other. On their basis, we feel that, in consideration of the fact that the Santa Cecilia Hall has dimensions that go well above the usual size of concert halls, its long-term reverberation time - equal to 2.4±0.2 s (which we tentatively extrapolate to 2.15±0.2 in presence of audience), as deduced from T_{20} and T_{30} measurements with an empty hall - inevitably exceeds the value of about 1.8-2 s, which is considered to be optimal for large-orchestra performances. One important merit is that the reverberation time is quite uniform over most of the hall and relatively constant in the whole range of frequencies of musical interest, with just a slight reduction at 125 Hz, which makes the hall somewhat "cold"; however, this partly compensates for the exceedingly long reverberation.

As a matter of fact, in spite of the long reverberation time, Clarity Indexes C_{50} and C_{80} and Center Time t_s appear to behave very satisfactorily, if the galleries surrounding the stage are ignored (C_{80} ranges between 0 and -4 dB, rather ideal behavior). To this result concurs also the fact that, at least for the best areas in the hall, the early decay time EDT is somewhat lower than the long-term reverberation time T_{30}. It should be mentioned that *EDT* appears to be rather less uniform that the long-term reverberation time, which is a rather normal occurrence. A strong reflection, echoing the direct sound after 120 ms, has been detected in the rear part of the parterre: this may be responsible for the lower clarity in this area. The Strength *G,* albeit measured in lack of a true free-field calibration of the sound sources, and hence potentially affected by some systematic error, appears to be too low in the medium-to-bass range, compared to the 1 to 8 kHz interval. This may explain the reported brilliance of sound and lack of warmth, providing some compensation for the long reverberation time. This behavior is typical of rooms largely covered by wood panels, which are good reflectors at medium-high frequencies, but tend to dissipate some energy at low frequencies.

The Inter-Aural Cross Correlation *IACC* takes good values between 0.4 to 0.6, but its behavior is surprising: according to the detailed spatial analysis made with the DAT recorder, *IACC* does not exhibit a gradual variation, showing rather inexplicable jumps between maxima and minima in adjacent zones, a feature that is accompanied by angular disuniformity of the sound field observed by the rotating head.

All in all, in its present condition the Santa Cecilia Hall boasts, no doubt, a number of merits, but it is also affected by some flaws which would call for some modifications and improvements.

The authors would suggest some reduction of the reverberation time at medium frequencies, bringing it down to less than 2.2 s with the empty room, so that the spectrum of the reverberation time stays flat between 125 Hz and 2 kHz, and a detailed investigation of the surfaces causing the annoying echo which can be perceived in the rear part of the parterre. A localized treatment of such a surface, employing scattering or absorbing panels, would easily fix this small defect.

The medium-frequency reverberation time can be easily controlled installing panels of porous material covered with a thin plastic film (for avoiding absorption at high frequencies), which can be placed behind the bended reflectors hanging over the stage, staying out-of-sight. The wooden surface causing the undesired echo can be covered with a further wooden structure, featuring small slots or holes, so that the sound impinging over it can be absorbed by porous material hidden behind the perforated wood panel.

Similar slight corrections to the acoustics of the hall have been successfully installed in the Auditorium of Parma "Niccolò Paganini", another recent concert hall designed by the same team (Renzo Piano Building Workshop and Muller BBM).