Acoustics in Practice

International e-Journal of the European Acoustics Association (EAA)

Vol. 1 • No. 1 • July 2013

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SUMMARY

editor in chief
Colin English

editorial assistant
Monika Rychtarikova

editing coordinator
Miguel Ausejo

edited by
European Acoustics Association (EAA)
secretary@european-acoustics.net • office@european-acoustics.net
www.euracoustics.org
c/o. Sociedad Española de Acústica (SEA)
Serrano, 144, ES-28006 Madrid, Spain
Legal Deposit: M-21922-2013 • ISSN: 2226-5147
Printing by DiScript Preimpresión, S. L.

www.euracoustics.org

Editorial letter

Acoustics in Practice (AiP) is the new journal of the European Acoustic Association (EAA). It is a great pleasure for us to present the first issue.

The journal will be published in English and cover the practical aspects of all areas of acoustics. It is intended that the journal will provide a Europe-wide platform for authors to disseminate their work. The wide access (based upon free open access) should make it a journal of first choice for many authors.

The primary journal audience is those practising in the fields of acoustics, noise and vibration. Contributors are likely to be practitioners: these include consultants, manufacturers, policy makers and regulators. The papers will not be peer reviewed, but will be reviewed by an editor to ensure a consistent quality and appropriate content. Practitioners will be the main target readership, although it is also intended that academics should read and contribute to the journal: it will provide a forum for academics to present the results of their work to practitioners in an easily accessible form. It will also give academics a window on topics of current interest to practitioners. Therefore Acoustics in Practice will be a way of information dissemination which is complementary to other ways of the EAA, such as Acta Acustica united with Acustica or the Nuntius newsletter.

The editorial board can be found in this issue on page 53. Many thanks to all members for their acceptance.

For the present issue, we warmly thank all contributors, as well as Miguel Ausejo, Antonio Pérez-López and Monika Rychtarikova for their valuable help.

Any comments and suggestions are welcome and can be sent to the EAA website https://www.euracoustics.org/

Colin English
(Editor-in-Chief AiP)

Jean Kergomard
(EAA President)

Evaluation and measuring procedure for strength in sport halls

Maarten P.M. Luykx, Martijn L.S. Vercammen
Peutz bv., Mook, Netherlands
Corresponding author: m.luykx@mook.peutz.nl

PACS: 43.55.Fw, 43.55.Hy

ABSTRACT

Although in the Netherlands there is a recent guideline for maximum allowable reverberation times in sport halls, there remain a lot of complaints about their acoustics. Because these complaints are mainly caused by noise due to activities, the reverberation time alone is not a fully valid parameter to judge also because it is influenced by flutter echoes that can be disturbing as well. Preferably the measured strenght (G) of the hall should be validated, that is determined by the effective amount of sound absorption present in the hall. This parameter determines in reality how much level (gain) at a normalized distance the sport hall will add to the sound power level of a (omnidirectional) source, and can therefore indicate whether there is an increased risk of too high noise levels due to activities and therewith a reduced speech intelligibility. Effort has been put into the development of a valid and efficient standard measuring procedure to determine the average strength of a sport hall at a standardized circle with a radius equal to the mean free path around a point source in the middle of the hall. This gives a possibility to assess the strength values and to compare these between different halls, irrespective of their volume or reverberation time. Practical experience with this method incorporating the effect of flutter echoes and relation with the amount of absorption will be treated.

1. INTRODUCTION

Since 2005 there are two guidelines in the Netherlands that set a limit for the reverberation time of sport halls. One guideline for competition use and another for school use [1, 2]. A maximum value for the reverberation time T_{20} averaged over 6 octave bands (125 Hz - 4 kHz) is set depending on the volume of the hall. These values are summarized in table I, together with related volumes.

The values set for T_{20avg} correspond to a minimum average absorption value α_{room} of all room surfaces (S_{tot}) of 0.25 (varying between 0.22 and 0.28), based on Sabine's law for an ideal diffuse (homogeneous and isotropic) sound field:

$$\tilde{\alpha}_{room} = \frac{A}{S_{tot}} = 0.161\frac{V}{T\,S_{tot}} \qquad (1)$$

Table I. *Maximum averaged reverberation time T20 (125 Hz – 4 kHz) for sport halls in the Netherlands [1].*

Category	V_{min}[m³]	V_{max}[m³]	T20avg[s]
A1	–	1,700	£ 1.0
A2	1,701	2,100	£ 1.1
A3	2,101	2,400	£ 1.2
B1	2,401	3,200	£ 1.3
B2	3,201	4,350	£ 1.4
B3	4,351	6,300	£ 1.5
C1	6,301	7,400	£1.7/1.6*
C2	7,401	9,500	£ 1.8/1.7*
C3	9,501	12,400	£ 1.9
D1	12,401	17,250	£ 2.0
D2	17,251	29,000	£ 2.3
E	>29,001		£ 2V/3S

* *values according [2].*

Furthermore it is required that the measured average T_{20} and the maximum reverberation time T_{20max} for each octave band fulfils:

$$\frac{T_{avg}}{T_{max}} < 0.7 \qquad (2)$$

2. NOISE LEVELS IN SPORT HALLS

Goal of the guidelines is not to obtain a certain subjective acoustic impression of the hall (as for concerthalls), but to limit the noise levels due to activities. Despite theses guidelines there remain a lot of complaints about the acoustics of sport halls. Most of these complaints concern noise due to activities. An example of several A-weighted noise spectra of different sport activities in a sport hall is given in figure 1. This figure shows that the A-weighted sound level is usually determined by the higher octave bands (500-2000 Hz).

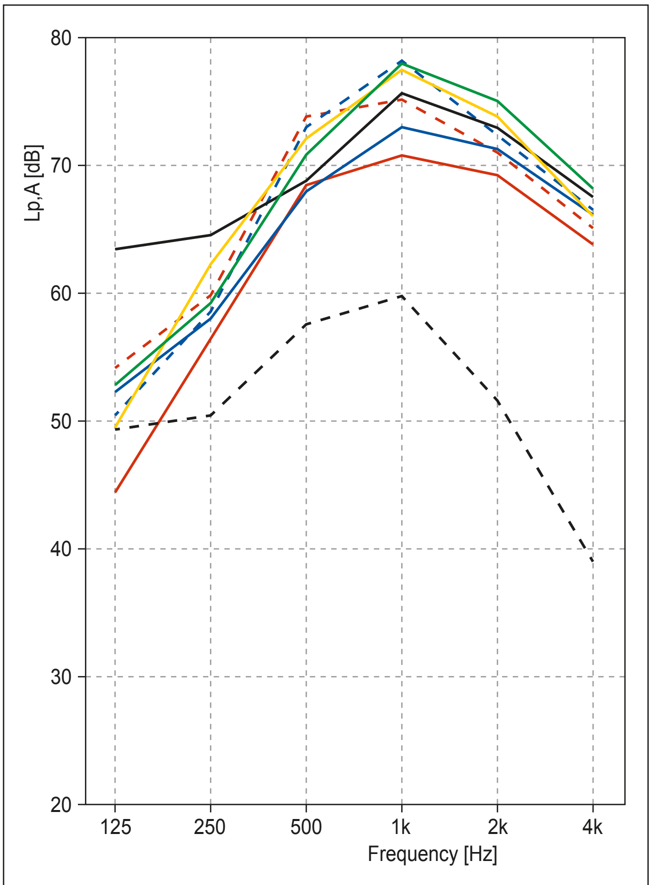

Figure 1. *A-weighted noise spectrum of several sport activities inside a sporthal.*

3. REVERBERATION TIME IN SPORT HALLS

Because most of the complaints concern the noise levels and therefore the loudness of the hall, the reverberation time (T) alone is not a sufficient parameter to judge, as stated earlier by de Ruiter [3]. Thereby, in practice the values of the reverberation time are influenced by non-diffusivity of the sound field that is rarely fully homogeneous and isotropic. Large enclosed spaces like sport halls have a high risk of an inhomogeneous sound field, because of the parallel and vertical walls that are large and distant and are often neither absorbent nor diffuse, whereas the ceiling is absorbent. In that case horizontal flutter echoes will easily be excited between the walls, and nonlinear decay curves will be measured (fig. 2). Both these effects can be disturbing in a sport hall, especially with discontinuous (impulsive) sources. With a double decay the decay curve is not a straight line, but the second part of the decay curve has a smaller slope (and therefore a longer T) than the first part of the decay curve (figure 2). Values for T_{20} and T_{30} will be different, and values T_{30} will easily differ between different measuring positions.

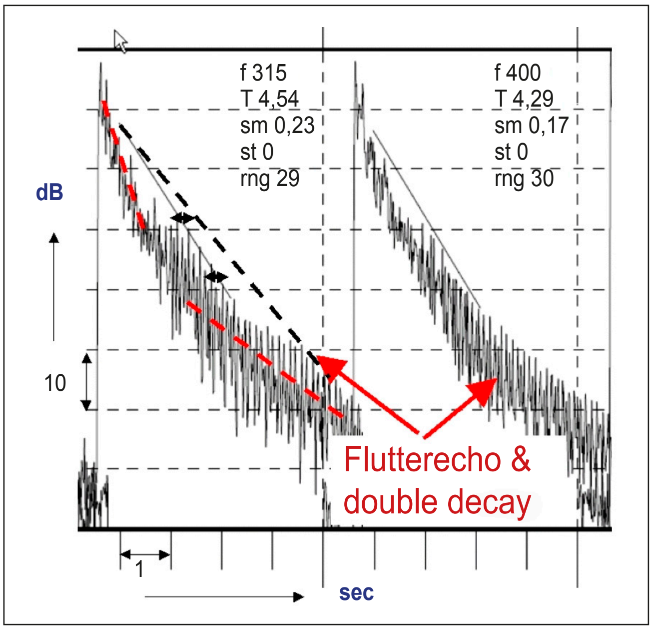

Figure 2. *Decay with flutter echoes and double slope for two 1/3 octave bands.*

In a sport hall where flutter echoes were measured (fig. 2) adding diffusion resulted in a significant reduction of RT (fig. 3, red line). In this case gym mats were used as temporal diffusion against one wall, which increased the diffusivity of the sound field, led to uniform decays and a reduction of T_{avg} to 2.2 s. This value for T_{avg} indicates an effective amount of absorption of ca. 600 m^2 (open window) in this 8,400 m3 hall, whereas design calculations predicted that more than 1,100 m^2 absorption (open window) had been applied inside the hall, consisting of an acoustic ceiling and absorption high against the walls (4-8 m+). This difference shows that Sabine's law is still not valid in this situation, because the sound field is not sufficiently diffuse due to the fully reflective and parallel lower parts (0-4 m+)of the concrete walls.

To meet the guideline ($T_{avg} \leq 1.8$ s.) absorptive panels (220 m^2, 85 mm thick, $\alpha_w = 0.90$) were applied against the low concrete parts of three walls at 0.5-3.5 m height. This resulted in a drastic reduction of the reverberation time to T_{avg} = 1.3 s (fig. 3, black line), even far below the reference curve (fig. 3, yellow line). This shows that the sound field has become more diffusive and that there are valid conditions for Sabine's law. The amount of effective absorption has increased with 500 m^2 to 1,100 m^2. Besides edge effects of the added acoustic paneling, this increase of effective absorption is mainly due to an improved coupling and energy-exchange between the vertical and horizontal sound field, resulting in an increased acoustic effectivity (i.e. absorption) of the materials already present at higher levels in the hall (high wall absorption, acoustic ceiling) and a situation with no more flutter echoes or double decays.

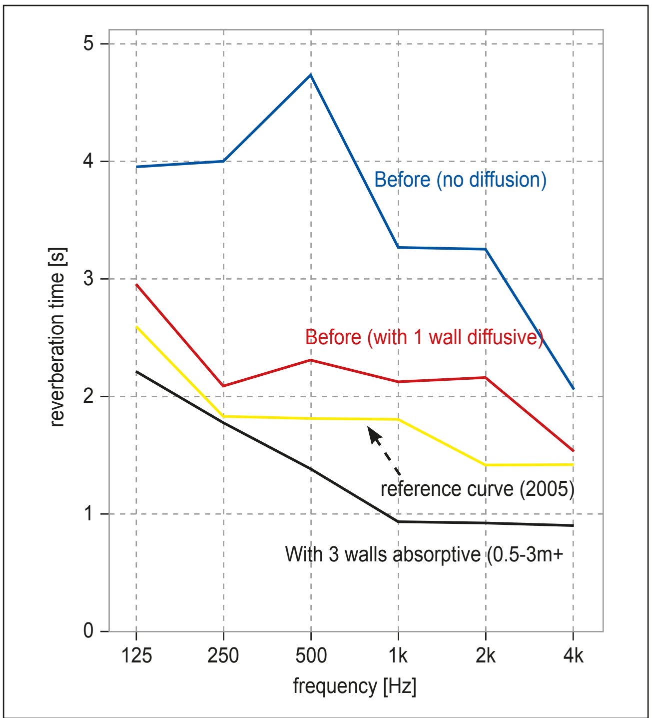

Figure 3. *Required and measured reverberation times (T_{20}) for 6 octave bands in a large sporthal (38 x 22 x 10) before and after measures.*

In the final situation the maximum allowable value of T_{20} for octave bands of T_{max} = 1.9 s (based on equation (2) and T_{avg} = 1.3 s.) is only exceeded at the 125 Hz octave band, due to insufficient low frequency absorption. With respect to noise levels this is not really significant. This maximum value for 125 Hz could have been met if less high frequency absorption would have been applied and T_{avg} would be 1.6 s. The loudness at the relevant octave bands (500-2000 Hz) would have been higher however in that case. This illustrates that by by limiting the allowable differences between octaveband values of T_{20}, the present guideline implicitely punishes low values of T_{20} at high frequencies, at the cost of higher noise levels in dB(A).

This triggers the question whether, instead or additional to reverberation time measurements, which are often disturbed by acoustic defects like flutter echoes, evaluating strength measurements in sport halls could be an interesting alternative for a more valid evaluation of the expected noise levels.

4. STRENGTH G IN SPORT HALLS

4.1. Measuring strength G in sport halls

The following procedure for measuring comparable strength values in sport halls is dealt with:

1. An omnidirectional (Q = 1) cone source is placed in the middle of the hall (1.5 m height) and a pink noise signal is generated;

2. The sound level L_p is measured (1.5 m height) starting at a distance of 10 cm, and for each following –2 dB distance (12.5 cm, 16, 20, 25, 31.5, 40, 50, 63, 80, 100, 125 etc.) across a straight line along the main axis. These measurements can be used in a so called "decrease of relative sound level (L_p-L_w) with distance" graph (fig. 4) to match theoretical decay lines and validate the sound power level and several room parameters [4].

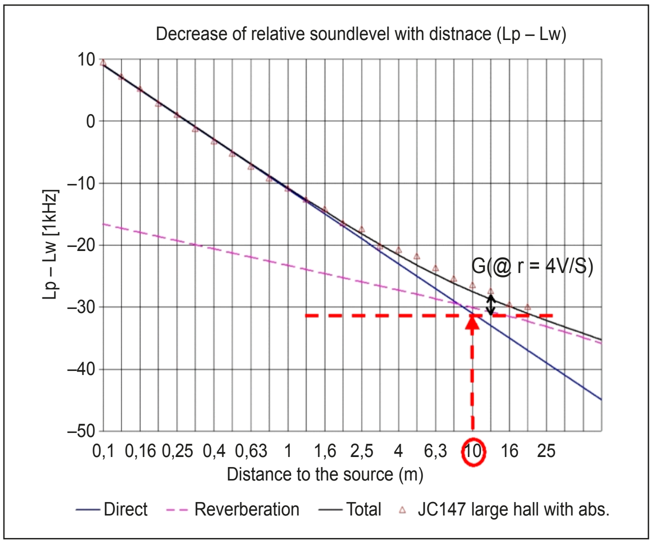

Figure 4. *Graph of measured and theoretical decrease of sound level (Lp – Lw).*

3. At a certain reference distance for which the mean free path (mfp = 4 V/S) is chosen as a consequence of Barron's correction [5], a circular pattern of measuring points around the source is used with a total of at least 6 to 8 points at different angles (0°, ±45°, ±90°, ±135°, 180° or 0°, ±30°, ±210°) from the long axis. Positions and angles are choosen such that the microphone is not closer than 3m to the walls. The levels measured are spectrally compared with each other to check for discrepancies (allowable

variation ±1 dB) and are averaged, resulting in $L_{p,avg}$ (4 V/S).

4. An estimate for the actual sound power level L_w of the source is obtained by averaging the L_p values measured over distances of 10 to 80 cm. This is spectrally compared with another estimated value for L_w from L_p (1m) minus 11 dB. Alternatively, L_w may also be determined from measurements in a free field (anechoic room) or reverberation chamber.

5. The average strength G of the hall at the reference distance (4V/S) is the difference between the average sound level at r = 4V/S and the sound level of the same source at 10 m distance in a free field [6]. It is calculated using equation 2:

$$G_{(@4V/S)} = L_{p\,avg\,(@4V/S)} - L_w + 31\ [dB] \qquad (2)$$

These measured values of G give a direct impression of the acoustic "amplification" of a hall at this reference distance compared with the same source at a distance of 10 m in free field (fig. 4).

4.2. Predicting values for strength G based on decrease with distance

The G values measured can also be compared with allowable values for G, when the acoustic demands set for T_{20} in the guideline are transferred into required values for α (using equation (1) and assuming Sabine's law) and a theoretical model for the expected decrease of sound level with distance is used. Three models can be distinguished:

The "classic" Sabine-Franklin-Jaeger theory assumes a constant level of the reverberant field, and subsequently G(r) follows:

$$G(r) = 31 + 10\log\frac{Q}{4\pi r^2} + 4\frac{(1-\alpha_{source})}{S\,\alpha_{room}} \qquad (3)$$

With:

– α_{source}= average absorption coefficient of room surfaces as "seen" by the source [7]

– α_{room}= average absorption coefficient of the room.

– S = sum of all room surfaces (m^2)

For a point source in the middle of a room the values of α_{source} and α_{room} are the same. Note that when directional sources are used (human voice) or a point source not in the middle, G can be influenced by the location of the absorption or the source [7].

At a distance r = 4V/S for an omnidirectional source (Q = 1) equation (3) becomes:

$$G_{(4V/S)} = 31 + 10\log\frac{S^2}{200V^2} + \frac{4\,(1-\alpha_{source})}{S\,\alpha_{room}} \qquad (4)$$

In reality the reverberant sound level is not constant but decreases with distance caused by a non-diffuse sound distribution. The correction on equation 3 according to Barron [5] is:

$$G(r) = 31 + 10\log\frac{Q}{4\pi r^2} + 4\frac{(1-\alpha_{source})^{\frac{rS}{4V}}}{S\,\alpha_{room}} \qquad (5)$$

This implies that at the mean free path (r=4V/S) the level of the reverberant field of Barron's theory agrees with the classic theory. Therefore this is considered as a suitable reference distance for G measurements in sport halls, which is a compromise between being out of the direct sound field and not being too close to the walls.

Peutz' model for the decrease with distance [4,8], used to match the measurements in figure 4, assumes that at a distance R_c (so called reverberation radius or critical radius):

$$R_c = \sqrt{\frac{QV}{300T(1-\tilde{\alpha}_{source})}} \approx \sqrt{\frac{QS\,\alpha_{room}}{50\,(1-\tilde{\alpha}_{source})}} \qquad (6)$$

the reverberant sound level equals the classic theory and also equals the direct sound level, and that the reverberant level decreases from there on with a factor Δ, that fulfils:

$$\Delta(r) = \frac{k\sqrt{V}}{hT}\ [\text{dB}/_{\text{doubling distance}}], \qquad (7)$$

with:

k = constant or room type indicator (≡0.2 ± 0.1)

h = room height (m)

Because the mean free path distance (4V/S) is usually larger than R_c (fig. 4) the sound levels predicted by Peutz' model at this reference distance (r = 4V/S) will usually be 1 to 1.5 dB lower than the predicted values by the other two models (the classic theory and Barron's prediction).

4.3. Evaluating measured strength G values

For the sport hall previously discussed in chapter 3, measurements of G have been performed in the final situation of the large hall with provisions (T_{avg} = 1.3 s.) according the previous procedure (par. 4.1). The average values measured for G(@4V/S) are summarized spectrally in figure 5. Also figure 5 gives limit values for G (red line), that are is not based on a flat T_{20} curve but on a (alternative) sloped T_{20} curve.

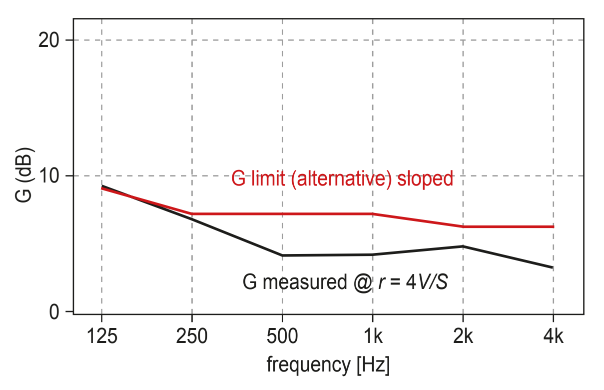

Figure 5. *G values measured (@11.3 m) in final situation of 8,400 m³ sport hall (T_{avg} = 1.3 s) and allowed values (according eq. 1 and eq. 4).*

From figure 5 it can be concluded that in the large hall with provisions (G_{avg} = 5 dB) the measured strength G(@4V/S) values are significantly (2 – 3 dB) below the allowed G-values (red line G_{avg} = 7) for mid- and high frequencies, and coincide with the allowed G-values at the lowest octave bands. The hall with provisions does therefore pass the test on strength G according the procedure.

Using a flexible curtain as a separation wall, the large sport hall under study can be divided into three separate smaller halls. Resulting values of T_{20} measurements in the separate 1/3 parts are spectrally summarized in figure 6. Because the hall volumes are now 1/3 smaller (V = 2,800 m³) the maximum allowed T_{20} values are lower (T_{avg} ≤1.3 s). Due to the reduced volume, the resulting allowed values for G(@4V/S(= 9m)) are 3 dB higher (G = +10 dB).

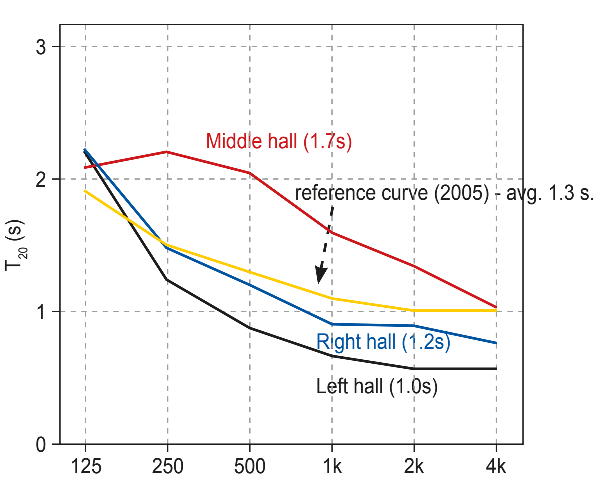

Figure 6. *Required and measured reverberation times (T_{20}) for 6 octave bands in three 1/3 parts of the sport hall.*

From figure 6 it can be concluded that the right and left hall parts fulfill the guideline for T_{20} except at the 125 Hz octave band. The middle hall part does not fulfil the guideline values at all due to an insufficient amount of absorption and flutter echoes between the parallel curtain walls. For middle hall parts this is often the case because there is insufficient fixed wall surface available for absorption and because the movable curtain/walls usually have a very low absorption coefficient.

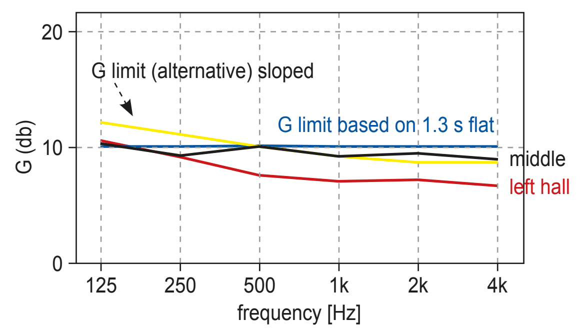

Figure 7. *G values measured (r = 4V/S = 9m) in 1/3 hall parts and allowed values (according eq.4).*

In a similar way as in the large hall, averaged G(@4V/S) values are measured in the left and middle 1/3 hall parts, with an omnidirectional source in the middle of each 1/3 hall. The average values measured for G(@4V/S) are summarized spectrally in figure 7. Also figure 7 gives 2 possible limit values for G, one (blue line) that is based on a flat T_{20} curve and another (yellow) line based on a (alternative) sloped T_{20} curve.

Based on figure 7 it can be concluded that in the left 1/3 hall the measured strength values (G_{avg}(@4V/S) = +8 dB) are significantly (–2 dB) below the allowed (sloped) G-curve (G_{avg} = 10 dB). In the middle 1/3 hall the measured strength values (G_{avg}(@4V/S) = 9.5 dB) are on average 2 dB higher than in the left hall, and the octave band values do not exceed the allowed (flat) G-curve (G_{avg} = 10 dB). Both 1/3 hall parts measured do therefore pass the test on strength G according the procedure, despite the flutter echoes and double decay measured in the middle 1/3 hall part. This is an interesting contrast with the measured T_{20} values in the middle 1/3 hall that exceed the reference curve widely.

Interestingly enough measured G values at the 250 Hz octave band are the same in the left and middle 1/3 hall parts, whereas there is a rather large difference in T_{20} value. This may be explained by the horizontal field and flutter echoes in the middle hall between the flexible walls. These flutter echoes and horizontal field apparently give no significant increase of loudness when measured with a continuous source, but do increase the reverberation time due to a double sloped decay. This can be explained if one realizes that flutter echoes usually only become visible quite late in the impulse response when most of the sound energy (early reflections of the vertical sound field) has died away.

From these measurements it can be concluded that measuring G values at the mean free path with a continuous source is a valuable tool to gain information about the acoustic “amplification” of a sport hall and to be able to compare halls on this aspect. An advantage of this method —unlike reverberation time measurements— is that it is not disturbed by acoustic defects like flutter echoes.

Because acoustic defects like flutter echoes can be possibly disturbing in sport halls, especially with discontinuous sources, it remains also necessary to use an additional method that is sufficiently discriminative to detect such acoustic defects. For that goal measurements of the reverberation time over a sufficiently long interval (>30 dB like T_{30}) are useful, preferably using the decay curves of an impulse source (e.g. gunshot or balloon) because such a source tends to excite the flutter echoes more audible that intermittent pink noise, and is more similar with the actual noise sources in a sport hall.

5. DISCUSSION

Compared with reverberation time measurements, which are quite accurate at least for a linear decay curve, the accuracy of the strength measurements may be a potential weakness, due to the limited accuracy of sound level measurements combined with possible inaccuracies in the calibration procedure of the source. It is therefore recommended to measure not only at the mean free path but also to measure and match a full decrease with distance curve (see fig. 4) in order to increase the accuracy.

Further experience with these aspects will have to be made, also with respect to the actual validation values for G to be used depending on the prediction models used.

6. CONCLUSIONS

Most complaints in sport halls are related to noise levels caused by activities. Measurements of the reverberation time are often influenced by acoustic defects like flutter echoes, and are therefore insufficient for a reliable evaluation of the strength or gain of the hall as well for a reliable prediction of the noise levels.

First experiences with the proposed measuring method to measure the strength G directly at the mean free path distance show that it is a sufficiently valid method to gain information about the strength of a hall and that it is not influenced by acoustic defects, and therefore has sufficient potential to be a reliable method for a valid prediction and judgement of the expected disturbance and noise levels.

To detect possibly disturbing effects like flutter echoes judging and measuring the reverberation time is a useful method, but only if a sufficiently long decay interval (>30 dB) is used with preferably an impulsive noise source.

It is undesirable that, at the cost of higher noise levels in dB(A), the present guidelines on T_{20} in sport halls punish low values of T_{20} at high frequencies by limiting the allowable differences between octave band values.

REFERENCES

[1] “Guideline for reverberation time and background noiselevel in multidisciplinairy sport accommodations”, NOC-NSF, ISA-US1-BF1 may 2005.

[2] “Standard for gymnastic and sporthalls for use by schools”, KVLO, January 2005.

[3] E. de Ruiter, “Time to reconsider reverberation time”. Proc. EAA Congress on Sound and Vibration, Ljubljana 2010.

[4] J.v.d. Werf, “Behaviour of loudspeaker sound in autotunnels , J.A.E.S. 90 1991.

[5] M. Barron, “Auditorium acoustics and architectural design”E&FN Spon, Londen (1993)

[6] L. Beranek, Concert Halls and opera houses, Music, Acoustics and Architecture. 2nd Edition, (Springer-Verlag New York Inc, 2004) pp. 617.

[7] R.A. Metkemeijer, “Speech-intelligibility and room-size”, NAG-journal 81 (1986).

[8] V.M.A. Peutz and W. Klein “Articulation loss of consonants as a criterion for speech transmission in a room”, J.A.E.S. 19, 915 (1971).

[9] L. Beranek, Acoustics (McGraw-Hill, New York, 1954), p.311.

Improving existing façade insulation against railway noise

Juliette A. Paris-Newton, David Chapman, Richard G. Mackenzie
Building Performance Centre, Edinburgh Napier University, UK
Corresponding author: j.paris@napier.ac.uk

PACS: 43.50.Jh, 43.50.Lj, 43.55.Ti

ABSTRACT

The Environment Round Table of the French government ("Grenelle de l'environnement") has focused efforts on the development of alternatives to road transport. A conclusion from these studies has been that railway usage is expected to increase in the future. Departmental noise transport committees were set up in 2001 in order to make an inventory of noise sensitive receivers and to look at technical solutions that could be implemented.

A pilot project is currently being undertaken by Building Performance Centre (BPC) of Edinburgh Napier University which studies the insulation offered by existing dwelling façades on approximately a thousand properties subject to railway noise. In order to quantify the sound insulation performance, measurements of façade insulation have been carried out. The performances have been compared to the day and night-time performance targets detailed by the policy document "Circulaire du 25 Mai 2004". Where necessary, the façade sound insulation and ventilation performances have been improved to meet the requirement of the aforementioned regulations.

This project is co-funded by ADEME (The French Environment and Energy Management Agency) and RFF.

1. INTRODUCTION

The public debate "Rhone Valley and the Environment Round Table" ("Grenelle de l'environnement") has focused on the development of alternatives to French road transport including rail. Throughout France, and in particular in the Rhônes-Alpes Region, the use of freight trains for goods transportation is likely to increase over the next few years. It is almost certain that this will impact the soundscape of areas located in the vicinity of affected railway lines.

In 2001 Departmental monitoring of noise generated by land transport infrastructure began. This work includes the identification of noise sensitive receivers, and deciding upon noise protection measures proposed by infrastructure managers.

A contract signed between Réseau Ferré de France and the French government in November 2008 holds the national commitment to process 2500 Noise Sensitive Receivers (NSRs) over the period 2008-2012. Implementation of the national policy against noise pollution has thus accelerated significantly since 2009. A law passed on 3rd August 2009 implementing suggestions put forward by the Environment Round Table has provided increased resources to mitigate against noise produced by rail infrastructure [2].

The government has made available to the Agency for Environment and Energy (ADEME) a national funding allocation for the treatment of NSRs. "Circulaire du 25 Mai 2004 [1]"addressing the funding of these measures to assess and treat NSRs (railway noise) was supplemented by an agreement signed on the 1st December 2009 between ADEME and Réseau Ferré de France (RFF). This agreement provides funding for insulating the façades of noise-sensitive buildings, supported 80 % by ADEME and 20 % by RFF, for the period 2009-2011 [3].

The project was won by BPC following a European tendering process. This paper presents a case study that highlights the steps carried out in order to provide NSRs located within three towns in the Rhone Valley region with an upgrade to the sound insulation performance of their façades. The main challenge of the project was to effectively mitigate against railway noise for a wide range of NSR types. These included different sizes of buildings, different construction techniques and different building periods, each of which requires catered noise mitigation measures. A particular consideration has been that the work demands direct contact between our consultancy team and the residents involved, as well as with professional building companies, and so care has been required in terms of the level of technical advice provided to residents.

2. APPLICABLE NATIONAL LEGISLATION

The regulations in place in France which define NSRs call for three conditions to be fulfilled. Firstly, the type of receptors must be residential, educational, or institutional. Secondly, the building permits must be dated prior to 6th October 1978. And finally, the noise levels outside of the buildings must be in excess of at least one of the threshold values outlined in Table 1.

Table 1. *Maximum railway noise levels at the building façade, in dB(A).*

Acoustic parameter	Railway noise level
$L_{Aeq(6\,h\text{-}22\,h)}$ (1)	73 (2)
$L_{Aeq(22\,h\text{-}6\,h)}$ (1)	68 (2)
L_{den}	73
L_{night}	65

(1) Parameters defined in article 1 of the guidance document from 5th May 1995; these are considered to be at 2 m from the façade with the windows closed; they can be measured in accordance with French Standard NF S 31-088 (Railway Noise).

(2) The guidance document from 8th November 1999 concerning the limitation of railway traffic noise defined a further criterion: IF = L_{Aeq} – 3 dB(A); with IF(6h-22h) = 70 dB(A) for daytime, and IF(22h-6h) = 65 dB(A) for night-time.

The sound insulation performance targets for the building façades are calculated based on the rules set out in the regulatory document “Circulaire du 12 juin 2001” [2] as follows:

– DnT,A,tr ≥ I(6h-22h) – 40 dB, which corresponds to an internal daytime noise limit of 40 dB(A),

– DnT,A,tr ≥ I(22h-6h) – 35 dB, which corresponds to an internal night-time noise limit of 35 dB(A),

3. INITIAL ASSESSMENT OF RAILWAY NOISE AT ALL NSRS

In 2009 a third party carried out railway noise impact assessments in the cities of Bourg-Saint-Andéol, La Voulte sur Rhône and Serrières in order to produce noise maps of the Givors - Nîmes railway line. This railway line, operational since 1880, is currently used exclusively for freight transport, but in the future is likely to carry some passenger trains. The noise maps thus modeled the predicted noise levels at the façades of all buildings near the railway line in 2030, in order for mitigation measures to protect against potential increased noise levels in the future.

Following these initial noise assessments, databases of NSRs were drawn up and a project was put in place to upgrade the sound insulation of all exposed NSR façades. 300 NSRs were highlighted in Bourg-Saint-Andéol, 323 in La Voulte sur Rhône and 363 in Serrières. The remainder of this paper provides a case study regarding the assessment of exposed NSR façades in the town of Serrières.

4. CASE STUDY: ASSESSMENT AND MITIGATION OF RAILWAY NOISE IN THE TOWN OF SERRIÈRES

4.1. Project outline

The Serrières project began with a public meeting held to outline the technical objectives of the noise impact assessment and mitigation measures to residents located within NSRs. This was of particular importance given the nature of the project and its requirement to deal directly with residents.

It was a key to the success of this project to establish the involvement of the community and landlords that may not be aware of the significance of the railway noise.

For each NSR an initial audit has been undertaken to assess both acoustical sensitivity and thermal performance. The acoustical survey examined sources of acoustic weakness such as windows, doors and trickle vents. It also took into account the type and design of the roof and walls. The acoustic recommendations were formulated based on the findings of the audit and the insulation requirements of the façade.

The assessment of thermal performance carried out as part of this initial audit took into account the overall energy consumption of the NSR, and together with details such as the type of heating system and existing insulation, allowed an additional set of recommendations to be given to NSR residents to improve thermal efficiency. Although no explicit steps were taken to implement these measures, it was within the scope of the project to provide this information in order to help residents reducing their carbon footprint and energy spending. It should further be noted that in many cases the implementation of measures to enhance the acoustical performance of NSRs would likely have a positive impact upon the thermal efficiency (e.g. upgrading of single glazing to double glazing).

These initial audits have shown than 44 % of residential buildings were still fitted with single glazing. Of the remaining double-glazed properties, 11 % had upgraded from single glazing without changing the existing window frames.

So far, in Serrières, 80 % of the NSRs' properties required acoustic façades treatments.

To carry out the audits each NSR property was visited and a report was produced outlining the acoustical improvements required in order to satisfy the relevant legislation [1]. The reports also included suggestions for measures to improve thermal performance. The audit reports were then used by the relevant NSR property owner to obtain quotes from building contractors (e.g. window fitters) and to obtain planning permission from the local authority.

4.2. *Method used for acoustical assessment of each NSR*

The main acoustical assessment tool was the noise map that included a model of the potential railway traffic in 2030. This allowed an estimate to be made of the predicted external noise levels due to likely increased railway traffic in the future. The key objective of this project was to use this data to suggest and implement noise mitigation measures on the NSR façades.

The steps involved in the assessment of NSRs' acoustical performance (before implementation of noise mitigation measures) are outlined in detail in Figure 1.

Afurther summary is presented below.

- All external windows and doors' dimensions are measured.

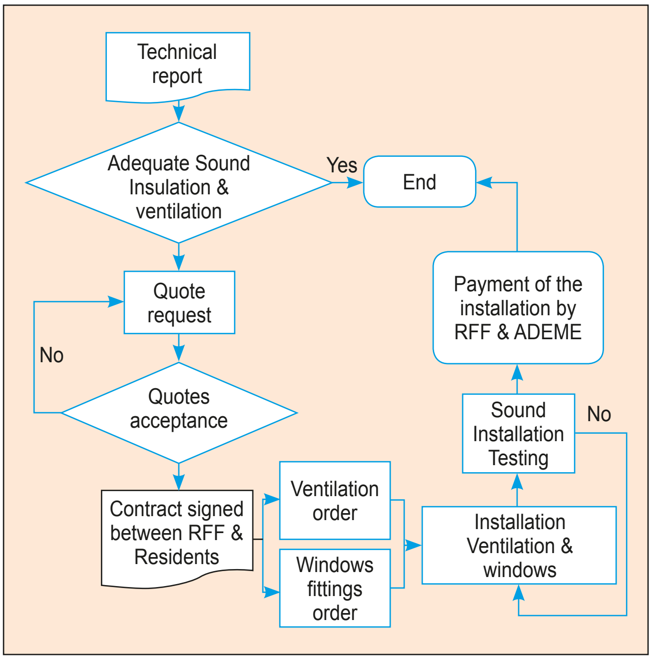

Figure 1. *Flowchart illustrating the steps required to assess noise exposure, propose noise mitigation measures, implement them and verify their performance.*

- All external windows and doors are acoustically assessed.
- If the window is single-glazed the level of insulation is known to be insufficient and the window is replaced without need for an acoustical measurement to be carried out.
- If the window is double-glazed and the frame is in good condition, a measurement of the façade sound insulation level is undertaken and compared with its given performance target.
- The ventilation is assessed for the entire property.
- If the windows are acoustically adequate but the ventilation is not in accordance with the French regulations, a new ventilation system is installed.

If the ventilation system is in accordance with the French regulations and the windows are replaced, care is given to make sure that the works do not degrade the ventilation system.

4.3. *Implementation of noise mitigation measures*

The main noise mitigation measure offered by the project involves the replacement of existing windows within NSR properties with high performance glazing. The design of custom windows is required, as they need to incorporate sufficient sound insulation technology. Some cases required windows with a sound insulation performance greater than 42 dB R_w+C_{tr}.

In French legislation any change to a building façade requires planning permission. As many of the NSR

Figure 2. *Example of mitigation solution, on the left single-glazed window without trickle vent, on the right double-glazed window with an acoustic trickle vent.*

properties in Serrières are located in historical parts of the town, most of the windows are required to be timber frame by the building control officer in charge. Such windows have to be replaced with aesthetically identical products as much as practically possible. Wooden frames are more expensive than PVC frames, but have the added benefit of being environmentally more sustainable when adequately sourced.

Further complications have included the fact that many local window fitters are not used to installing acoustic windows. The recommendation for acoustic through-wall vents in residential properties has also brought up issues with local contractors, most of whom were previously unfamiliar with the technique and the products available on the market.

4.4. Assessment and funding of implemented noise mitigation measures

Pre-completion acoustic testing is undertaken for each NSR property following completion of the building works to verify their conformity to the regulatory targets. A test certificate is then prepared and has to be signed by all the parties involved, namely the contractor (generally a window fitter), the property owner and the consultant undertaking the acoustic test.

Acoustical testing is performed in accordance with building standard NF EN ISO 10052.

Figure 3. *Example of façade sound insulation measurement in accordance with NF EN ISO 10052.*

Testing undertaken on the completed installations; the results were typically within 3 dB of the design predictions.

Providing the funding cap is not exceeded, the contractor is paid directly by RFF after work completion so down payments are not required from property owners. Funding caps are calculated for a given NSR property according to the number of rooms impacted by railway noise above the regulatory threshold.

5. CONCLUSION

The primary outcome of this project has been the design and implementation of façade noise mitigation measures on a large number of noise sensitive receiver (NSR) properties distributed across the towns of Bourg-Saint-Andéol, La Voulte sur Rhône and Serrières. These towns are located in the Rhône Valley region of France, and the NSRs are likely to be exposed to increased levels of noise due to the predicted increase in railway traffic over the coming years.

Noise pollution has been reduced for affected residents, but has also improved the aesthetics to the towns concerned. Improving the sound insulation performance of the façades has further provided increased thermal efficiency for many NSR properties, hence decreasing the carbon footprint of each upgraded building. For most NSR properties the existing ventilation system was inadequate given the improved air tightness gained from the refurbishing works and therefore required the installation of acoustic trickle or through-wall vents despite the associated inherent thermal loss. This suggests that the upgrading procedure is unlikely to have any negative impacts on residents' health or NSRs' building fabrics caused by decreased fresh air renewal, which can occur in renovation project involving increased building air tightness.

A key challenge of the project was that many local window fitters selected to carry out the façade upgrades were inexperienced in the installation of acoustic windows or acoustic ventilators. This was further exacerbated by the fact that many ventilation products are still not efficient enough for residential properties in sunny and warm climates, such as the Rhônes-Alpes Region. In such climates many people prefer to leave windows open during the summer months to ensure adequate ventilation, and find that closing windows due to noise disturbance significantly degrades the efficiency of the ventilation system in the property.

ACKNOWLEDGMENTS

The authors thank ADEME, Réseau Ferré de France, the local authorities, the mayors of Bourg-Saint-Andéol, La Voulte sur Rhône, Serrières and the DDTs.

REFERENCES

[1] Circulaire du 25 Mai 2004 relative au bruit infrastructures transport terrestres, Legifrance (2004).

[2] CERTU "Isolation acoustique des façades - guide technique et administratif pour le traitement des Points Noirs Bruit" (2003).

[3] Circulaire du 12 juin 2001 relative à l'observatoire du bruit des transports terrestres - Résorption des points noirs du bruit des transports terrestres, Legifrance (2001).

[4] Arrêté du 3 mai 2002 pris pour l'application du décret n° 2002-867 du 3 mai 2002 relatif aux subventions accordées par l'Etat concernant les opérations d'isolation acoustique des points noirs du bruit des réseaux routier et ferroviaire nationaux, Legifrance (mai 2002).

[5] NF EN ISO 10052 - Mesurages in situ de l'isolement aux bruits aériens et de la transmission des bruits de choc ainsi que du bruit des équipements, AFNOR (2005).

Quality management within a large strategic noise mapping project

Simon J. Shilton
Acustica Ltd, Manchester, UK
Corresponding author: simon.shilton@acustica.co.uk

PACS: 43.50.Rq, 43.50.Sr

ABSTRACT

EC Directive 2002/49/EC relating to the assessment and management of environmental noise requires the results of strategic noise mapping to be reported by Member States every five years. Lessons learned from the first round of mapping in 2007 indicated that variations in the approach taken both within and between Member States reduced the consistency of strategic noise maps, and therefore reduced the robustness of comparisons between different sets of noise maps. In order to reduce the variation within the Member State, a number of national authorities determined to undertake a single project approach to deliver all the strategic noise maps required within the country. This in turn led to very large projects which needed an extended multi-disciplinary team of experts in order to ensure successful delivery. Implementation of quality assurance and quality control systems are then imperative to maintain consistency between technicians and within multi-disciplinary teams. It is also essential to ensure the control of processes and the ability to review inputs, intermediaries and deliverables. This paper presents experience of the implementation of quality assurance procedures used in several EU countries during the successful completion of projects within the first and second round of strategic noise mapping during 2007 and 2012.

1. INTRODUCTION

Following the adoption of Directive 2002/49/EC (END) [1], the process of strategic noise mapping and action planning across the EC Member States (MS) and the Candidate States has now entered the second round (R2). Summaries of the results from the first round of strategic noise mapping in 2007, published by the European Environment Agency (EEA) on the Noise Observation and Information Service for Europe (NOISE) [2], indicate that for the first round of the Directive assessments were undertaken for over 82,000 km of major roads, 12,000 km of major railway, 76 major airports and over 160 agglomerations containing some 120 million inhabitants. The challenge associated with R2 was even more extensive, as the thresholds for inclusion of agglomerations, major roads and major railways within the scope of the strategic noise mapping all reduced significantly, so the extent of the mapped area increased. For example, the extent of major roads in Ireland increased fivefold from approximately 700 km to over 3,500 km, whilst the number of agglomerations in England increased from 23 to 65.

Lessons learned from the first round in 2007 [3], and the on-going work in the development of the proposed common method of assessment, CNOSSOS-EU [4], have influenced the approach to R2 mapping, there being more of a focus on consistency to aid comparison of results between and within Member States. Within most MS the Directive was transposed to national Regulations which designated the organisations and authorities responsible for strategic noise mapping. The most common approach was to designated City authorities as responsible for agglomeration mapping, airport operators as responsible for airport mapping, and national road and rail authorities as responsible for major roads and railways. This has tended to produce a fractured landscape of responsibilities, with many different organisations involved, and the very real potential for duplication in efforts or gaps in coverage. Within the United Kingdom and Malta a different approach was taken, where the national authority responsible for environmental noise was designated as the body responsible for strategic noise mapping. The potential benefits of this approach included a greater degree of consistency within the Country, access to economies of scale, and a reduced project management burden, the potential risks included lack of detailed local data, such as road traffic flows, and the size of the project becoming too large to successfully deliver, which in turn could lead to over simplification in order to have a reduced workload.

For R2 strategic noise mapping England, Wales, Northern Ireland, Scotland and Malta each undertook production of the strategic noise maps under a single project, combining agglomerations, major roads and major railways; whilst in the Republic of Ireland a hybrid approach was taken with the major roads produced under a single centralised approach which included all the extents which were the individual responsibility of the National Roads Authority and the 28 local authorities outside the agglomerations. These single project approaches led to some projects which included multiple agglomerations, and extensive lengths of major roads and major railways. To be successfully delivered an extended multi-disciplinary team of experts was required, with experience in acoustics, noise mapping, data management, GIS, project management, quality assurance and quality control.

The single project approach also put an onus on the contracting authority to ensure that the project was delivered in line with their requirements and expectations. Under the approach set out within the END, the strategic noise mapping represents the baseline evidence for the management of environmental noise, development of actions within the MSs, and development of Community actions. Throughout the process there are the potentially conflicting requirements of good quality robust results, and minimisation of costs. The scale of the challenges within large mapping projects leads to time and cost savings being sought at various stages within the process to ensure that the process is cost effective, and the results obtained fit for purpose, with the delivery likely to be procured under a fixed price, fixed timescale contract, the authority needs to remain diligent over the contractor's approach to increased efficiency. If one considers the input data requirements for the EC recommended interim methods, or existing national methods, over large areas of the urbanised regions of the EU, the resulting requirements for the collection and collation of input datasets becomes extensive. Within GIS, these requirements may lead to a desire to adopt "low cost methods for data collection", or a desire to utilise existing datasets which may offer a "reasonable fit" to the requirements, or the extensive use of WG-AEN GPG Toolkits [5]. Within the noise mapping software it may lead to a desire to dramatically reduce the resolution of the datasets to reduce object counts, or use many time saving efficiency techniques to help reduce processing time [6].

Experience gained during the delivery of a number of strategic noise mapping projects during both R1 and R2 has led to the development of a quality assurance process to support the managed development of the collated input datasets and finalised acoustic models. Quality control procedures have also been developed which maintain consistency during the delivery of the mapping results between technicians and within multi-disciplinary teams, spread geographically and across multiple organisations. These procedures enable delivery of the strategic noise mapping within a controlled environment, in line with the PRINCE2 approach to project management, and set out controls over the process providing the ability to review inputs, intermediaries and deliverables.

2. OVERVIEW OF THE NOISE MAPPING PROCESS

Quality assurance of a strategic noise mapping project cannot be established without first having an understanding of the process being undertaken. Each noise mapping process can be described by the seven main stages as shown on Figure 1.

Each of the stages includes many decisions, which may result in many different resolutions, and each may potentially have a strong impact on two key aspects of the noise mapping: (1) uncertainty within the assessed noise levels, and (2) extent of the required project budget. The range of possible "solutions" and the degree to which cost and uncertainty may be traded against each other may help to explain why the figures widely published for noise mapping projects range from € 0.2 to € 2.0 per inhabitant. From a technical perspective it is understood that within a specified project extent, the project budget can be strongly influenced by the decisions made regarding:

- definition and resolution of the input data;
- data conversion and processing;
- simplification strategies to speed up calculations; and
- management of results uncertainty.

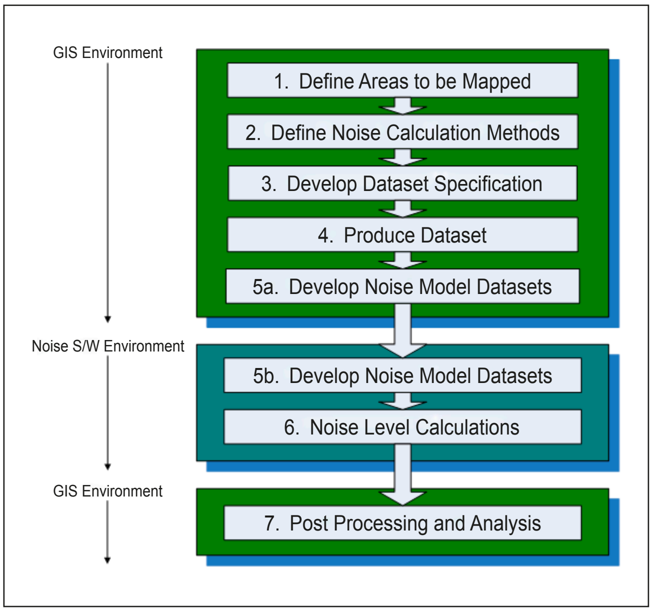

Figure 1. Overview of the noise mapping process [EPA Ireland [7]].

The extent of uncertainty within the assessed noise levels is influenced by the various sources of uncertainties, which can be grouped into the four main areas [5], Figure 2:

- estimation of uncertainties in model inputs and parameters (characterisation of input uncertainties);
- estimation of the uncertainty in model outputs resulting from the uncertainty in model inputs and model parameters (uncertainty propagation or sensitivity);
- characterisation of uncertainties associated with different model structures and model formulations (characterisation of model uncertainty);
- characterisation of the uncertainties in model predictions resulting from uncertainties in the evaluation data (uncertainty of evaluation data).

Uncertainties in the raw supplied input data [14, 15, 16], or the calculation model formulations will lie outside the control of the project, whilst many aspects of the uncertainty propagation introduced will be the result of the decision taken within the project regarding noise model preparation and noise software calculation parameters. This leads onto a secondary issue within the noise mapping process being the (un)intentional use of the various simplification strategies and efficiency techniques available to speed up the calculation process, which may have significant impact to the accuracy of the calculated results [6].

In common with other quality assurance procedures, the noise mapping QA procedure developed needed to cover each of the processing steps, and balance the need for tracking information, traceability and management reporting with a desire to minimise documentation requirements. The right balance needed to be struck between usability and control. It was also important that the process was flexible and wide ranging enough to be effective in a typical multi-disciplinary process with noise mapping and geo-processing teams working in collaboration.

3. OVERVIEW OF THE QA PROCEDURE

The QA procedure was designed in the context of an electronic data management process, which functions with initial datasets, intermediaries and final datasets all in electronic format. The QA procedure was designed such that it supported remote working, web/VPN access and inter-office collaboration whilst providing each team member with access to the relevant element for the stage in the process they were working on.

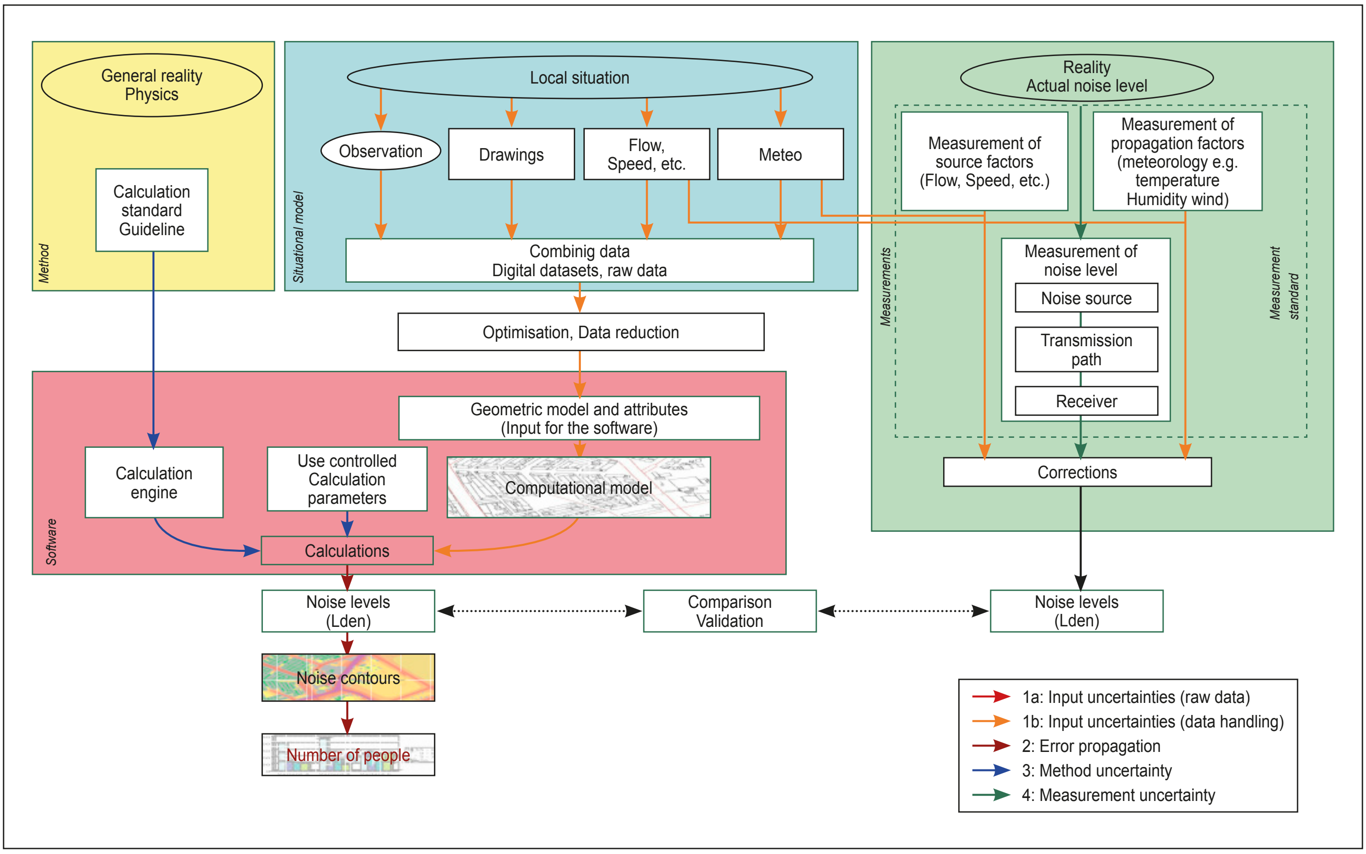

Figure 2. Uncertainties within the noise mapping process.

3.1. Stage 1 – Areas to be mapped

The main task of Stage 1 was to ensure that the areas to be mapped were completely defined and that the datasets provided the required coverage and had appropriate content.

In most cases the area definitions were developed with reference to the Regulations, and were in line with Toolkit 1 of the GPG v2 [5]. For major roads and railways a preceding process was required which undertook a review of traffic flow levels across the network in order to identify relevant sections above the flow threshold. For agglomerations the area to be mapped was either clearly defined within the Regulations, or required defining based upon the definition within the END *"having a population in excess of 100,000 persons and a population density such that the Member State considers it to be an urbanised area"* [1].

With the agglomeration boundaries clearly defined, and the extents of the major sources identified, the model areas were determined by applying a buffer distance to include relevant sources and features to ensure the calculated noise levels included all relevant effects. This buffer distance ranged from 700 m to 3 km, dependent upon the source, and the level of traffic flow. The QA procedure set out an approach to determining the relevant extents for the project, rather than fixed buffer distances, in order to provide flexibility relevant to the specific project area.

Once the calculation areas, and the buffered model extent areas, were determined, they set the mask for data capture, collation and concatenation in the next stage. For example the R2 mapping of roads and railways in England had a total model extent of approximately 79,000 km^2, which is approximately 59 % of England.

3.2. Stage 2 – Noise calculation methods

Within many Member States, the task of defining the method of assessment is already undertaken within the national legislation transposing the Directive into Regulations. Until the introduction by the Commission of a common method of assessment, the END presents two broad options:

- Member States' national computational methods, or
- interim methods set out in the END.

This stage remains of key relevance for two reasons:

- national legislation within some Member States retains the option of national or EU Interim methods, thus a selection is required;
- adaptation:
  – the recommended Interim Methods must be adapted in line with the EC decision [9];
  – many national methods require adaptation [10].

Thus an important task is a clear statement of the methodology to be used, including any necessary adaptations, as this sets the requirements for the data schema design and list of input datasets.

A typical example regarding input datasets is the use of long-term meteorological data for the determination of the occurrence of favourable sound propagation conditions. Whilst the recommended interim methods require this information, some national methods such as CRTN [11] or RLS-90 [12] do not.

3.3. Stage 3 – Dataset specification

With knowledge of the required area of coverage, and the method of assessment to the utilised, it was now possible to develop an input data schema specification.

Despite the fact that the data required for producing acoustical model layers are similar in every noise mapping project, the detailed requirements vary according to the calculation method being used, the noise mapping software being used, the resolution of different input datasets and even the projection system being used. These significant detail changes mean that it is necessary to produce a data specification schema for each project.

The input datasets required are usually classified into three categories:

- source data, i.e. definition of the position and characteristics of the noise sources;
- pathway data, i.e. definition of the environment within which propagation occurs; and
- receiver data, i.e. building use, number of residents, number of dwellings.

Broadly it can be said that the recommended interim methods for road, railway and industry require similar information for the definition of the pathway, whilst the source information required is unique to each method.

The data specification then set out a detailed list of the model layers required, and a full set of object and attribute definitions, including any relevant constraints and object geometry rules. During the development of each project specific data schema there was an opportunity to review and test input datasets and data processing methods which were available within the

Member State or project area, which may not have been available elsewhere. The QA procedure set out the means by which input datasets were to be reviewed, and how the effects on noise level results of any necessary input data processing would be tested and quantified. This approach provided flexibility to respond to local data situations whilst ensuring that subsequent decisions were taken on a similar basis.

At this stage it was typically most efficient to also select the noise calculation software which was to be utilised in Stage 6, that way the specification drawn up matched the requirements of the calculation software, and made the transition from GIS to noise calculation environment as seamless as possible.

Experience gained through the development of several such specifications clearly indicates that this is a key crossover document which needs to be developed in a combined approach with both GIS and noise modelling expertise. The resultant specification then enables full development of GIS datasets which may be successfully imported into the noise mapping software and processed through the calculation kernel without any secondary issues.

3.4. Stage 4 – Dataset production

Within this stage the raw GIS datasets were collected, collated and catalogued, with a gap analysis and audit undertaken against the specifications drawn up within Stage 3. Due to the wide range of input datasets required for strategic noise mapping, data acquisition was often performed by third parties, and existing data acquired for other purposes was pressed into service.

The base ground model layers used to develop the acoustical pathway were often obtained from State surveying and mapping authorities with predefined formats and resolutions. Decisions were then often required as to how to process this data to make it most efficient for the noise modelling. Automated processing of the datasets was often required, and final output resolution and consistency with the input datasets needed to be managed.

Source data for roads and railways was commonly held by the relevant state agencies, private companies or private traffic consultants. The original format and definition of these datasets was often significantly different from the format required within the noise modelling process. Processing of these datasets was frequently a manual or semi-automated process, which required documentation to provide traceability and repeatability.

Following collection and collation of data from the various sources, the results of the appraisal and gap analysis were used to determine how any incomplete datasets could be finalised, such as through data capture or use of GPGv2 toolkits. The GIS and noise experts worked in collaboration to design the various processing stages which produced the noise model input layers from the available raw input data.

3.5. Stage 5 – Noise model datasets

At the completion of stage 4 a collection of data layers were available in GIS format which have been processed from raw data and general geographical data files to meet the defined specification. At this stage the data layers were transferred into the noise mapping software environment, and a number of pre-flight checks undertaken to ensure smooth processing of the models and the successful delivery of noise result datasets.

During the dataset production on large national mapping projects it was necessary to have a team of GIS personnel working in parallel on the production of the various noise model datasets. For this reason it was appropriate to set up quality control (QC) procedures for the specific steps and processes involved in developing the noise model layers from the raw input data. These documented QC procedures ensured consistency of approach between personnel, but also between areas of the project in cases when the complete coverage was to be split into a number of discrete sections. For example R2 mapping in Wales was split into eight geographical areas, whilst R2 mapping of roads and railways in England was split into 92 different geographical areas.

Once the GIS team had produced the noise model layers in line with the data schema specification drawn up in stage 3 they were catalogued and handed on to the noise calculation team. At this stage each of the model data layers, in each of the project areas, was tracked through the various processing stages. This provided a clear view on the status of project progress against milestones, but also helped to identify any risks, delays or queries which may have arisen during the various process steps. During the R2 projects the tracking documentation was hosted on a cloud based project management tool which enabled all the team members and clients direct access to the latest versions of the tracking documents.

Input checks

Following receipt of the GIS datasets, the noise calculation team undertook initial checks for the following:

- conformity (verification that the datasets were in line with the data specification document);
- coverage (whether data covered the relevant project extents); and
- content (whether the correct data had been provided and contained the correct attribution).

All the checks undertaken were documented within a QC procedure to ensure consistency of approach between team members and project areas. Any anomalies identified were flagged at this first stage and resolved prior to the specific layers progressing to the next stage.

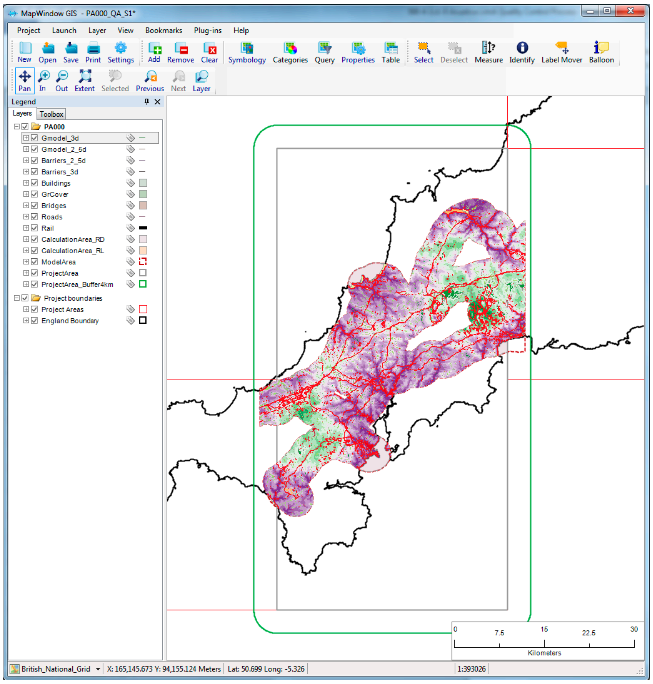

Figure 3. *Example of initial noise model review.*

Data conversion checks

The GIS datasets were then converted to the proprietary file format supported by the noise mapping software system. The results of each conversion were checked, followed by additional testing of the objects within the noise mapping application. The QC procedure covered the various stages of the process, and has built up a number of common issues and resolutions based upon the cumulative results of many mapping projects across R1 and R2 over the past seven years.

Initially the acoustical model layers were checked individually, and once signed off they were then tested in combination to ensure that the 3D model environment was properly resolved when all the model layers were combined. Interaction between bridges, roads, railways, building, embankments and hillsides (etc) are checked. Figure 4 shows an example of one possible issue which could arise.

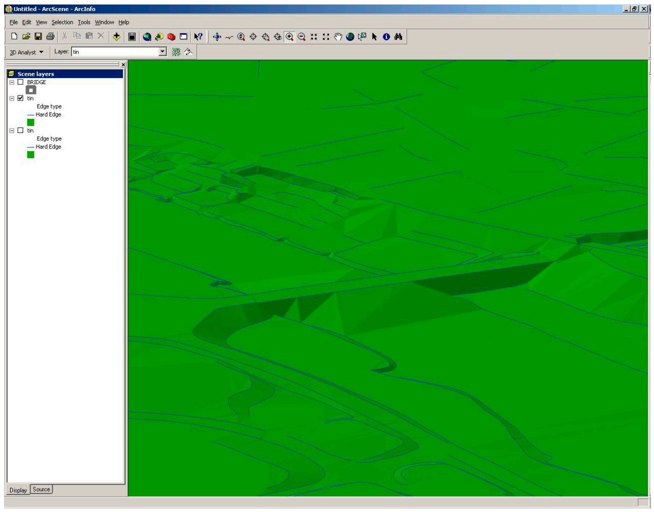

Figure 4. *Incorrect interpretation of bridge and terrain over a river.*

The data layers were catalogued through a tracking spreadsheet, and any anomalies identified were documented in a standard format, with a query log per project area. The query logs were also held on the hosted project management workspace, and formed a connector between the GIS and noise mapping teams to discuss and resolve any specific issues identified. The resolutions were then documented within the query log, and revised data issued by the GIS team as required under the version control protocol.

Across the 92 project areas within the England road and rail calculation project there were over 1,200 GIS data layers received, checked and signed-off prior to the noise calculations.

3.6. Stage 6 – Noise level calculations

Setup calculation environment

During Stage 2 of the QC procedure the noise calculation methodology was fixed. At the beginning of Stage 6 the noise calculation software system was setup and tested, and the calculation parameters to be used were determined and set.

On large national projects it was necessary to establish a calculation capacity which was capable of processing the total project coverage within the timetable agreed with the contracting Authority. During R1 and R2 projects a set of 10 server class calculation machines with a total of 40 CPU cores was utilised. The noise mapping software was installed and tested on each, and a series of test and validation models run to ensure that the correct results were being generated. For example with the UK CRTN and CRN methodologies the Annex models from the standards were run on each machine, and the results documented in order to demonstrate compliance.

Within the noise mapping software environment (pink in Figure 2), the calculation method and the input datasets meet within the software calculation engine during the calculation process. One specific aspect within the map of uncertainties is the uncertainty introduced by the "User controlled calculation parameters". These are the settings used within the calculation software to control how the calculation engine processes the 3D model data and generates the noise level results.

Many of the "acceleration" techniques available to the users of mapping software reduce calculation time by simplifying the propagation path between the source and the receptor, therefore reducing the time taken to determine the various attenuation factors. This may inherently lead to a loss in accuracy if undertaken in a crude or heavy handed manner, which may lead to under or over estimation of the noise level at the receptor.

Using one of the project areas a series of test calculations were run for a few randomly chosen 1 x 1 km tile areas. They were first run with the software configured with "crisp" reference settings, in line with the standard, without any of the acceleration techniques enabled. A series of meta-calculations were then run when each of the noise mapping software's various calculation parameters were varied one at a time. Examples of these can include: sources search radius, radius for reflections, reflection depth, dynamic error margin, simplify propagation etc. The results of each meta-test were then statistically analysed against the "crisp" results, in order to determine a cost/benefit relationship, cost being uncertainty introduced into the results and benefit being the reduction in calculation time. The best performing settings, i.e. lowest introduced uncertainty for largest reduction in calculation time, were then used together for a further meta-test to confirm the final calculation settings. For the

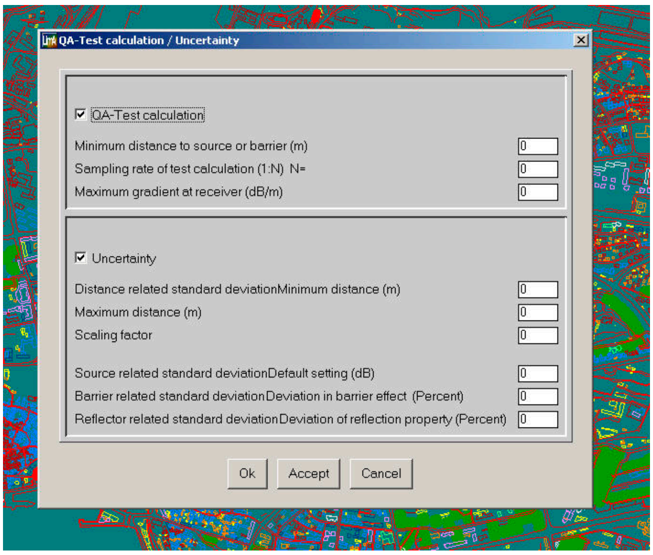

Figure 5. LimA QA Calculation set-up.

projects run in R1 and R2 these final settings, when compared with the reference results, typically introduced an uncertainty of less than 0.5 dB(A) 95 % CI whilst providing a 75 to 95 % reduction in calculation time.

The process used is a parallel to that described within DIN 45687 [13], for which most of the commercial software packages provide a tool for assessment, Figure 5, however it is considered more robust as the statistical analysis is undertaken across all of the grid points in at least two 1km^2 calculation areas, rather than a sample of only 20 random points as described in the DIN standard. Furthermore the 95 % CI is used as this can then be compared with the input data uncertainty values presented within GPGv2 and the research which underpins them [14, 15].

Calculations in tiles

Prior to sign off for final calculations, a preliminary calculation check was undertaken. This runs the whole project area as a single job, with a grid spacing of 100 m using the final calculation settings. This provided a complete test that all model layers run without error, and provided a test calculation at 1 % of the final run, therefore providing a good estimate of the total calculation time. Provided that all the checks were passed, and the results from the 100 m grid calculation appeared plausible, the project area was signed off for final calculation in tiles.

In most large noise mapping projects so called "tiled" mode calculations are preferred, Figure 6. This is due to several factors, including: the size of the acoustical model; the extent of the project area; the software architecture; and the desire to balance processing across multiple computers. The calculations are typically undertaken based upon a 1 x 1 km tile to be calculated, which is loaded with data from the surrounding tiles in the buffer area. For example, the 1 x 1 km calculation area would be at the centre of a 7 x 7 km model area used for calculations when the buffer distance is 3.0 km.

The noise mapping software was able to automatically generate the calculation tiles within the total project extent, and each tile was processed as an individual job with up to 40 being processed in parallel across the system. During the calculations the various indicators required under the Regulations were generated in a single run. This could be limited to L_{day}, L_{eve}, L_{night} and L_{den}, or as in the case of the UK it could include additional supplementary indicators such as $L_{A10,\ 18hr}$ and $L_{Aeq,\ 16hr}$.

Once all tiles had been processed within a project area it was confirmed that all tiles had processed without error, before the results from the individual tiles were

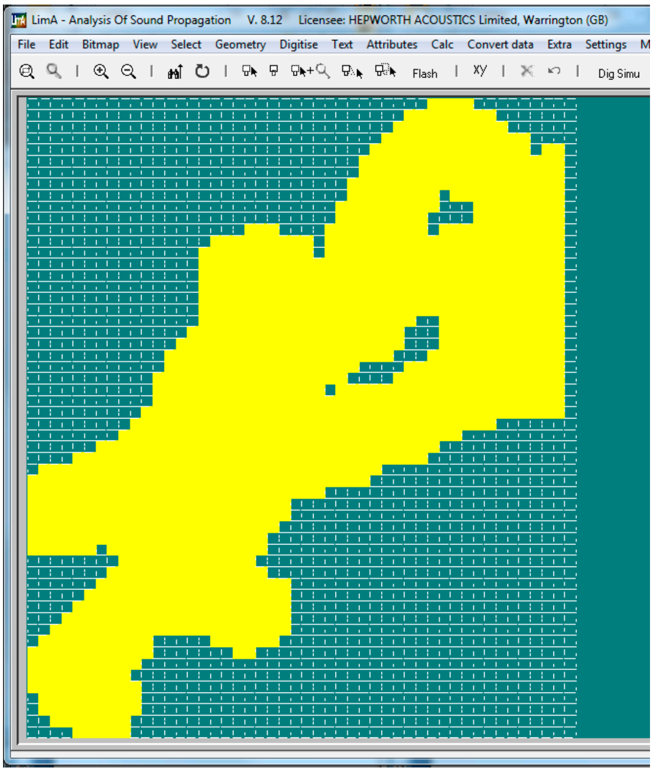

Figure 6. *Example of tiled calculation.*

automatically combined into a project area results set and exported to a GIS format for delivery back to the GIS team to undertake the exposure analysis. The final noise level results were then delivered back as either ESRI Shapefile point files, or ARC/INFO ASC Grid files.

The final combined results sets contained over 2,000 km^2 of results, with grid points at 10m intervals, and up to seven noise indicators per grid point. For the road and rail calculations in England, over 93,000 km^2 of road traffic noise calculations were undertaken, and over 23,000 km^2 of railway traffic noise calculations were undertaken, totalling almost 350 million grid receptor points. Individual 1 km^2 tiles could take between 5 minutes and 12 hours to process, with the 40 core calculation system processing an average of approximately one tile per minute over the whole project.

3.7. Stage 7 – Post processing and analysis

Following completion of the assessment of noise levels, the results were first reviewed to check that they are plausible and in line with expectations. Particular attention was typically paid to the results around the boundaries of the calculation tiles and near the assessment boundary.

The area, dwelling and population exposure analysis based upon the results of the strategic noise mapping would then be undertaken within a GIS system, or occasionally within the noise mapping application. Wherever the analysis was undertaken, the crucial task within the exposure analysis was the proper distribution of inhabitants onto the residential buildings. It was therefore necessary to correctly define the attribution of building objects in the data specification, and special attention was paid to mixed urban areas, where residential occupancy of building often starts above ground floor level. Depending upon the nature and format of the population information, and the complexity of the built environment, was often appropriate to bring in a GIS specialist with expertise in demographic assessments to ensure that the population exposure assessment was undertaken in a robust manner.

During R1 a variety of methods were used to undertake the exposure assessment for dwellings and numbers of people [3, 17], for example some assessments were based upon the grid receptor results assigned to the closest building facades, some were based on interpolation between grid receptors onto façade receptor points, and others were based upon façade receptor points with levels calculated within the noise mapping software. The recent work under CNOSSOS-EU [4] has proposed a more consistent approach to be used in the future, however it remains likely that R2 continued to see a number of differing approaches being applied across Europe. Even the assessment of exposed area is open to interpretation, as it could be assessed as a simple matter of each grid point result representing 100m^2, or as has been seen in a number of agglomerations, the building footprints may be excluded from the exposed area such that only the un-built area is reported.

4. CONCLUSION

This paper describes an approach to the process of strategic noise mapping delivered through the successful implementation of a Quality Assurance Procedure which includes a number of quality control protocols to manage specific aspects of the process. This QA procedure promotes a staged approach and supports team working within multi-disciplinary and multi-company project groups. The described methodology has been successfully employed on a number of R1 and R2 strategic noise mapping projects, as well as EIA noise assessment, and has delivered efficient value for money mapping projects within short timescales.

The capture and tracking of key project decisions and quality indicators provide contracting Authorities means of managing large complex mapping projects, and a set of criteria against which contractors may be asked to report. The concept behind the procedure could also be developed into a possible approach for an accreditation schema in the field of quality assurance of noise mapping consultants.

REFERENCES

[1] Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise, *Official Journal of the European Communities*, (OJ L 189,18.07.2002, p12), 2002.

[2] http://noise.eionet.europa.eu/ [Accessed May 2013].

[3] "Noise Mapping in the EU Models and Procedures", Edited by Gaetano Licitra, CRC Press, 2013. (ISBN 978-0-415-58509-5).

[4] "Common Noise Assessment Methods in Europe (CNOSSOS-EU)", Joint Research Centre of the European Commission, 2012. (ISBN 978-92-79-25282-2).

[5] European Working Group - Assessment of Exposure to Noise, "Good Practice Guide for Strategic Noise Mapping and the Production of Associated Data on Noise Exposure", Version 2, January 2006.

[6] Hepworth, P., Trow, J. and Hii, V. "Reference settings in noise mapping software – the effects on calculation speed and accuracy", *Proceedings of EuroNoise 2006*, Tampere, Finland.

[7] Environmental Protection Agency, Ireland, "Guidance Note for Strategic Noise Mapping", Version 2, August 2011.

[8] Shilton, S., Van Leeuwen, H., Nota, R., "Error propagation analysis of XPS 31-133 and CRTN to help develop a noise mapping data standard", *Proceedings of Managing Uncertainty in Noise Measurements and Prediction*, Le Mans, June 2005.

[9] AR-INTERIM-CM, Adaptation and revision of the interim noise computation methods for the purpose of strategic noise mapping, B4-040/2001/329750/MAR/C1, 2003.

[10] Converting the UK traffic noise index LA10,18hr to EU noise indices for noise mapping, P G Abbott and P M Nelson, TRL Limited, Project Report PR/SE/451/02, 2002.

[11] Department of Transport publication, 'Calculation of Road Traffic Noise', HMSO, 1988 ISBN 0115508473.

[12] "RLS-90"; "Richtlinien für den Laermschutz an Strassen", Edition 1990., Bundesminister für Verkehr, Abteilung Strassenbau, Deutschland.

[13] DIN 45687 "Software-Erzeugnisse zur Berechnung der Geräuschimmission im Freien - Qualitätsanforderungen und Prüfbestimmungen".

[14] *"WG-AEN's Good Practice Guide and the implications for acoustic accuracy"*, NANR 93, Defra, May 2005. See http://archive.defra.gov.uk/environment/quality/noise/research/wgaen-gpguide/ [Accessed May 2013]

[15] *"Noise modelling"*, NANR 208, Defra, May 2007. See http://archive.defra.gov.uk/environment/quality/noise/research/nanr208/ [Accessed May 2013].

[16] Ausejo, M; Recuero, M; Asensio, C; Pavón, I. Reduction in calculated uncertainty of a noise map by improving the traffic model data through two phases. Acta Acustica United with Acustica, Vol. 97 (2011) 761-768.

[17] Comparative Analysis of Methods to Estimate Urban Noise Exposure of Inhabitants. Licitra, G.; Ascari, E.; Brambilla, G. Acta Acustica united with Acustica, Volume 98, Number 4, 2012 , pp. 659-666(8).

Impact of the new French thermal regulation on office indoor environment: combine innovative cooling technology and high acoustic demand

Y. Le Mue, R. Machner
Saint Gobain Ecophon, France
Corresponding author: Yoan.le-muet@saint-gobain.com

PACS: 43.55.Dt, 43.55.Br, 43.50.Jh

ABSTRACT

As with many regulations the French thermal regulation (Réglementation thermique 2012) fixes goals to achieve but gives no guidelines about the technologies to be implemented. After few years of experimentation in order to prepare RT2012 implementation it seems that a consensus was agreed around a similar concept using thermal capacity of the structure mass to provide thermal comfort. This technique provides stable thermal conditions and is perceived to be long term energy efficient. The thermal issues require the structure (typically concrete) to remain exposed to the room environment. A priori this kind of technique is not compatible with traditional suspended ceilings, covering a room from wall to wall. The reason for this is that the ceiling, positioned between the soffit and the users, would then be a mask for radiation and would stop convection. The challenge is to combine this constraint with the French High Environmental Quality Label's acoustic specifications for office spaces, described through Equivalent Absorption Area (EAA). The purpose of this paper is to show acoustic and thermal tests that have been conducted and a few environmentally labelled projects implementing innovative acoustic and thermal technologies.

1. INTRODUCTION

Thermal performance is increasingly taken into consideration in the programming and design of office buildings. Many of these offices are using the thermal capacity of the structure's mass to provide thermal comfort. This technique provides stable thermal conditions and is perceived to be long term energy efficient. The thermal issues require the structure (typically concrete) to remain exposed to the room environment. Traditional fitting surfaces, such as wall to wall suspended ceilings, are said to be inappropriate. The challenge is to combine this constraint with acoustic requirements for office spaces, described through reverberation and propagation. Measurements have been performed according to EN 14240:2004. Two treatment configurations, based on discrete elements, have been tested, with a coverage ratio of 45 % of the room floor area. Two plenum heights have been used. The influence on the thermal effect of the cooling ceiling surface is less than the coverage ratio. This could indicate that the part of the thermal exchange related to radiation —a priori more affected by the masking effect of the panels— is less than the convection part. As a matter of fact, the higher the plenum above the acoustic element, the easier air can circulate around the panels. According to the same principle, the larger the distance between the panels and the concrete ceiling, the better the absorption performance, since acoustic energy is better spread around the panel. Several completed projects confirm that it is possible to attain acoustic comfort in office buildings cooled by natural (free) cooling. Also, these projects point out the importance of interaction of acoustic treatments with (prefabricated) concrete elements, lighting, ventilation and cable management. Finally, they emphasize the need for dialogue and coordination between the acoustician and other building engineering disciplines.

2. THERMAL PERFORMANCE OF OFFICE BUILDINGS

At this date, the new regulation on thermal performance of office buildings define challenging target values around 50 kWhPE/m²/year for the total energy consumption of the building in use. In general, energy consumption of an office building is shared between 40 % for equipments (computers, servers, copy machines, etc.), 40 % for lighting and 20 % for ventilation and air conditioning. An efficient way to reach this value is to avoid air conditioning, which is very energy consuming. The solution to cool such "AC-free" buildings is to use the thermal mass of the concrete core: baring walls, soffits, etc for summer cooling. For physical reasons, the surface that contributes most to comfort is supposed to be the ceiling. Therefore, the soffit should be as exposed to the room as possible, in order to facilitate the energy transfer.

2.1. Summer cooling : energetic challenge for office buildings

All figures should be centered inside the framing boxes. The energetic challenge for office buildings is to prevent overheating during summer, avoiding energy consuming systems such as air conditioning. The potential energy savings are large, since energy consumption related to the cooling of an office building can be as much three times higher than for heating. One of the techniques available to designers is overnight ventilation, together with buildings with a high thermal mass.

2.2. Overnight ventilation and thermal mass

The principle is that the structure of the building, and particularly the soffit, participates in the cooling of the ambient air during summer days. For this to be possible, one has to "load" the structure with cold when ambient air is cooler, i.e. at night. The structure elements to load are those with a high density, such as concrete, bricks, etc. At night, a draught is created by opening windows

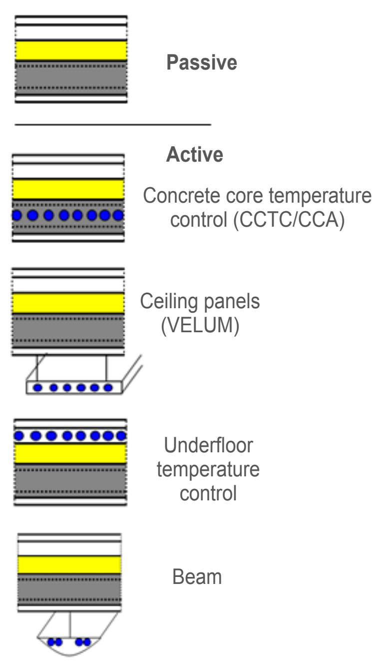

Figure 1. Main concepts using concrete inertia properties. The active form is the combination of the inertia and hydraulic fluid in order to cool down the slabs or bring a thermal comfort using radiation transfer.

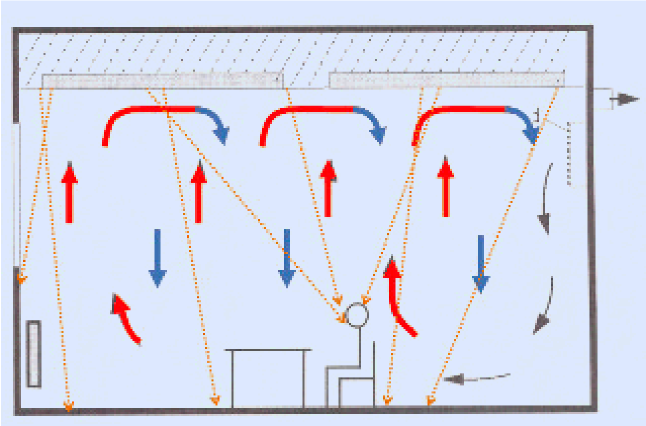

Figure 2. Contribution of thermal mass to summer comfort, through both convection radiation. Regarding convection, warm air (in red) rises and is cooled by contact with the soffit which has been loaded with cold during the night. Cooled air sinks again to the bottom of the room. The dotted lines illustrate radiation.

on the main façades of the building. This technique is defined as overnight ventilation. Before employees arrive at the office, windows are closed so as to avoid draughts. The cold that has been loaded into the structure during the night is returned to the users during the working day, in such a way that it compensates for the raising of the ambient air temperature due to sun, equipment (computers, etc) and human activity. The energy transfer between elements with high thermal mass and the room is made through both convection and radiation. The technique has its limitations and one should be prepared to accept a degraded comfort due to temperatures between 26 and 28 °C a few days a year.

This kind of technique for thermal regulation is a priori not compatible with traditional suspended ceilings, covering a room from wall to wall. The reason for this is that the ceiling, positioned between the soffit and the users, would then be a mask for radiation and would stop convection.

3. ACOUSTIC TREATMENT OF OPEN PLAN OFFICES

Parallel to the development of these cooling techniques, acoustic comfort in offices is a growing issue. In France, regulations on working conditions (Code du travail) do not specify anything precise nor relevant regarding acoustic treatment of offices. On the other hand, two other documents French Standard NF S31-080 [1] and the High Environmental Quality (HQE) building performance specification "Offices and schools" (target 9: acoustics) [2] provide designers with a relevant acoustical approach and target values. These two documents do not display how to attain a certain "in situ" performance. Furthermore, the requirements are expressed in two different ways.

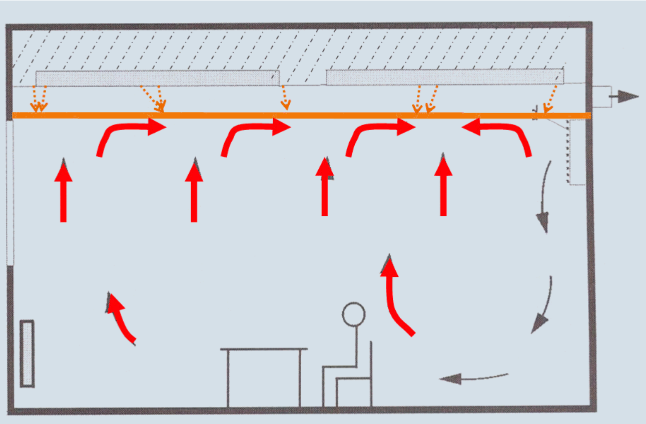

Figure 3. *Interaction principle between a full covering acoustic ceiling and thermal exchange in the room. The ceiling is both an obstacle to thermal exchange via radiation and convection.*

3.1. French Standard NF S31-080

French Standard NF S31-080 assigns values to the main types of sound in an office and the descriptors to evaluate them. For room acoustic treatment in open plan offices, the standard asks for a value of the rate of spatial decay per doubling of distance (DL2). For a room of 250 m^3 or more (i.e. approximately 100 m^2 as floor area), the rate of spatial decay should be 3 dB at least for the level called "Efficient" and 4 dB for the level "Highly Efficient". Generally, such values are attained in empty or scarcely furnished rooms by means of a high performing ceiling on the whole ceiling area. In fact, due to the presence of installations, such as luminaires, ventilation in- and outlets and chilling beams, the effective surface covered by absorbers is between 80 and 90 %.

3.2. ISO 3382 - 3

ISO 3382-3 specifies methods for the measurement of room acoustic properties in open-plan offices with furnishing. It describes measurement procedures, the apparatus needed, the coverage required, and the method for evaluating the data and presenting the test report. In this international standard, the sound power spectrum of normal speech is used. The octave band values represent normal effort unisex speech (average of female and male speech). The determination of D2.S (an application of DL2 defined in ISO 14257, but using the spectrum of normal speech and A-weighting over the whole frequency range) is made from the results at measurement positions at distances within the range 2 m to 16 m from the sound source. A logarithmic distance axis and linear regression is used. The standard also defines sound pressure level at 4 m (LpA,S,4m) which is determined via linear regression from the line, and a distraction distance (rD), defined as the distance where the speech transmission index (STI) is equal to 0.5. Recommendations of levels are given in the annex of the standard as follows: D2.S ≥ 7, LpA,S,4m ≤ 48 dB, and rD ≤ 5 m.

3.3. Environmental performance specification for offices

High Environmental Quality (HQE) specification uses the Equivalent Absorption Area (EAA). Defined as the product of the absorption factor _ and of the surface (_ * S), EAA is a way to require a certain absorption quantity in the room. In order to fulfil the level called Basic, cumulated EAA for the floor and the ceiling surfaces (AAEfloor + ceiling) should be superior to 60 % the floor area. For the "Efficient" level, AAEfloor + ceiling should be at least 75 % times the floor area. This is a degrading compared to the former version of the specification (2006); which applied the same requirement to the ceiling only. Though, since the absorption performance of flooring materials is very poor, the ceiling should on its own provide for reaching these values. For the "Efficient" level, it means:

- 100 % of the ceiling surface covered with a material with an absorption coefficient of 0.75.
- 75 % of the ceiling surface covered with a material with an absorption coefficient of 1.

3.4. Less surface for more performance

As a matter of fact the ceiling is the largest clear surface homogeneously in contact with the room. The larger the room (shared office, open plan office) the more prominent this rule is. In such rooms, wall surface is small compared to floor surface. In the case of buildings using thermal mass, such spaces will be defined by hard reflecting surfaces. This is a challenge from the

Figure 4. *High acoustic performance horizontal free hanging units based on glass wool.*

point of view of sound propagation. Although some compensations can be found with partly absorbing coverings on furniture items (back of filing cabinet, screens) the ceiling remains a critical surface for acoustic treatment of open plan offices involving cooling techniques by mean of thermal mass. There appears a contradiction.

- On one hand a raise of the necessary absorption quantity
- On the other hand a reduction of the available surfaces for acoustic treatment

The consequence of the two being that solutions should be more and more acoustically efficient per surface unit. How then can we quantify their acoustic and thermal performance?

4. CHARACTERIZATION OF PERFORMANCE OF FREE HANGING ACOUSTICAL UNITS

Horizontal free hanging solutions based on glass wool have been developed for more than a decade. They are positioned with sufficient spacing so as to not prevent thermal exchange. Although the principle is simple, it is necessary to describe their interaction with the room in a precise way. Especially to be able to provide input data to thermo-dynamic simulations conducted in order to predict the energy consumption of buildings aiming for an environmental certification (HQE). For that reason, laboratory studies have been performed on horizontal glass wool free hanging units in order to:

- Quantify the incidence of a discontinuous ceiling on thermal exchanges between soffit and room and evaluate the proportion of the exchange based on convection respectively radiation.
- Characterize the acoustic performance of horizontal free hanging units by correlating the absorption contribution with a fully covering acoustic ceiling.

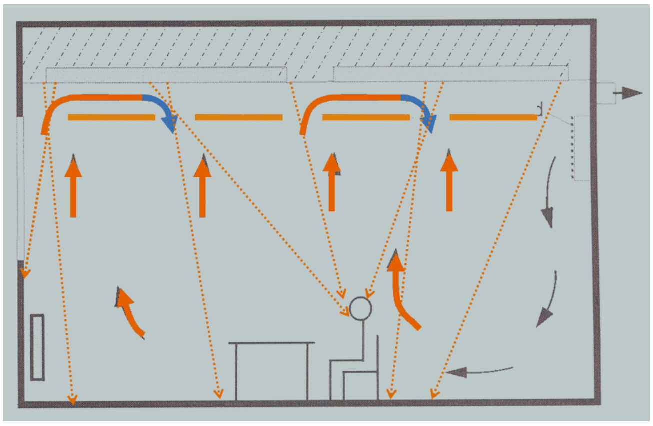

Figure 5. *Interaction between a discontinuous acoustic ceiling and a room. The horizontal free hanging units should be positioned with enough space between each other, so that they are not an obstacle to convection nor to radiation.*

4.1. Incidence on thermal exchanges

A test has been conducted at SP, Technical Research Institute of Sweden. "Testing of acoustic ceiling boards influence on cooling capacity" which refers to European Standard EN 14240:2004 - Ventilation for buildings. Chilled ceilings. Testing and rating [3], as well as European Standard EN 14518:2005 - Ventilation for buildings - Chilled beams - Testing and rating of passive chilled beams [4]. Measurements have been performed in a "room in the room" test set up. Room (2) is inside room (1). Room (2) is fitted with a water chilled ceiling. By mean of the temperature difference between inlet and outlet water as well as the water flow rate, one can calculate the "full regime" cooling effect of the ceiling surface. This "full regime" effect is then more or less degraded by the positioning of horizontal free hanging acoustic elements between the chilled ceiling and the temperature measurement devices located in the room.

Test procedure implies that the temperature of room (2) is maintained constant by modulating the temperature in room (1). Since the varying parameter is the outlet temperature from the chilled ceiling, it is possible to calculate the effective cooling effect of the ceiling in the room for each configuration of free hanging horizontal units in the room. The comparison with the full regime situation is expressed in %. For instance, a 20 % decrease (with free hanging horizontal units) means that the effective cooling effect in the room is 80 % of the full regime effect (empty room).

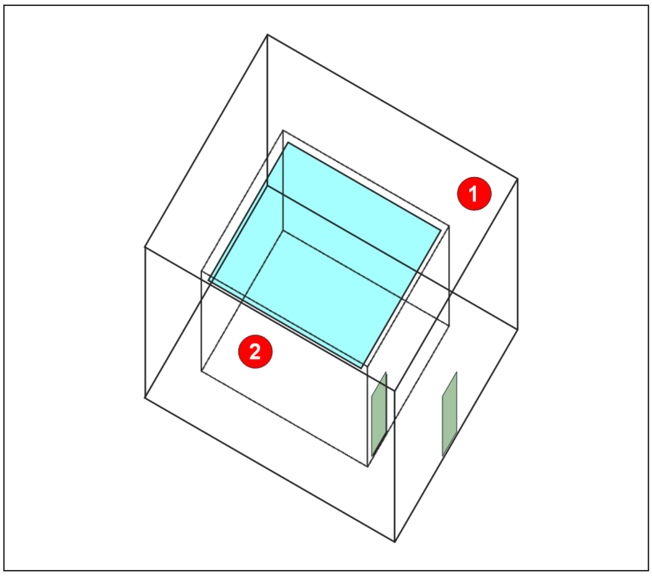

Figure 6. *Axonometric view of test set-up at SP, Technical Research Institute of Sweden. In blue, the water chilled ceiling.*

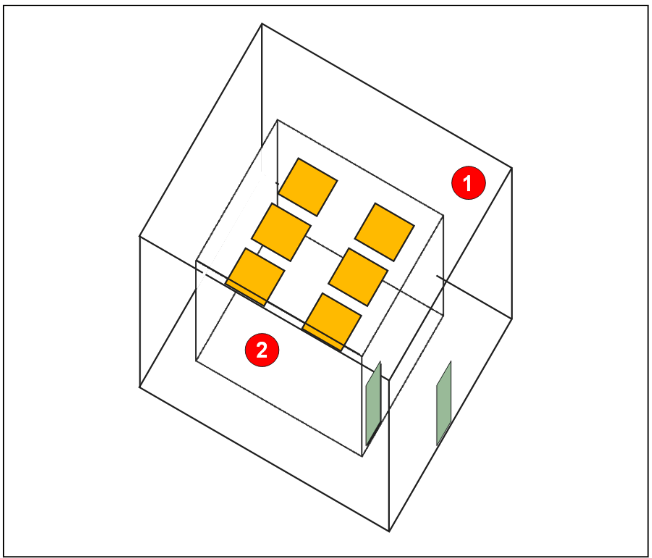

*Figure 7. Axonometric view of one of the tested configurations, bases on 1.2 m * 1.2 m glass wool panels. Suspension height = 0.8 m below chilled ceiling (not represented). Two configurations have been tested, consisting of 6 glass wool panels of 1.2 m x 1.2 m. Two suspension heights below the chilled ceiling have been used: 0.2 m and 0.8 m. The cumulated surface of the panels is 8.5 m2, corresponding to approximately 45 % of the floor surface. 45 % corresponds to the mid point of the interval of the coverage ratio recommended by thermal engineering consultants, i.e. 30 % to 60 %, depending on the project.*

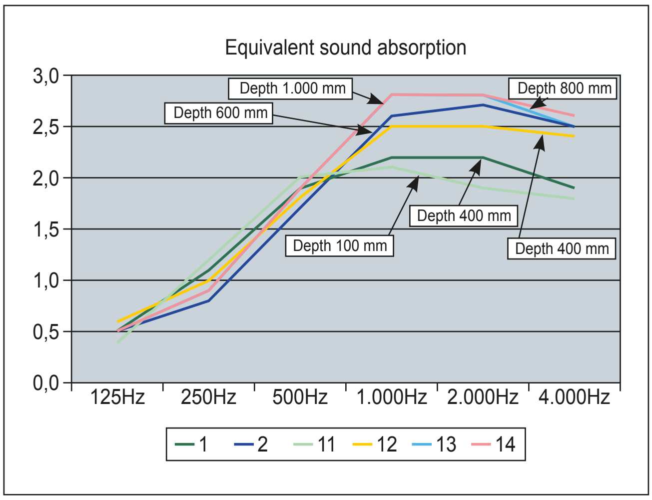

Figure 8. Examples of equivalent absorption area values per octave band, for glass wool free hanging horizontal units of 1.2 x 1.2 m suspended at 200, 400, 600, 800 and 1000 mm from the slab.

4.2. Thermal aspects : results and interpretation

A The test shows a decrease of the thermal exchange effect due to the presence of the free hanging horizontal acoustic of 16 % when the suspension height is 0.2 m and of 12 % when the suspension is 0.8 m. The more the free hanging element is suspended the better the energy transfer. Also the distance between panels is important to allow the air to circulate by convection. In the case radiation would have been the main exchange mode between the chilled ceiling and the room, the effect decrease should have been equal to the coverage ratio. For a coverage ratio of 45 %, the effect drop of the cooling effect of the chilled ceiling should have been close to 45 %. On the contrary, the test results tend to indicate that convection is a more important energy transfer mode than radiation is for room cooling via the ceiling. Also, instability of the temperature at the six measuring points in the room strengthens further this hypothesis. Finally, a separate study conducted by the Dutch acoustic consultancy firm Peutz [5] concludes in similar terms that “the reduction of the radiation part of the thermal capacity is less than the coverage percentage of the concrete due to the suspended ceiling”.

4.3. Characterization of the acoustic performance

Characterization of the acoustic performance of free hanging horizontal acoustic units is conducted by measuring equivalent absorption area in a reverberant room. Since such solutions are monolithic, they are specified and used in the acoustic treatment as a number of units, and not as a number of m^2. They are objects, assumed to absorb sound through more than the visible surface. Therefore, the absorption coefficient of the material they are made of is not an adequate performance indicator. More than twenty configurations have been tested and compiled [6], combining three sizes of free hanging units, several suspension heights, panels alone or clustered, if clustered —different distances between panels, etc.—. For each configuration, equivalent absorption area per octave band is presented.

The two main parameters acting on the acoustic performance are first, the suspension height of the panels and second, the distance between panels. The larger the suspension height, the larger is the equivalent absorption area. A panel mounted very close to the soffit will tend to work only on the visible side, while a panel located at mid height of the room will virtually work equally on both sides. Also, the larger the distance between the panels, the higher is the equivalent absorption area. Two panels positioned too close to each other will tend to “disturb” each other since acoustic energy will not distribute optimally around the panel. According to the same principle as for thermal performance, the more acoustic energy will be allowed to develop around the panel, the more the rear side (facing the soffit) will be made accessible to sound energy in order to be absorbed, and the higher will the total acoustic performance of the panel be. In order to simplify the application of these results in projects, the mean value of equivalent absorption area at octave bands 500, 1000 and 2000 Hz is calculated. This value is then divided by the surface of one side of the panel. This result tends to be close to 1.5. One can then say that 1 m^2 of free hanging horizontal acoustic unit brings the same quantity of absorption to the room as 1,5 m^2

of traditional acoustic ceiling made of the same material but with a closed plenum. Therefore, by covering the equivalent of 60 % (1 divided by 1,5 is 0,6) of the room surface with free hanging horizontal acoustic units, one creates acoustic conditions comparable to that of the same room covered with a continuous "wall to wall" ceiling of the same material.

Further tests should be made concerning the acoustical performance of free hanging horizontal acoustic units with regard to sound propagation, preferably based on ASTM, standards on interzone attenuation. Data from in situ measurements of rate of spatial decay and excess of sound pressure level in open plan offices are presently collected. They include sites treated by mean of free hanging horizontal acoustic units. It seems that there is a good correlation between these measurements and the results one should expect from the same room fitted with a continuous acoustic ceiling. Also, if we look at these results in regards of the target values proposed by the HQE document discussed above (AAEfloor + ceiling superior to 75 % of the floor area for the level "Efficient"), it seems possible to combine acoustic comfort with cooling though thermal mass.

5. EXAMPLES : PROJECTS WITHIN FRANCE & GERMANY

Completed projects can be found in Germany and France. Here are some examples:

- Austra Tower Hamburg Germany.
- Green Office Meudon France.
- MAAF Odysée Niort France.
- WOOPA Lyon France.

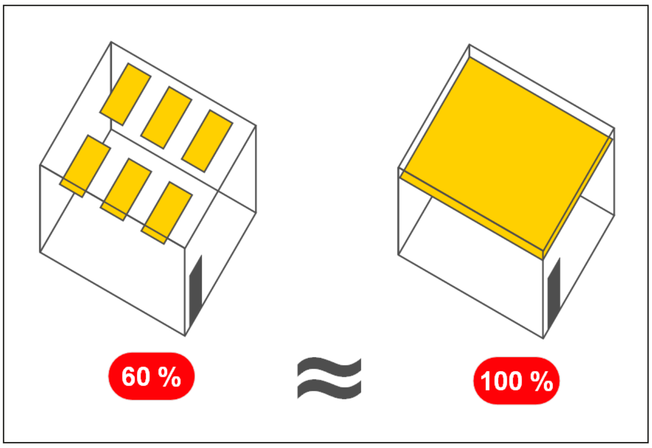

Figure 9. Simplified equivalence principle of the contribution of free hanging horizontal acoustic units compared to that of a traditional acoustic ceiling made of the same glass wool material and covering 100 % of the room surface (closed plenum).

6. CONCLUSIONS

The influence of free hanging horizontal acoustic units on the energy exchange between the soffit and the room is limited. The degradation of the cooling effect

Austra Tower Hamburg Germany.

Green Office Meudon France.

MAAF Odysée Niort France.

WOOPA Lyon France.

compared to the “full regime” situation (no acoustic treatment suspended) is between 15 and 20 %. Furthermore, the reduction of the radiation part of the thermal capacity is less than the coverage ratio of the concrete due to the free hanging horizontal acoustic units. This tends to indicate that the convective part of the energy exchange is larger than the radiating part. Acoustic performance of such free hanging units is presented through equivalent absorption area in different configurations. A simplified equivalence principle is proposed. It says that free hanging horizontal acoustic units covering the equivalent of 60 % of a room surface will create acoustic conditions comparable to that of the same room covered with a continuous “wall to wall” ceiling of the same material. Since the required 60 % are within the interval for coverage ratio claimed by thermal consultants (30-60 %), it seems therefore possible to obtain a certain acoustic comfort (corresponding to level Basic of the HQE reference document) in offices where thermal comfort is solved —totally or partly— by mobilisation of the thermal mass of the structure. For higher performance levels, such as Efficient, complementary absorbers should be installed on the walls. Nevertheless, beyond these principles, each office project remains unique. Comfort criteria will have to be validated by end-users and workspace designers. They will have to be interpreted and translated by acoustic and thermal experts. For that to happen smoothly, it is important that the different view points are confronted early in the project, ideally already at the stage of the program of demand.

ACKNOWLEDGEMENT

To Pierre Chigot.

REFERENCES

[1] Certivea, “Référentiel pour la qualité environnementale des bâtiments bureau/enseignement”, Paris, december 2008.

[2] NF S31-080, Acoustics - Offices and associated areas - Acoustic performance levels and criteria by type of area, janvier 2006 (in English).

[3] CEN European Standard 14240:2004 - Ventilation for buildings. Chilled ceilings. Testing and rating.

[4] CEN European Standard EN 14518:2005 - Ventilation for buildings - Chilled beams - Testing and rating of passive chilled beams.

[5] Peperkamp, H., Vercammen, M., Thermically activated concrete slabs and suspended ceilings, Proceedings of NAG-DAGA International Conference on Acoustics, Rotterdam, 23-26 March 2009.

[6] Determination of equivalent sound absorption area in a reverberation room according to ISO 354, SP Laboratory, Boras, 2008, 38 p.

Noise Dose Assessment of Wind Farm Noise

Andy McKenzie
Hayes McKenzie Partnership, Salisbury, UK
Corresponding author: andy@hayesmckenzie.co.uk

PACS: 43.50.Cb, 43.50.Yw, 43.28.Vd

ABSTRACT

A method is proposed for a unified approach to assessment of wind farm noise which takes account of residents exposure to noise as it varies with time of day, wind speed and wind direction. It is proposed that the method is also extend to take account of existing noise level as it varies with time of day, for non-wind dependant sources, wind speed, for wind dependant sources, and possibly wind direction which may have an effect on both or neither. The method follows in the footsteps of the European Noise Directive's use of the Lden descriptor, but extends this to the concept of a yearly noise dose as has been implemented more recently for the Night Noise Guidelines for Europe, published by the World Health Organization. The advantage of this method is that it produces an assessment which is independent of any country specific planning regulations but takes into account noise dose and noise change. It is not anticipated that this is likely to replace existing planning guidelines, nor that it would replace noise control measures such as planning conditions or other regulatory limits, but should be seen as a useful addition to both if used appropriately and for the right purposes.

1. INTRODUCTION

Environmental Impact Assessment is the process by which decision makers evaluate whether larger projects should be allowed to proceed, either in the form which they are submitted, or incorporating mitigation identified as part of the EIA process. The method by which such assessments are carried out can be a contentious issue, whatever the impact which is being assessed (ie. landscape and visual, ecological, archaeological etc.) and whatever the source of such impact (new road scheme, power generation project, minerals extraction etc.). Wind turbine projects and noise are, of course, no exception to this.

Noise impact assessment tends to be carried out with reference to the particular assessment methodology which has been laid down in planning guidance for the particular country in question. It has been argued that noise assessment required for planning purposes may not always be indicative of the "true" noise impact which may occur in practice. Noise impact is, of course, a purely subjective issue and it can be argued, on the other hand, that the noise impact can only be assessed by reference to the criteria laid down by the planning process and that the planning process should not, by it's very nature, allow development to go ahead if significant impacts are predicted.

Notwithstanding the above, the prediction of noise impact has always been something of a holy grail for noise professionals, with a great deal of effort going into subjective studies of various environmental noise sources and the production of resulting dose response curves. One of the outcomes of these type of studies is the use of the L_{den} measurement index as a strategic assessment tool, and this has been adopted as such in Europe through the Environmental Noise Directive [1]. This index is, effectively, a long term L_{Aeq} corrected by the addition of 5 dB for noise occurring during the evening hours (19:00-23:00) and 10 dB for noise occurring at night (23:00-07:00) although the definitions of the time periods are flexible and may be adjusted to allow for local circumstances.

This study shows how the use of L_{den} could be applied to the assessment of wind farm proposals to provide an objective approach to wind turbine noise assessment, taking into account the range of wind speeds and wind directions, and hence noise levels at specific residential or other properties, occurring "long term" for measured wind conditions at a specific site. It is not argued that this methodology would necessarily predict subjective impact any better than that which is being currently used in any particular country for either impact assessment or planning purposes. It is, however, a means for quantifying impact which takes account of the existing noise environment and the predicted noise environment due to the development which is being proposed, taking into account the variation in both existing and predicted noise due to wind conditions. It should be noted that this metric is unlikely to be suitable for practical noise control purposes which normally form part of the conditions or limits on wind farm planning consents. It may be that, nevertheless, it may constitute a useful control measure to be applied at the design stage, given the practical difficulties encountered in the measurement of noise from operational wind farms.

2. NOISE IMPACT ASSESSMENT

Noise limits for planning or assessment purposes can be expressed as absolute limits, relative limits, or as a hybrid of the two approaches. Absolute limits refer to a fixed decibel value which may, or may not, be dependant on time of day (ie. day, evening or night) or type of area (ie. mixed industrial, urban residential, sub-urban residential, rural etc.). Relative limits are limits which relate to a permitted level of noise change or a permitted level of noise increase above the existing background noise. Hybrid noise limits involve an element of both of these such as the ETSU-R-97 [2] UK limits commonly applied to wind turbine noise which relate to the existing background noise except for situations where background noise levels are very low, at which point absolute limits apply.

One of the unique factors of wind turbine noise assessment is that not only does the source noise level change with wind speed but the level of existing noise, in most cases, also changes with wind speed. As with most noise sources, the propagation of noise from source to receiver also changes with wind direction. The level of existing noise may also change with wind direction and the effect of wind direction may also depend on wind speed!

The most common approach for wind turbine noise assessment is either to compare the turbine noise with fixed noise limits under specific operational conditions (ie. at a fixed "reference" wind speed or at the rated power[1] of the turbine as is commonly used in continental Europe), or with hybrid noise limits related to a derived background noise level, or a fixed limit if background level is low, as is commonly used in the UK, Australia [eg.3] and New Zealand [4].

In the Netherlands, the assessment methodology has recently been changed to the use of a 47 dB yearly L_{den} criterion [5]. This does not, however, make any reference to the existing L_{den} prior to the site becoming operational. Although it is helpful, therefore, in terms of providing for an aggregate noise level once the variation in noise level with wind speed and direction is taken into account, it does not continue this approach to looking at the change in yearly L_{den} caused by the operation of the site. What is proposed here is a comparison of the L_{den} prior to, and subsequent to, the operation of the wind farm.

3. CALCULATION OF NOISE DOSE FROM A WIND FARM

In order to calculate noise dose with any degree of accuracy, access is required to a full year of wind speed and direction records, for consecutive intervals of maximum 1 hour duration, at the hub height of the proposed turbines. Where only sub-hub-height wind speeds are available, a reasonable approximation to hub height wind speed for each measurement interval may be calculated from two or more wind speeds at lower height. This can then be converted to "standardised" 10 metre height wind speed[2] as used by wind turbine manufacturers for the specification of sound power level data[3]. In this way the noise output from the turbine can be defined for each hour of the whole year of records or for shorter intervals if the data is available.

The noise output can then be combined with wind direction information, together with other propagation factors including geometric, atmospheric, ground and barrier attenuation as specified in an appropriate prediction algorithm such as ISO9613, Part 2 [6]. In this way, the noise levels for every hour (or less) of the whole year of records can be predicted and used to calculate the L_{den} over the whole year by adding 5 dB to predicted levels for wind speed measurement intervals falling during the evening periods and 10 dB for those falling during the night-time periods.

In the absence of the incorporation of wind direction information in the prediction algorithm used[4], it may be helpful to refer to the work of Wyle Laboratories [7] which suggests an upwind attenuation increasing from 0 dB at the edge of the shadow zone, taken as 5.25 x hub height, increasing linearly to 20log(f) – 30 dB at the point at which the shadow zone is fully formed, taken as 15.75 x hub height (Figure 2). A reasonable approximation to cross-wind propagation may be to apply an attenuation

1 The point at which the turbine is generating its specified power (eg. 2MW). Source noise level does not generally increase above the point at which it reaches rated power for pitch regulated turbines.

2 10 metre height wind speed converted from hub height assuming reference ground roughness conditions of z = 0.05m.

3 Where noise data is specified in terms of hub height wind speed this conversion is not required.

4 ISO9613-2, for instance, only predicts short term noise levels for "moderate downwind" conditions.

Figure 1. *Typical wind farm in UK.*

of 2 dB which relates more to the change in source noise level for cross-wind propagation. For any given wind direction, each wind turbine may be categorised as falling into downwind, upwind or crosswind propagation directions relative to the receiver location which is being evaluated. Any number of different receiver locations can then be evaluated with the result that a receptor located in the same direction as the prevailing wind from the site[5] will receive a significantly higher L_{den} than one located in the opposite direction, not only due to the greater statistical prevalence of those wind directions but also due to the higher wind speeds, and hence higher noise levels, for such wind directions.

4. CALCULATION OF PRE-WIND FARM NOISE DOSE

Measurements of "background noise level" are routinely carried out for wind farm noise assessment in the UK, Australia and New Zealand, where appropriate noise limits are usually derived from such measurements by assessing the typical background noise for different wind speed conditions and adding an allowed exceedance at each wind speed[6]. This is, in effect, a legacy from industrial noise assessment standards which commonly allow a similar 5 dB exceedance. It is relatively unusual, certainly in wind farm noise assessment, for the existing noise to be quantified in terms of the L_{Aeq} or L_{den} measurement index where a measure of background noise such as LA90 or LA95 is normally used. It is, however, possible for existing noise level to be specified in terms of the L_{Aeq} index as it varies with wind speed based on best fit curves to plots of measured L_{Aeq} values against hub height wind speed. The best fit curves effectively represent an average L_{Aeq} value, as it varies with wind speed for the corresponding times of day. These can be used to define a reasonable approximation to the corresponding hourly L_{Aeq}, in the absence of noise from the proposed wind farm, for each wind speed value as used for the calculation of the wind farm noise dose. If sufficient data is available it may also be possible to subdivide this data into various wind direction sectors. This can then be used to predict a reasonable approximation to the whole year L_{den} in the absence of the proposed wind farm, with the appropriate corrections to noise levels occurring during the evening

[5] ie. located to the north-east for a prevailing south-westerly wind direction.

[6] In the UK, for instance, noise limits are commonly set at 5 dB above this "prevailing" background noise at each wind speed except at very low background noise levels where a fixed limit applies.

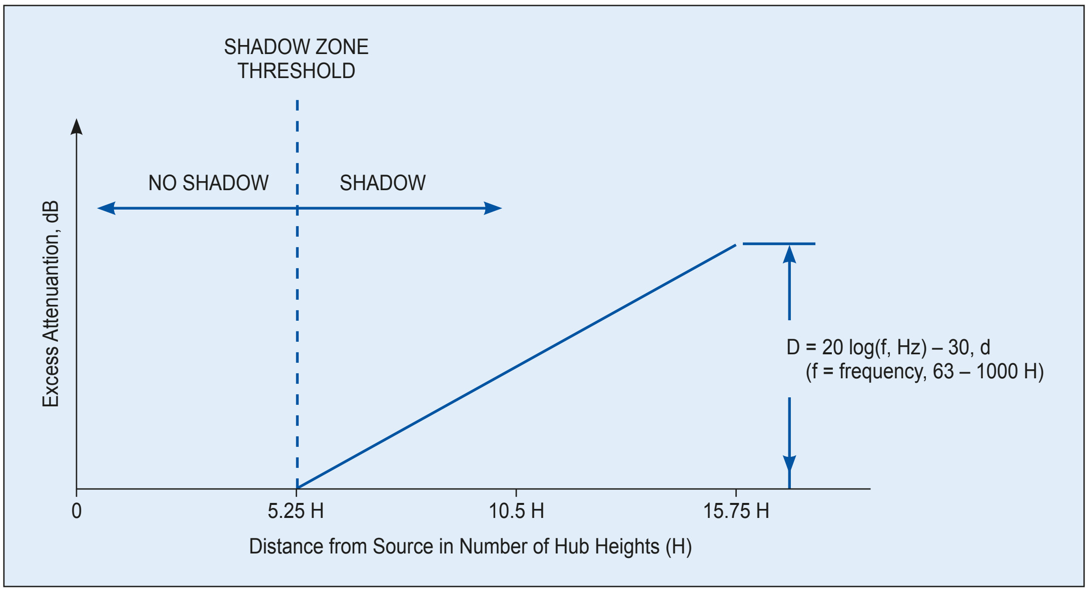

Figure 2. *Upwind Noise Propagation from [7].*

and night-time periods. It should be noted that this methodology does not allow the L_{Aeq}, as it varies through the day, evening and night periods to be taken into account. For situations where there is no variation in L_{Aeq} with wind speed, such as is likely to occur in more populated area where it would be expected to be more affected by non wind related sources, this could provide a variation to the approach proposed.

5. CALCULATED CHANGE IN NOISE DOSE

The above data can be used to provide the change in yearly L_{den} noise dose by comparing the dB addition of the post wind farm noise dose (ie. wind farm noise dose plus pre-windfarm noise dose) to the pre-wind farm noise dose. It could reasonably be expected that this would show a higher noise dose for properties subject to downwind propagation for more commonly occurring wind directions and higher wind speeds than those in other sectors, and a higher degree of noise dose change where a property is exposed to lower levels of existing noise, especially at night where higher levels of wind farm noise relative to background noise would be accentuated by the application of the 10 dB correction applicable to noise levels generated at night.

6. SUMMARY AND CONCLUSIONS

A method is proposed for strategic assessment of wind farm noise which takes into account the variation in wind speed and wind direction over a typical year of operation and the increased annoyance which may result from noise during the evening period and during the night. This is compared with noise from existing sources, quantified in a similar way. In this way an assessment of the existing noise dose, the proposed additional noise dose, and a comparison between the post and pre-development noise dose can be assessed for representative properties around a proposed wind farm scheme to provide a more comprehensive assessment than is provided by more traditional comparisons of worst case propagation conditions with absolute or relative noise limits.

REFERENCES

[1] Directive 2002/49/EC. The Environmental Noise Directive. European Commission, 2002.

[2] ETSU-R-97. Assessment and Rating of Noise from Wind Farms. ETSU for the DTI, 2006.

[3] Wind Farm Noise Guidelines. Environmental Protection Authority South Australia, 2009.

[4] NZS 6808, Acoustics-Wind farm noise. Standards New Zealand, 2010.

[5] M. Dijkstra and T. Kerkers, Continuous Noise Monitoring of Wind Turbines, 4th International Conference on Wind Turbine Noise, Rome 11-14 April 2011.

[6] ISO9613, Acoustics-Attenuation of Sound During Propagation Outdoors, Part 2 General Method of Calculation. International Standards Organization, 1996.

[7] Wyle Research Report WR 88/19. Measurement and Evaluation of Environmental Noise from Wind Energy Conversion Systems in Alameda and Riverside Counties. Wyle Laboratories, October 1988.

Acoustic and Audience Response Analyses of Eleven Venetian Churches

Davide Bonsi
Acoustics Laboratory of the Fondazione Scuola di San Giorgio in Venice, Italy

Braxton Boren
Music and Audio Research Laboratory, New York University, New York, USA

Deborah Howard
Faculty of Architecture and History of Art, University of Cambridge, UK

Malcolm Longair
Cavendish Laboratory, University of Cambridge, UK

Laura Moretti
School of Art History, University of St. Andrews, Scotland, UK

Raf Orlowski
Ramboll Acoustics, Cambridge, UK
Corresponding author: davide.bonsi@scuoladisangiorgio.it

PACS: 43.55.-n

ABSTRACT

This study brings together three approaches to characterising the acoustic properties of eleven Renaissance Venetian churches: (i) the audience response data derived from audience questionnaires, (ii) the acoustic characterization according to an experienced professional acoustician, and (iii) quantitative data on the acoustic characterization of the churches for different locations of the source and microphone. The average responses to the audience questionnaires agreed remarkably well with those of the professional acoustician. Correlations between these data are given quantitative substance by the acoustic measurements. Striking relationships were found between the audience assessment of reverberance and the measurements of the EDT and T30 indices, and between the perceived clarity and the measurements of the C80 index.

1. INTRODUCTION

This study of the interaction between music, acoustics and architecture in Renaissance churches in Venice is based upon a research project carried out at the University of Cambridge, U.K. over the last five years in which equal emphasis was placed on each of three key disciplines, architectural history, musicology and acoustics. The main questions to be addressed were:

- How far did architects consider acoustic needs when designing new churches in Renaissance Venice?
- How far were different types of churches adapted to the particular use of sacred music in the liturgy?
- How far did composers take account of the acoustics of church interiors when writing sacred music?
- How could complex polyphony be appreciated in churches with very long reverberation times?

This paper concerns principally the first two questions.

2. BACKGROUND

There was a remarkable flowering of architecture and music in Renaissance Venice during the sixteenth century. At the church of San Marco, *cori spezzati*, or split choirs, were probably introduced into Venice by composer Adriaan Willaert and later exploited by the Andrea and Giovanni Gabrieli and Claudio Monteverdi. The printing of music enabled compositions to be performed in many other churches. There were innovations in the architectural design of churches by the most eminent architects of the time, in particular, by Jacopo Sansovino and Andrea Palladio.

What did these architects know about acoustics and music? Sansovino and Palladio had many musical friends, some of whom were composers. Sansovino, for example, worked with Willaert, the *maestro di cappella* at San Marco, for 30 years and so they must have known each other well.

The above list of issues may be refined into a more specific set of questions in architectural and musicological history:

- To what extent did architects seek particular acoustic effects in the churches they designed?
- Did they discuss music matters with clergy and musicians?
- What did they know about scientific and practical acoustics?
- Was acoustics for speech taken into account?

These questions have been discussed in detail in the book *Sound and Space in Renaissance Venice* by two of the authors (Howard and Moretti 2009). Understanding of acoustics in the sixteenth century was largely based on the work of the Roman architect Vitruvius. For example, he stated that cornices are important for reflecting sound back into the interior. Palladio was a follower of Vitruvius and would have been familiar with his ideas. There was much discussion of ceiling types in Renaissance Italy. Some considered vaulted ceilings were difficult for speech saying that they caused too much reverberation. It was suggested that flat wooden ceilings with beams gave a better sound. The church of San Francesco della Vigna presents an interesting study of ceilings (Sect. 9). Another idea was that relief is important and that smooth dome surfaces cause too much reverberation. Yet another view was that niches in music rooms improved the quality of sound by interrupting reflections. These concepts have a strong resonance with current issues in auditorium acoustic design.

To address these questions, a research study was carried out integrating a detailed discussion of architectural design with musical performances of the repertoire of the period, together with comprehensive acoustical measurements. Following an initial conference in 2005 in Venice (Howard and Moretti 2006) and a second meeting in Cambridge in 2006, eleven churches were identified for detailed investigation, San Marco, two monastery churches, three friaries, three parish churches and two hospital churches. Sansovino's surviving churches were included, as well as Palladio's two Venetian masterpieces, San Giorgio Maggiore and the Redentore.

The responses of the audiences to the music they heard using questionnaires to quantify their subjective impressions are analysed in Sect. 4. The determination of the acoustic properties of the churches for different locations of the sound source and the listener and the analysis of these data are described in Sect 5. The correlations between the subjective audience data and the acoustic data are discussed in Sect. 6. The effects of different acoustical spectra are discussed in Sect. 8. The churches were specifically selected to provide representative examples of the complete range of acoustic environments from the largest and most magnificent buildings to modest parochial churches.

3. THE CHORAL AND ACOUSTIC EXPERIMENTS

The week of choral experiments carried out in April 2007 in the eleven Venetian churches was the culmination of a two-year period of preparatory investigations. An extensive programme of choral experiments was undertaken in each of the churches. The choir of St John's College, Cambridge was chosen because of its recognised excellence in the performance of sacred music and the ability of the singers to perform complex Renaissance polyphony at sight. The choir consisted of fifteen male choral scholars and seventeen boy choristers with two organ scholars (Fig. 1). The director was David Hill, then Director of Music of the St. John's choir.

The purpose of the choral experiments was to enable subjective evaluations to be made, comparing different musical styles, varying choral forces and different relative positions of the singers and listeners. A detailed description of all the experiments is given in Howard and Moretti (2009) and recordings of those discussed in the book are available at www.yalebooks.co.uk/soundandspace —all the tracks were used for later study in suitably equipped acoustic laboratories—. The subjective evaluations were made by the audience, as well as the researchers and singers. The music performed by the choir was selected by musicologist Iain Fenlon and architectural historian/ musician Laura Moretti, in consultation with those who took part in the symposia of 2005 and 2006, as well as with David Hill. The choice of music was informed by these musicological historical researches, with particular emphasis upon the spatial separation of the choirs which relates to the emerging tradition at the time of split choirs.

4. AUDIENCE RESPONSE DATA

The experiments had been widely advertised in Venice and an open invitation given to all who might be interested in participating as an audience. One of the authors (RO) made available the questionnaire which is used professionally in assessing the qualities of different acoustic spaces. This questionnaire has been developed

Figure 1. Members of the choir of St.John's College, Cambridge, which participated in the musical experiments, performing Giovanni Gabrieli's fifteen-part Jubilate Deo in the chancel of the Redentore.

over many years and has been used to test the acoustic properties of concert halls in the UK and world-wide. It has been shown to be a robust means of assessing the different qualities of acoustic spaces for trained listeners (Barron 1988). Barron's procedures and analysis built upon the earlier pioneering studies of Schoeder (1974). More recent examples of the application of this approach to the subjective study of the acoustics of churches, concert halls and rooms include the papers by Soulodre and Bradley (1995), Martellotta (2008) and Lokki *et al.* (2012). Martellotta's paper specifically concerns the acoustics of Italian Catholic churches.

The questionnaire was slightly modified to take account of the Venetian context and included both the questions themselves and an explanation of the different acoustic qualities for non-specialist listeners (see pages 206-7 of Howard and Moretti (2009)). The questions concerned most of the standard qualities discussed by Beranek (2003) and were: "Loudness", "Clarity", "Reverberance", "Envelopment", "Intimacy", "Warmth", "Brilliance", "Echo", "Timbre", "Background Noise" and "Overall Impression of Acoustics".

The audience was invited to fill in the questionnaires for one specific piece of music in each church. They also indicated their listening positions on plans of each church so that variations in audience response according to location could be assessed. Fig. 2 shows the locations of listeners who completed the questionnaires for San Marco. There was no time to give the audiences any training, but each sound quality had a verbal description on a scale from 1 to 10 so that even an untrained audience member could distinguish between, for example, `muddy' and `clear' in response to the question about clarity. Many

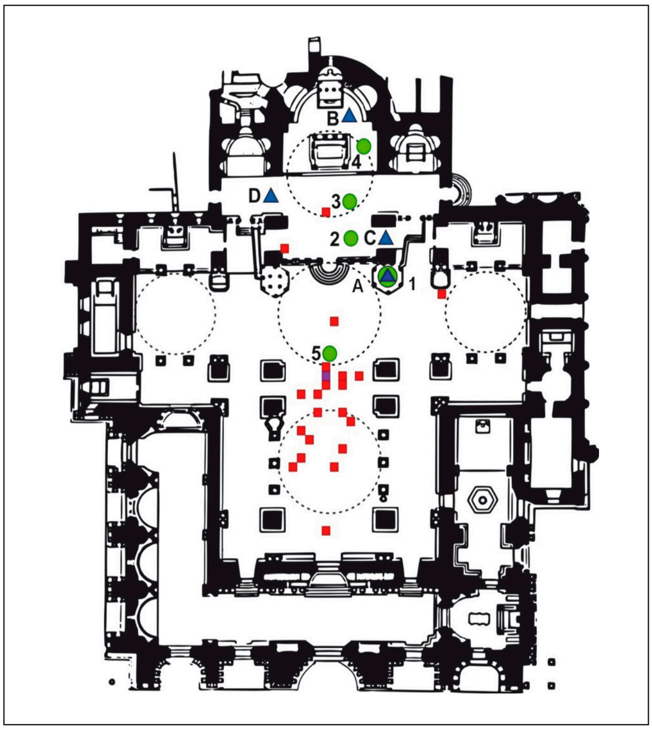

Figure 2. A plan of the church of San Marco showing: red square —position of a member of the audience who completed a questionnaire; purple square— location of RO; blue triangle —location of acoustic measurement source, identified by letters; green circle —position of acoustic measurement microphone, identified by numbers. Note that: positions A and 1 are in the bigonzo, slightly raised, position C is in the right pergola in the chancel and position D is the organ gallery, high above the left side of the chapel.

also had a deep commitment to the project since they had attended the earlier conferences, or were relatives of the choir members, or were choir members "off-duty". Members of the public, such as local parishioners and visitors to Venice, also attended individual sessions; others were professional architects or musicians from the general public. Generally, about 20 to 40 completed questionnaires were obtained for each church. RO provided his own set of scores for each church and these are compared with the audience responses in Sect. 4.2.

4.1. Analysis of the Audience Response Data

The first question to be addressed is whether or not, given the untrained audience, the responses to the questionnaires contain useful data. It was clear from the questionnaires that the audience had done their best to provide good assessments and helpful comments. As might be expected in such an exercise, there were a few anomalous scores. All the data were used in the initial analysis and statistical procedures employed which were not sensitive to rogue data (see Sect. 4.2).

Key issues concern how representative the data are for the purposes of our analysis and the biases and selections effects which could affect our conclusions. Although the vast majority of the questionnaires were not completed by trained experts, we are convinced that the audiences made every effort to provide the best judgements they could. Because of the limited time availability for experimenting in the churches, it was not always practical to use the same test piece, but all the examples tested had similar degrees of polyphonic complexity and numbers of singers.

An important issue was that the responses were expected to vary from one part of each church to another, but in practice, the audience tended to cluster in the main bodies of the churches, as illustrated by the red squares in Fig. 2. Correlation diagrams were drawn for all the acoustic qualities against position along the axes of all the churches. There was no evidence for any significant variation of the qualities with position within each church, except for a weak correlation in the case of the Frari, which can be attributed to the different listening experiences in the chancel and the main nave (see Howard and Moretti 2009, Appendix 2, The Frari). All the data were therefore plotted as histograms for each quality for each church. Examples of the audience response data for the qualities "Loudness" and "Clarity" for the Ospedaletto and the Redentore are shown as histograms in Figs. 3(a) and (b).

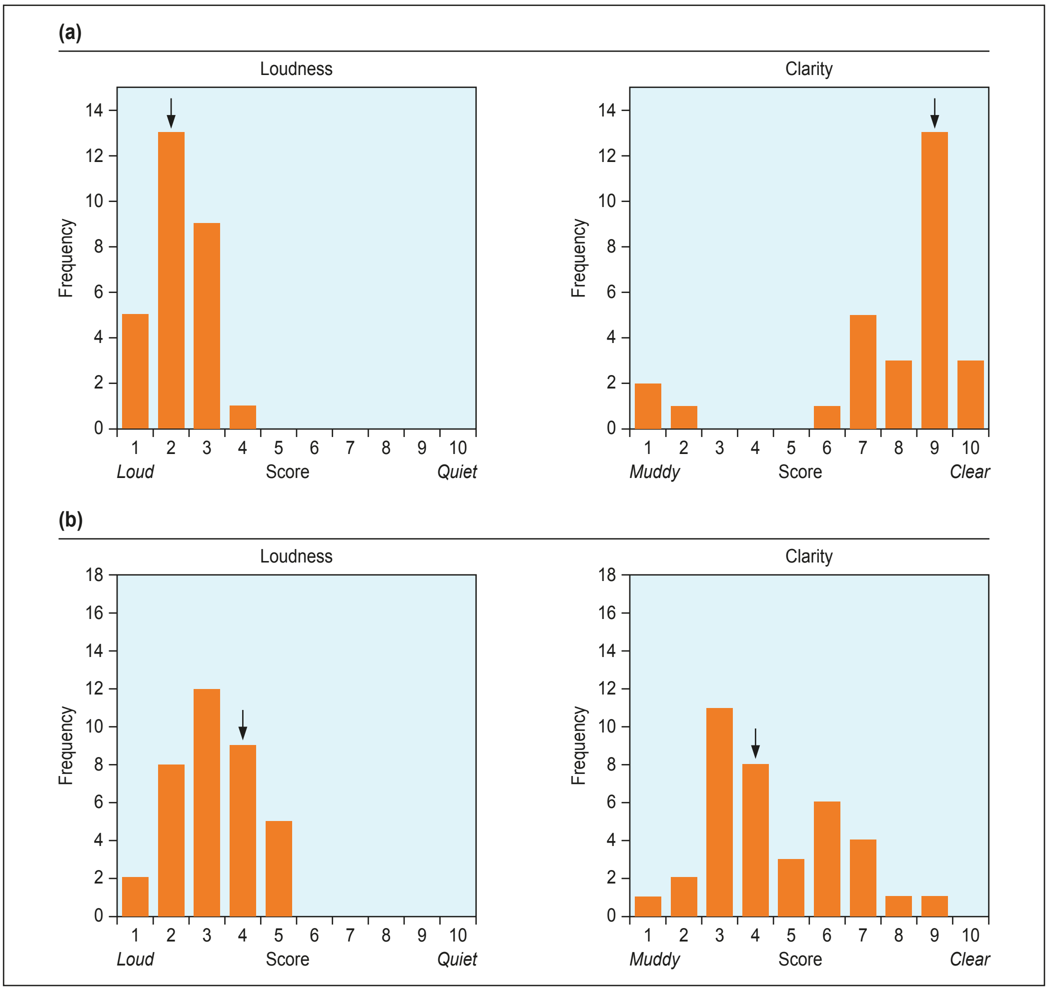

Figure 3. (a) Audience response data for the qualities "Loudness" and "Clarity" in the Ospedaletto. (b) The same data as in (a) for the Redentore. In both cases, the arrows indicate the assessments of RO.

On each histogram, the arrows indicate the assessments of RO, which are regarded as reference values. It is apparent even without carrying out a statistical test that there are real data in the histograms. For example, there were clear differences in “Clarity”, “Reverberance”, “Timbre”, “Brilliance” and “Overall Impression” between the Ospedaletto and the Redentore. Furthermore, with some notable exceptions, the average scores of the audience were not so different from those of RO. Even with trained listeners, there are often discrepancies of one or two between scores for the same acoustic experience. Where there are disagreements between the assessments of the audience and RO, these are almost certainly because the audience was unsure about what they were being asked to assess —this applies particularly to the quality “Echo” (see Sect. 4.2)—.

4.2. *Quantitative Analysis of the Audience Response Data*

To make the comparisons quantitative, medians and interquartile ranges (IQR) were used rather than means and standard deviations, which are much more sensitive to outliers in the data. Each quality was scored on a scale of 1 to 10. If the data were random, corresponding to the same frequency of the scores from 1 to 10, the median would be 5.5 and the interquartile range 5. Medians and IQRs were worked out for all the qualities for each church; these data, as well as the scores of RO, are presented in Table I of Appendix 1 of Howard and Moretti (2009).

Inspecting the histograms for the Ospedaletto, for example, the “Loudness” histogram shows clearly that the audience agreed that the music was loud. The median is 2 and interquartile range IQR = 1, clearly very much less than 5. In the case of the “Clarity” histogram, the median is 9 and the IQR = 2, despite the three outliers which have discrepant values compared with the bulk of the data. In these cases, the median scores of the audience and those of RO are in excellent agreement.

How well did the audience responses agree with those of RO? It was first necessary to establish which of the histograms contained data which were too scattered to provide reliable information. The average IQR values for each quality for all the churches were ranked, 1 having the smallest value of the IQR and 11 the largest —“Echo” (mean IQR = 3.64) had the greatest scatter while “Loudness” (mean IQR = 1.43) had the smallest—.

In the case of “Echo”, RO scored no echo for almost all the churches, since he required there to be a definite repetition of the sound to constitute a true echo. In contrast, the audience scored essentially the complete range of values between 1 and 10 for “Echo”. The likely source of the confusion is that the audience interpreted “Echo” as being the same as “Reverberance”. This is supported by the very strong anti-correlation between “Echo” and “Reverberance” shown in Fig. 4 for the median values of these qualities for each church. It is therefore reasonable to exclude the “Echo” scores from the comparison of the audience and RO.

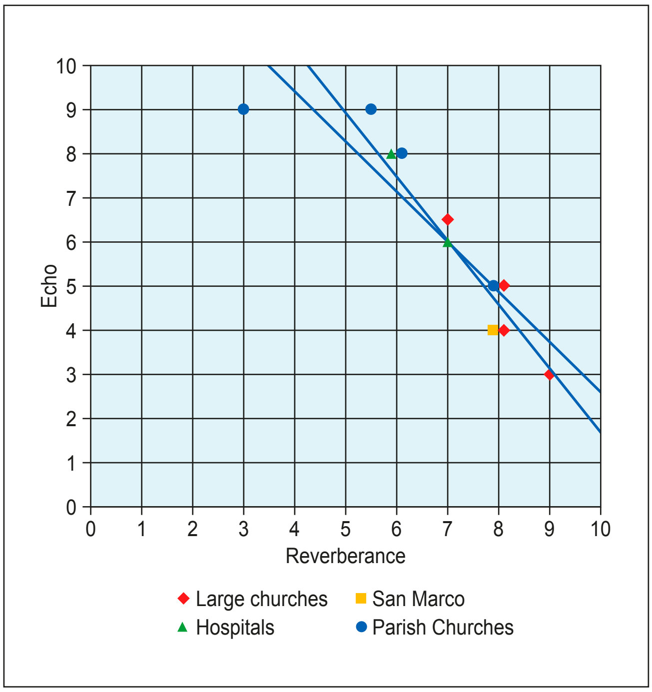

Figure 4. *A plot of the average perceived “Echo” against average perceived “Reverberance”, according to the audience responses for all eleven churches. The blue lines are the regression lines of y against x and x against y, showing the very strong anti-correlation. The correlation coefficient r = –0.88.*

Excluding the “Echo” data, the median scores for the audience are plotted against RO’s scores in Fig. 5. The 105 data points are in the form of integral or half-integral values and so the points often fall on top of one another. The convention has been used of plotting the size of the data point on the grid roughly proportional to the number of scores, the key to the number of scores being shown beside the diagram —there were 12 occasions on which the audience and RO agreed on the score 7—. There is clearly a very significant linear correlation between the two sets of scores. To test the strength of the correlation, the two linear regression lines of *y* against *x* and *x* against *y* are shown in Fig. 5 as blue solid lines. A best-fit line bisecting the two regression lines would lie very close to a 45° line which is shown as a dotted line corresponding to perfect agreement between the audience and RO.

Another way of comparing the audience scores with those of RO is to plot a histogram of the differences

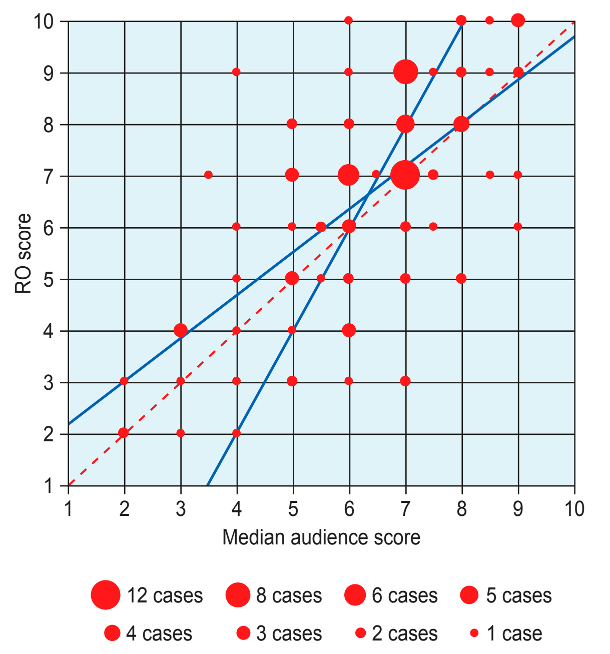

Figure 5. Plot of the mean audience response against RO's scores excluding only the "Echo" scores. The correlation coefficient is r = 0.66.

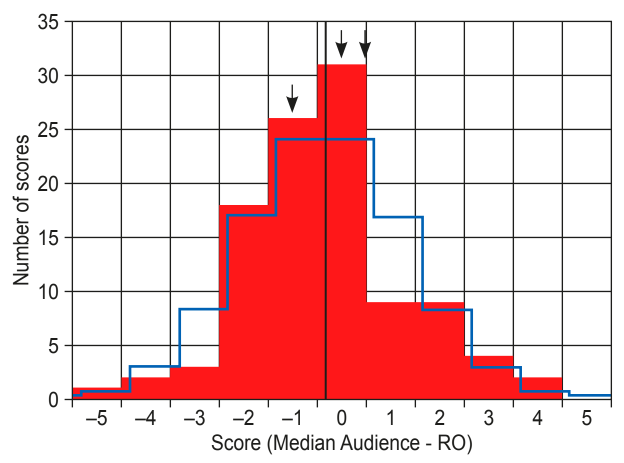

Figure 6. A histogram showing the difference between the median audience score and that of RO for 105 data points. The downward pointing arrows show the lower quartile, median and upper quartile of this histogram. The vertical black line shows the mean of the distribution and the blue histogram the expected Gaussian (or normal) distribution for the measured standard deviation of the data.

between their scores for the 105 data points in Fig. 5, that is, excluding the "Echo" scores. In Fig. 6, the median of the histogram is zero and the interquartile range 1.5 units, as indicated by the downward pointing arrows. As expected according to the Central Limit Theorem, the distribution tends towards a Gaussian, or normal, distribution. The histogram can be compared with the expectations of a normal distribution. The mean of the solid (red) histogram is -0.295 units and the standard deviation 1.64 units. For the 105 data points included in Fig. 6, the expected distribution of scores about the value -0.295 is shown as a blue histogram. There is reasonable agreement between this estimate and the experimental data, given the relatively small numbers involved. The data are somewhat more "peaky" than a Gaussian distribution, but this is not unexpected since the data included large IQRs for qualities such as "Envelopment" and "Warmth". The analysis was repeated excluding these qualities from the sample, but the results were not significantly different.

As expected, the inferred standard deviation for an IQR of 1.5 for a normal distribution, 1.1, is less than the value of 1.64 found for Gaussian statistics since the latter gives more weight to points more distant from the mean. The median audience scores are within 1.5 units of those of RO in 63 % cases, which is not dissimilar from the figure of 68 % expected within 1 standard deviation of a normal distribution.

Figs. 5 and 6 show clearly that the average audience scores can be helpful in assessing the qualities of the churches, despite the fact that they had not been trained. As noted above, even professionally trained acousticians typically have a difference of one unit in their scores. This agreement also indicates that there are not likely to be serious biases in the data. The data can be used to determine which qualities provide the best discriminators between the acoustic properties of the churches. In order of increasing values of IQR, the best discriminators are "Loudness", "Reverberance", "Background Noise", "Timbre", "Overall Impression", "Intimacy", "Clarity", "Brilliance", "Warmth" and "Envelopment".

We conclude that the audience response data contain real information about most of the perceived acoustic properties of the churches and these can be compared with objective acoustic characterisations of the buildings.

5. THE ACOUSTIC CHARACTERISATION OF THE CHURCHES

The acoustic characterisation of the churches was carried out using a vectorial Microflown® probe (De Bree 2003) which enables both the pressure impulse response and the velocities of the air particles to be measured simultaneously in three perpendicular dimensions. The analysis presented here refers only to the pressure-based indices: G_{rel}, EDT, T15, T30, C80, D50 and Ts were determined for different source-detector positions within the churches. Note that G_{rel} rather than G has been used since these measures are not absolute, but relative to the intensity at the shortest distance between the source and microphone positions for a particular church.

Two of the authors (DB and LM) supervised the acoustic characterization measurements over a period of a year before the experiments with the choir. The combinations of source and microphone positions were agreed on the basis of historical relevance for the relative positions of singers and audience - these included singer and audience locations in choir stalls, side chapels and main naves. Experiments were carried out for ten of the eleven churches for which permissions were granted, only San Michele in Isola being omitted because of its impending restoration. The details of the locations of the sources and microphone positions are included in Appendix 2 of Howard and Moretti (2009).

The acoustic parameters were derived in octave bands centred on 62.5, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz, as well as for the overall acoustic signal - for most of the present analysis, attention has been devoted to the acoustic parameters for the overall acoustic signal. The parameters of most interest for this study are the standard quantities, the early decay time (EDT), the decay times T15 and T30 and the clarity index (C80).

Perhaps the most revealing diagrams are the plots of the early decay time (EDT) summed over all frequencies against T15 and T30. If the signal decays as a pure exponential, EDT = T15 = T30. The case EDT < T15 < T30 corresponds to rapid initial decay of the signal followed by a long tail which decays with an increasing time constant. This type of behaviour is found in large spaces where the source and microphone are quite close together. The early decay time measures the decay of the sound in the local space, whereas T30 measures the response of the much larger volume of the acoustic space.

5.1. The Overall Picture

The overall picture of the acoustics of all the churches is most easily appreciated from the plots of EDT against T15 (Fig. 7(a)) and EDT against T30 (Fig. 7(b)). The values of EDT, T15 and T30 are plotted for all the combinations of source and microphone position which were measured in each church. The data have been coded by different symbols (and colours) as indicated on the diagrams. A pure exponential decay would be represented by a diagonal line at 45° joining the points (0,0) to (8,8). Fig. 7(a) shows that the EDT is always very closely linearly proportional to T15, which is still sampling the early decay of the sound signal. In general, the EDT and T15 are short for the small acoustic spaces, while for the large churches, the EDT can be up to 7 seconds.

The only cases of short EDTs and T15s in large churches were for small confined spaces within the larger volumes, seven of them having values of EDT less than two seconds (red diamonds). Two are associated with the friars' choir in the Redentore, two

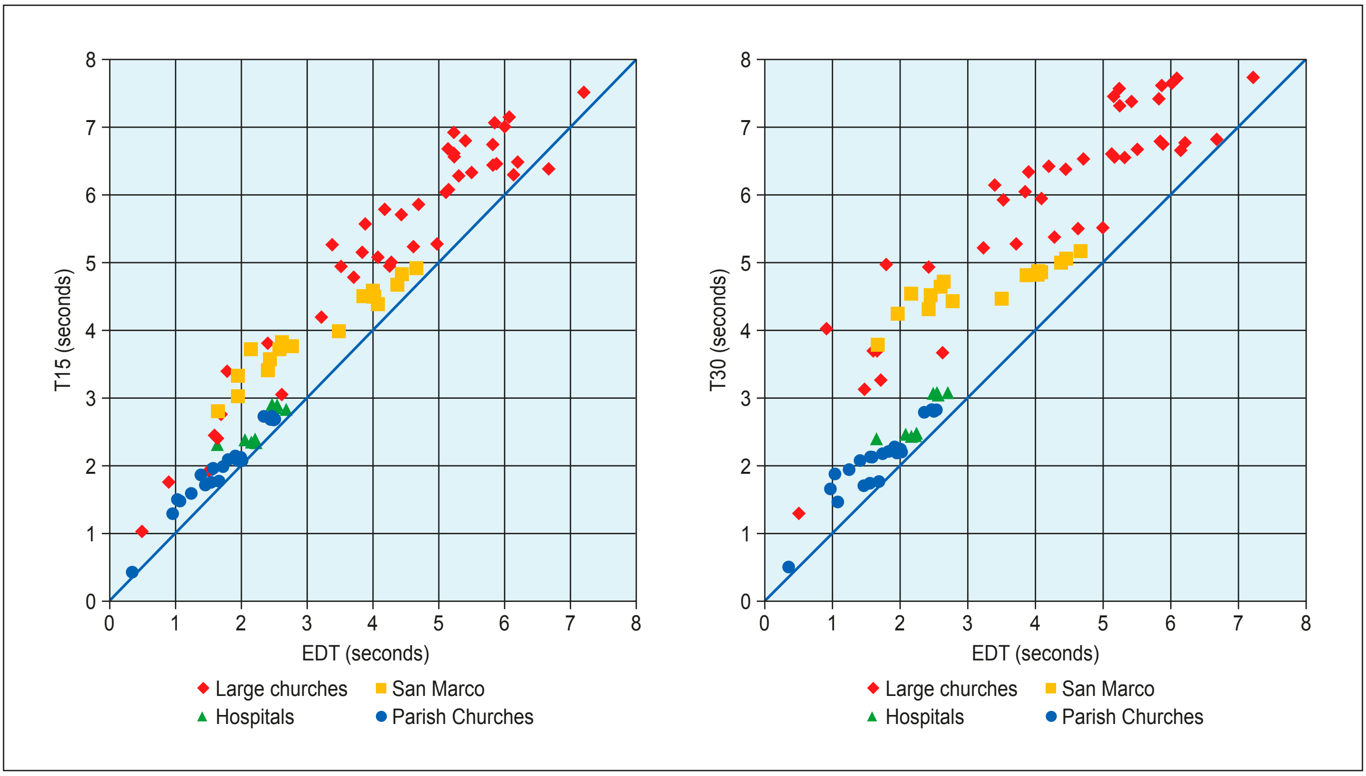

Figure 7. *(a) A plot of T15 against EDT for all ten churches and all combinations of source and microphone positions for which data were taken. (b) The same plot as (a) for T30 against EDT for all ten churches. In both diagrams, a 45° line is shown.*

are associated with measurements in a small chapel in the transept of the Frari, one is associated with the monks' choir in San Giorgio, and one with the friars' choir and one with a side chapel in San Francesco della Vigna. In all these case the sources and microphones were located within the friars' or monks' choirs or small chapels which had very much smaller acoustic volumes than the churches. The values of EDT and T15 are similar to those found in the parish churches. Note also the three cases of short EDTs for San Marco (orange squares) - two of these are from the south *pergolo* to locations within the chancel (C2 and C3) and one from the high altar to the centre of the chancel (B3).

In Fig. 7(b), EDT is plotted against T30 and there is a very much larger spread in the data away from the 45 degree line, particularly for the large churches and San Marco. The values of T30 are much larger than those of the EDT, indicating that, even if the EDT is short, which would result in good clarity, the sound decays with a longer time constant in the larger volume of the acoustic space. This is also found for most of the small volumes within the large churches, which are indicated by red diamonds with EDTs less than 3 seconds. The only case in which this was not observed was in the chapel in the Frari, the source and the microphone both being located well within the chapel and not acoustically coupled to the very much larger volume of the church.

5.2. The Small Churches

Figs. 8(a) and (b) show separately the small churches, each being given a different symbol and colour code. In Fig. 8(a), the points all lie close to the 45° line and are strongly clustered. The implication is that, for the small churches, it does not greatly matter where the source and receiver are located —they always sample the same acoustic volume—. This is particularly noticeable for the experiments carried out in San Lazzaro dei Mendicanti, San Martino and Santa Maria dei Derelitti (Ospedaletto). Even in the plots of EDT against T30 in Fig. 8(b), the points are still strongly clustered and not far above the 45°. In fact, for the small churches, the acoustic performance can be well characterised by a single number, which could be either the EDT, T15 or T30.

5.3. The Large Churches

The symbol and colour coding of the large churches show that they are also clustered. In Fig. 9(a), in which T15 is plotted against EDT, the points lie somewhat above the 45° line, but the early time behaviour is still being sampled. In contrast, in Fig. 9(b), the plot of T30 against EDT shows a clear "striation" —the points for a particular church tend to have similar values of T30, independent of the EDT—. In fact, to a good approximation, the churches can be characterised by the value of T30, which separates the

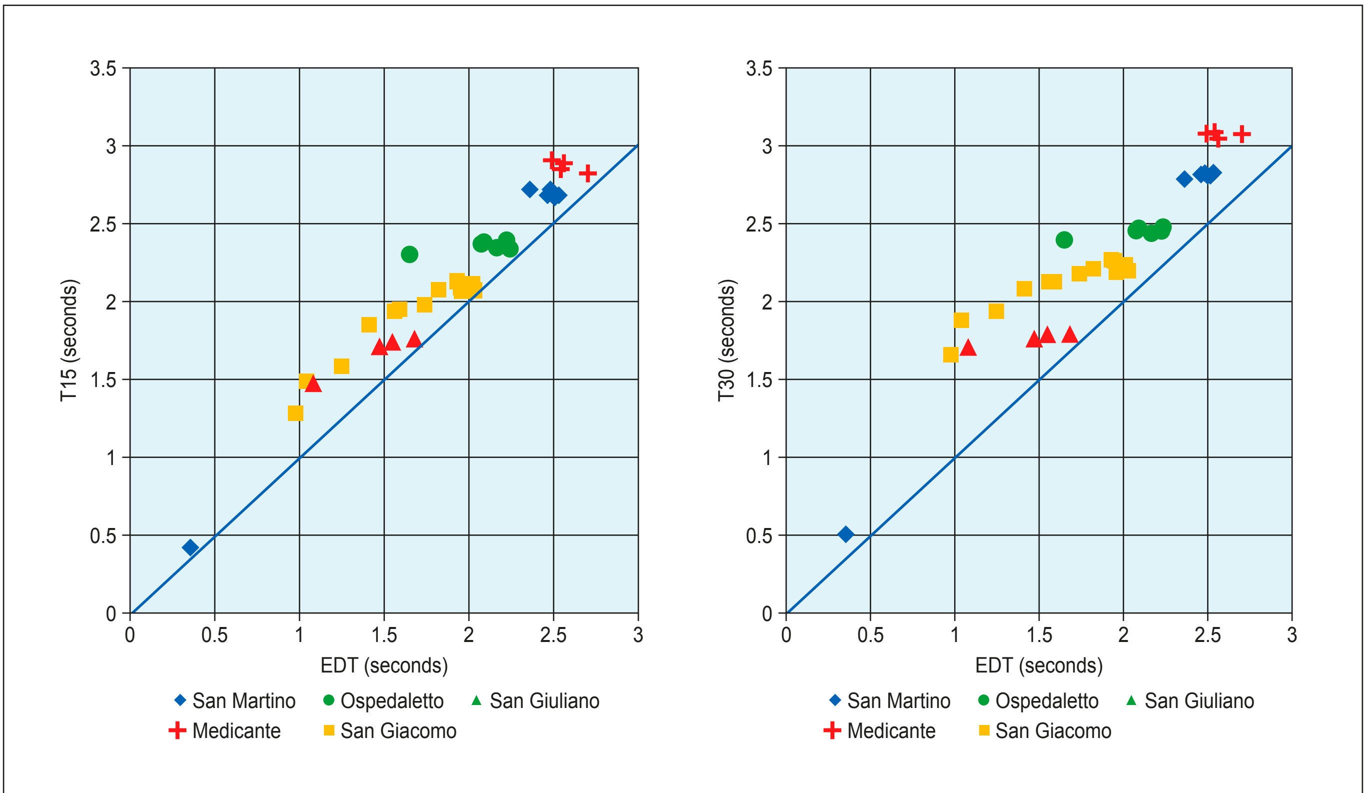

Figure 8. (a) A plot of T15 against EDT for five small churches and all combinations of source and microphone positions for which data were taken. (b) The same plot as (a) for T30 against EDT for the five small churches. In both diagrams, a 45° line is shown.

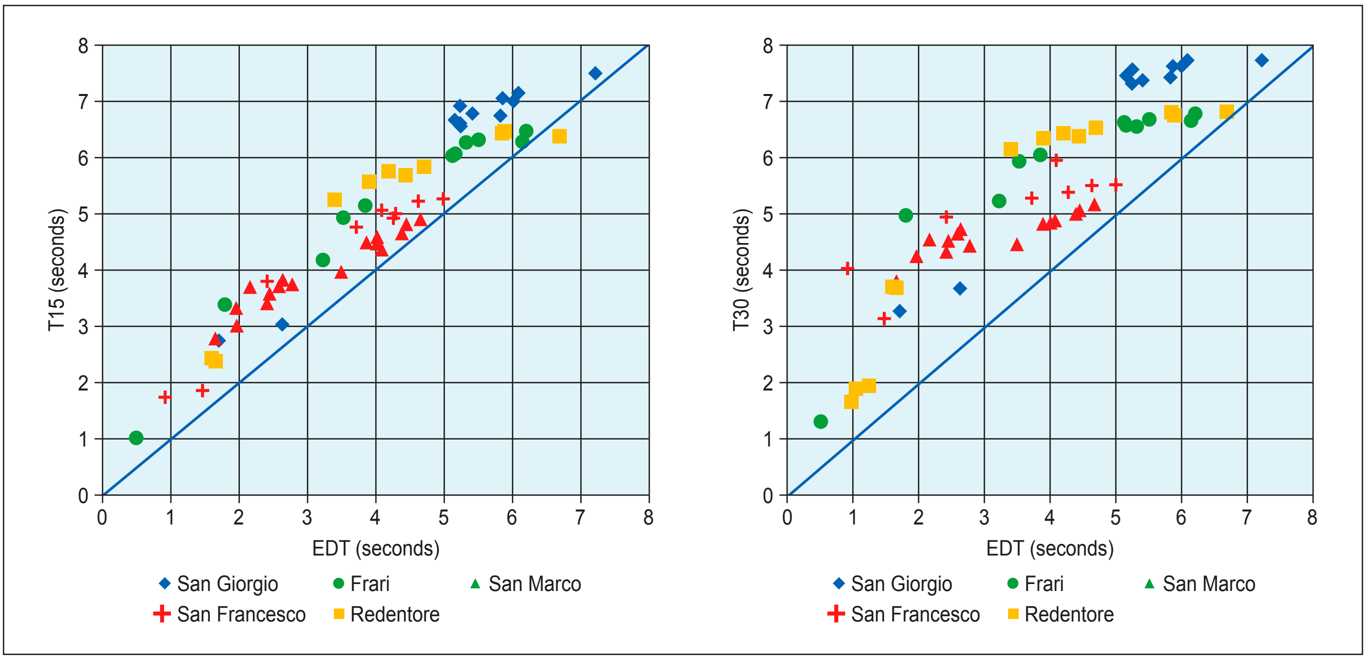

Figure 9. *(a) A plot of T15 against EDT for five large churches and all combinations of source and microphone positions for which data were taken. (b) The same plot as (a) for T30 against EDT for the five large churches. In both diagrams, a 45° line is shown.*

different symbols rather clearly. T30 characterises the overall acoustic volume which is always more or less the same. Consequently, there will always be a long "afterglow" accompanying the musical signal even if the EDT and clarity indices indicate an acoustic suitable for complex and fast music.

The non-linearity of the acoustic responses, as indicated by the differences in the correlations between EDT and T15 and T30 for the large churches, can be attributed to a number of factors. These include the coupling of large and small acoustic volumes, the presence of lateral naves and apses and other geometrical/acoustical factors. The first of these possibilities is explored in more detail in a forthcoming paper (Boren, Longair and Orlowski 2013).

6. COMPARISON OF THE RESULTS OF THE AUDIENCE QUESTIONNAIRES AND THE QUANTITATIVE ACOUSTIC DATA

The most striking correlations between the results of the questionnaires and the quantitative acoustic data are the comparisons of the subjective estimates of reverberance and clarity with the T30 and C80 indices respectively. The source-microphone positions were selected to be as close as possible to the singers-listener locations in each case.

Fig. 10 shows the remarkably strong correlation between the T30 index and the average perceived reverberance for the ten churches. The hospitals and parish churches have the shortest reverberance while

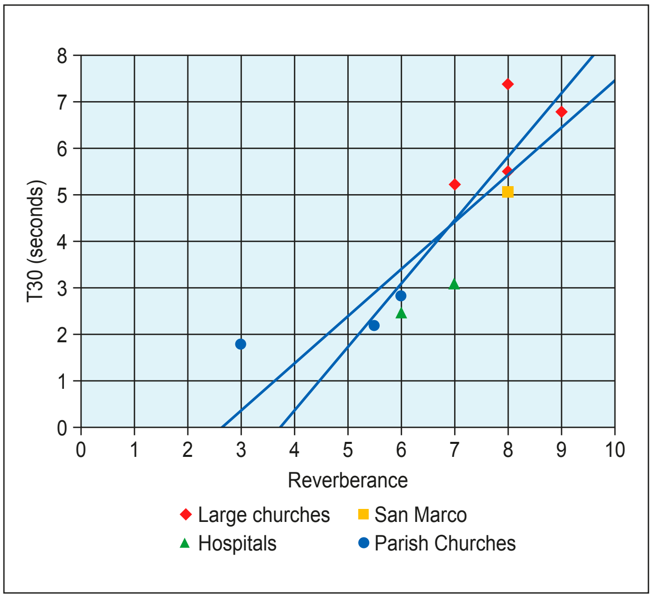

Figure 10. *Plot of T30 against average perceived "Reverberance". The blue lines are the regression lines of y against x and x against y. The correlation coefficient is r = 0.87.*

San Marco and the monasteries and friaries have the longest reverberances, both perceived and measured. This diagram also quantifies what it means to have a short or long reverberance in these churches. A listener in the nave of a large church typically experiences a reverberation time of 5 to 8 seconds. In the earlier study of organ music in San Giorgio Maggiore, the audience estimated subjectively a mean reverberation time of 4 seconds (Howard 2006) compared with a value of T30 between 7 and 8 seconds. This difference can be attributed to the fact that the acoustic parameters are extrapolated to -60 dB which is below the level at which the untrained audience would probably have been able to perceive the decay of the sound.

Fig. 11 shows a clear correlation between the clarity index C80 and the subjective estimates of the clarity by the audience. The rules for acceptability of the acoustics for concert halls have also been plotted in Fig. 11. These support the trend of the data that the hospitals, in particular, have good acoustics for complex music while the monasteries generally do not. The one exception is the combination A4 in the Frari ("Clarity" = 8, C80 = 0.8 dB). In this case, the audience was located in the choir which formed a much smaller "church within a church" with good clarity.

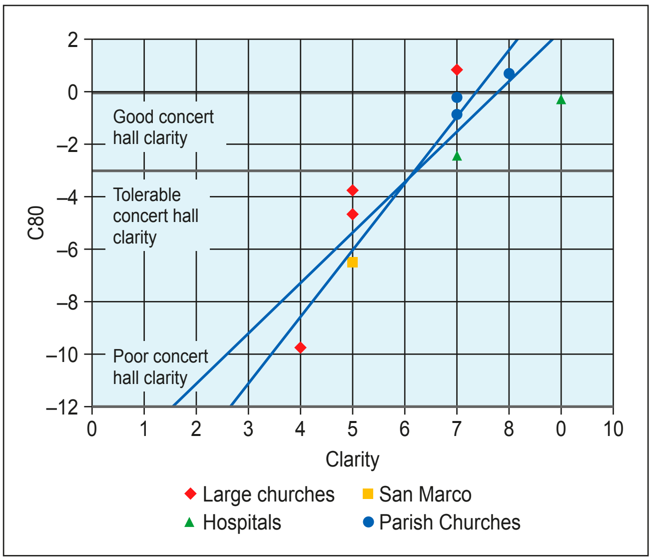

Figure 11. *Plot of C80 against perceived clarity. The blue lines are the regression lines of y against x and x against y. The correlation coefficient is r = 0.89.*

7. THE BEST LISTENING POSITIONS IN THE CHURCHES

The Reverberation Time and EDT analyses give an overall picture of the acoustic properties of the churches, but within any given church some locations have much better acoustics than others. To estimate the best combinations of source and listening positions, each of the acoustic parameters for a particular church has been ranked, with 1 as the highest rank, 2 the next highest rank and so on. For the purposes of this project, the priority is "Clarity" of the acoustic so that the complexities of polyphony and the stereophonic effects of *coro spezzato* can be heard to best effect. Therefore, the following empirical rules have been adopted:

- For G_{rel}, the louder, the higher the rank;
- For EDT and T30, the shorter the time, the higher the rank;
- For C80 (Clarity Index), the larger the value, the higher the rank;
- For D50 (Definition Index), the larger the percentage, the higher the rank;
- For Ts, the shorter the time, the higher the rank.

The rankings for each church are presented in Appendix 2 of Howard and Moretti (2009).

The acoustic data for all the tested combinations of source and microphone positions showed a good degree of consistency between the rankings of the different parameters for each position. All the ranks for a particular combination of source and microphone positions were then averaged and these averages ranked again. For San Marco, for example, three of the best four combinations involve the singers being located in the south *pergolo* (C2, C3, C1) (see Fig. 2) and the listeners in the chancel. The top-ranked combination of source and listener locations (C2) corresponds to the choir being in the south *pergolo* and the listener in the position of the Doge within the chancel. Of the five lowest ranked combinations of source and listener, four involve the listener being in the nave (D5, B5, C5, A5) where there was low "Clarity" and long EDT and Reverberation Times. These objective assessments are consistent with the experience of listeners who registered almost "perfect" acoustics in the chancel and a much poorer musical experience in the nave. It was almost as if there was a "church within a church".

These results have a significant bearing upon the history, architecture and music of the period. The Doge in the first part of the 16th century, Andrea Gritti, became too overweight and unwell to take his place in the elevated pulpit known as the *bigonzo* (location A,1) and moved his position into the chancel (location 2). Willaert, the *maestro di cappella* at that time, was promoting the new musical genre of *coro spezzato* (split choir) and it has been suggested by one of the authors (Moretti 2004) that he collaborated with architect Sansovino to construct the two balconies, known as *pergoli*, on either side of the chancel to accommodate the split choirs. Given the excellent acoustic qualities of the C2 combination, this suggests that the composer and architect may well have collaborated to provide a very high quality acoustic environment for a new musical genre, but restricted to the location of the Doge and his entourage.

A similar analysis has been carried out for all the churches for which acoustic data was obtained and these are included in Appendix 2 of Howard and Moretti (2009).

8. THE FREQUENCY SPECTRA AND RESPONSES TO THE QUESTIONNAIRES

There are differences in the frequency dependences of these parameters for the different types of churches, as is apparent from a comparison of the frequency dependence of, for example, the EDTs for large churches such as the Redentore and small churches such as San Martino. These are shown for typical listening positions in the naves in Figs. 12(a) and (b). In the Redentore, the EDT in the frequency range up to 1000 Hz is about 8 seconds, whereas at high frequencies, 4000 Hz, the EDT is only 4 seconds. This contrasts strongly with the case of San Martino in which the EDT up to about 1000 Hz is about 3 seconds, whereas at high frequencies it is 2.3 seconds.

Inspection of the spectral data for all the churches shows that the EDT, T15 and T30 all have essentially the same frequency dependence within a given church -- these data are given in Table 4 of Appendix 1 of Howard and Moretti (2009). To quantify the difference in decay times the treble ratios, defined as TR = [EDT(2000 Hz) + EDT(4000 Hz)]/[EDT(500 Hz) + EDT(1000 Hz)], were evaluated for each church at typical listening positions and these are plotted as a histogram in Fig. 13 in order of increasing treble ratio.

There is a systematic trend for the large churches to have low values of the treble ratio and the small churches high values. Although the treble ratios range only from 0.4 to 0.9, this corresponds to a huge

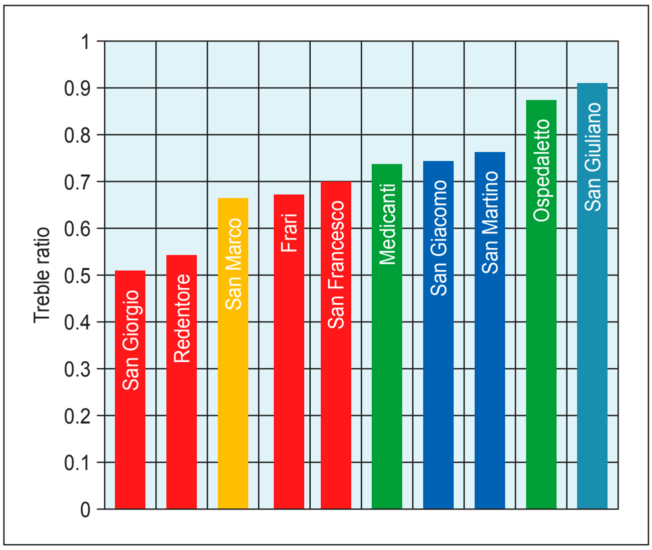

Figure 13. The treble ratio for the 10 churches. The data have been ordered in increasing value of the treble ratio.

difference in the perceived sound since the numbers are exponential decay constants as a function of frequency. As is well-known, the increase in the treble ratio with the volume of the church is due to molecular absorption of sound by air molecules.

The treble ratio has been correlated with all the subjective parameters derived from the questionnaires and some significant correlations were found. In Figs. 14(a) and (b), the mean scores for “Clarity” and “Brilliance” are plotted against treble ratio. The correlation between reverberance and treble ratio is

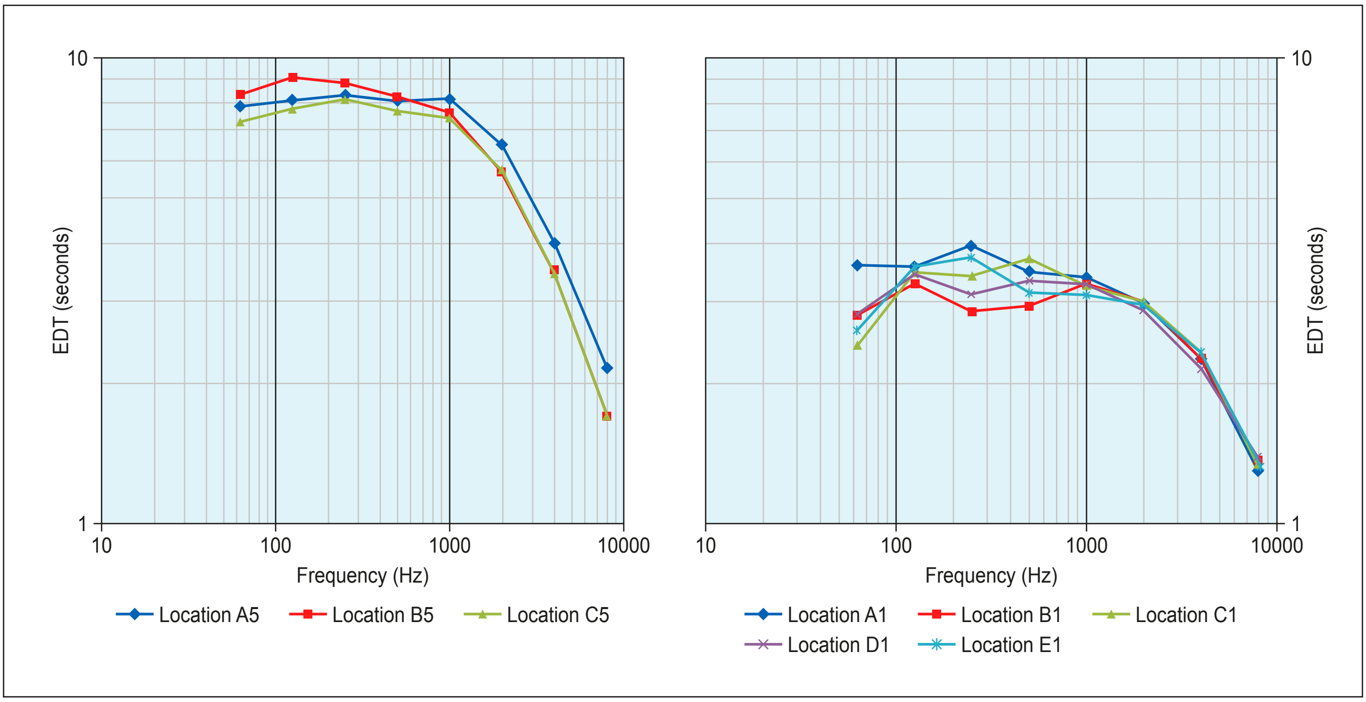

Figure 12. (a) EDT as a function of frequency for listeners in the nave of the Redentore at locations A, B and C. (b) EDT as a function of frequency for listeners in the nave of the San Martino at locations A, B, C, D and E.

probably associated with the underlying correlation of reverberance with the size of the churches. The correlation between treble ratio and perceived clarity (Fig. 14(a)) suggests that there is improved clarity if the high frequencies are present. There is some evidence that brilliance increases with the presence of the high frequencies, with the exception of the data point for San Giuliano ((blue) circle at treble ratio 0.9), where the dryness of the acoustic made the sound more harsh than brilliant (Fig. 14(b)). It is likely that the dryness of the acoustic was exacerbated by the heavy drapes covering the site of the restoration of the chancel.

9. THE QUESTION OF CEILING DESIGN

The friary church of San Francesco della Vigna was the first Venetian church for which documentary evidence indicates that attention was paid to acoustic issues during the design process. A famous document on the design of the new church by Sansovino was written by the prominent Renaissance humanist scholar and friar Francesco Zorzi in 1535. He recommended the provision of vaults in the chapels and the choir, where singing would take place, but recommended a flat coffered ceiling in the nave to improve the audibility of sermons. In the actual construction of the church, the flat timber ceiling in the nave was never built; the current plaster vault was installed at a later date. The ceiling in the friars' choir, however, has a barrel vault and the side chapels, which are dedicated to eminent families, are also vaulted.

The acoustic measurements indicated that there are 3 different types of acoustic space in the church, a feature common to all the friary churches.

- Inside the friars' choir, the EDT was 1.5 seconds and T30, 3 seconds. This correlates well with the subjective impressions of the singers who enjoyed singing in this enclosed space.
- In the main body of the church, the EDT increased to 5 seconds and T30 to 6 seconds. Here the space was suited to plainchant but less so for complex polyphonic music.
- In one of the side chapels, the EDT decreased to 1 second whereas the T30 remained at 4 seconds. In these side chapels, with the choir facing the altar and the listeners close by, the sound was clear and satisfying and the polyphony distinct, and yet the acoustics were resonant enough to give volume and spiritual intensity to the music.

In the nave, speech from the pulpit could not be easily understood. The Reverberation Time was much too long for the spoken voice. Would the proposed timber ceiling have improved the conditions for speech and also polyphony? This question was addressed using the technique of acoustic computer modelling and auralisation, which is the subject of a companion paper by two of the authors (Boren and Longair 2013). Using the well-known acoustic computer modelling software Odeon®, a computer model was built and calibrated to give the same results as those measured in the actual

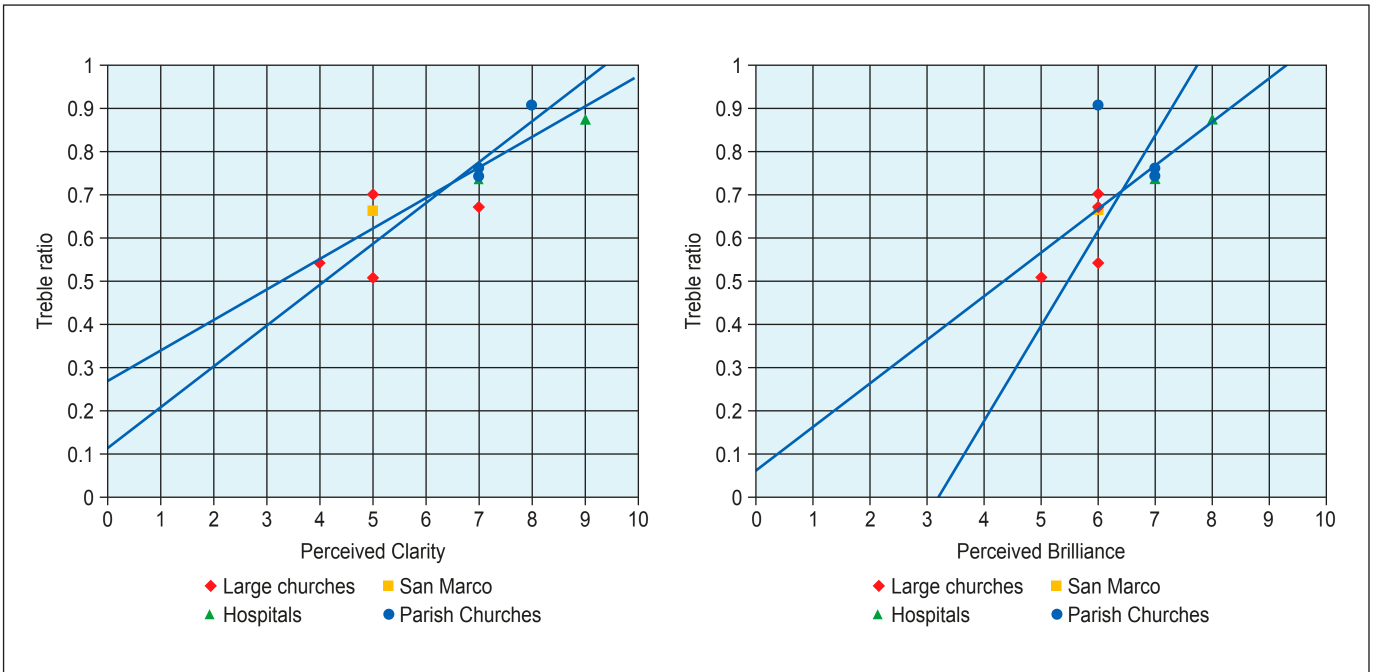

Figure 14. (a) The plot of perceived clarity against treble ratio as estimated by the audience. The blue lines are the regression lines of y against x and x against y. The correlation coefficient is r = 0.87. (b) The plot of perceived brilliance against treble ratio as estimated by the audience (diamonds). The blue lines are the regression lines of y against x and x against y. The correlation coefficient is r = 0.67.

building. A timber ceiling was then inserted into the model at two possible heights and the acoustic parameters re-calculated. The models predicted that there was no change in the D50 or other acoustic parameters and so little improvement in speech intelligibility was found. This was confirmed by subsequent auralisations of speech within the virtual church. This is perhaps not surprising as the ceiling was not sufficiently low to increase early reflections necessary for enhancing speech. In contrast, the audience responses to the speech experiments carried out in the much smaller church of San Michele in Isola, which has a flat coffered ceiling, showed that it had excellent acoustics for speech. Thus, Zorzi›s proposal for a flat timber ceiling to improve speech was not borne out for the large volume of San Francesco della Vigna, although, if the ceiling had been low enough, it would have been helpful. His suggestions about vaulted spaces for the chapels and choirs seem to have been correct.

10. CONCLUSIONS

The principal conclusions of this study are as follows:

- The average responses to the audience questionnaires agreed remarkably well with those of the professional acoustician. This indicates the usefulness of this type of audience data in characterising the subjective impressions of non-expert listeners in different locations within the churches.
- There are strong correlations between the subjective impressions of listeners and the quantitative acoustic data, particularly for `Reverberance' and `Clarity' and the acoustic parameters EDT, T30 and C80.
- The analysis of reverberation time reveals a clear ordering of the churches by typology and size:

– Parish churches: driest

– Hospital churches: optimum for complex polyphonic music

– San Marco: reverberant but still good

– Monasteries/friaries: very reverberant, but good for plainchant

- Even in large churches, however, there are spaces which are very good for music:

– The chancel in San Marco

– The choir spaces for monks, friars and singers

– Individual chapels

- The treble ratios for the churches are correlated with “Reverberance”, “Clarity” and “Brilliance”.

The complex polyphony developing in the 16th century needed a fine balance between clarity and reverberance. High quality, concert-hall-standard acoustics were found in the hospital churches. Venetian state hospitals became internationally renowned for the musical skills of the girls in their orphanages. These spaces therefore developed over the next two centuries into proper concert halls in the modern sense. The acoustics of the naves of the large churches were not suited to complex music but, as shown in a companion paper(Boren and Longair 2013), the acoustics of these large spaces was significantly improved on the great festal occasions when they were full of people and heavy tapestries and other absorbent materials decorated the churches.

The crucial question —and the most difficult to answer conclusively— is how far the architects themselves deliberately sought particular acoustic characteristics. It is significant that Sansovino’s five churches had, or were meant to have, flat timber ceilings in their naves. There is also suggestive evidence that Sansovino worked with the composer Willaert to install the two choir balconies which produced such excellent listening conditions for the Doge and his entourage. This conjecture is supported by the subjective and objective acoustic measurements. In the case of Palladio, the question remains largely unanswered. His two great churches, San Giorgio Maggiore and the Redentore, are very reverberant and not suited to complex music. It is argued in the companion paper that on the great festal occasions the acoustics of the Redentore became much more suitable for polyphony. Whether Palladio anticipated this, we do not know.

The composers writing for San Marco certainly adapted their music to the specific acoustic conditions of that church. Nevertheless, with the rapid growth of music printing in 16th century Venice, once the music was published, it could be performed in any acoustic space.

This project has aimed to restore the acoustic and aural dimension to the study of Renaissance churches in Venice, in the process increasing our understanding of the original impact of these churches on the people of Venice and enhancing our appreciation of these churches today.

ACKNOWLEDGMENTS

The research for this project was principally funded by a major Research Grant awarded by the Arts and Humanities Research Council of the UK for the period 1 February 2005 to 31 January 2008. Further sponsorship was provided by the British Academy, the Gladys Krieble Delmas Foundation, St. John’s College Cambridge, the Fondazione Scuola di San Giorgio, Venice and the John

Stewart of Rannoch Fund of the Faculty of Music, University of Cambridge. We are most grateful to all these sponsors. We are also most grateful to Philip Garsed of Clare College Cambridge who was supported by the UROP (Undergraduate Research Opportunities Programme) scheme of the University of Cambridge during the summer of 2007 to assist with converting all the questionnaire responses and acoustic data into machine-readable form and to carry out an initial analysis of these data. BB gratefully acknowledges the award of a Fellowship from the Gates Cambridge Trust which supported this research during the academic year 2009-10 at the University of Cambridge.

REFERENCES

M. Barron, Subjective Study of British Symphony Concert Halls, *Acustica*, **66**, 1-14 (1988).

L.L. Beranek, *Concert Halls and Opera Houses: Music, Acoustics, and Architecture*, (Springer Verlag, Berlin, 2003).

H.-E. de Bree, An Overview of Microflown Technologies, *Acta Acustica United with Acustica*, **89**, 163-172 (2003).

D. Bonsi, Characterization of the Acoustic Ambience of the Church of San Giorgio Maggiore by Quadaphonic Impulse Responses, in D. Howard and L. Moretti (eds), op.cit., 201-219 (2006).

B. Boren, M.S. Longair, Acoustic simulation of the church of San Francesco della Vigna, *The Journal of the Acoustical Society of America*. 09/2012; 132(3):1880 (2013).

B. Boren, M.S. Longair and R. Orlowski, Acoustic Simulation of Renaissance Venetian Churches, *Acoustics in Practice* (submitted) (2013).

D. Howard, The Innocent Ear: Subjectivity in the perception of Acoustics, in D. Howard and L. Moretti (eds), op.cit.,, 239-257 (2006).

D. Howard and L. Moretti (eds.), *Architettura e musica nella Venezia del Rinascimento*, (Bruno Mondadori, Milan, 2006).

D. Howard and L. Moretti, *Sound and Space in Renaissance Venice*. (Yale University Press, New Haven and London, 2009).

T. Lokki, J. Pätynen, A. Kuusinen, and S. Tervo, Disentangling preference ratings in concert hall acoustics using subjective sensory profiles, *The Journal of the Acoustical Society of America*, **132**, 3148–3161 (2012).

F. Martellotta, Subjective study of preferred listening conditions in Italian Catholic churches, *Journal of Sound and Vibration*, **317**, 378-399 (2008).

L. Moretti, Architectural Spaces for Music: Jacopo Sansovino and Adrian Willaert at St. Mark's, *Early Music History*, **23**, 153-184 (2004).

M. Schroeder, D. Gottlob, and K. F. Siebrasse. Comparative study of European concert halls: correlation of subjective preference with geometric and acoustic parameters, *The Journal of the Acoustical Society of America*, **56**, 1195-1201 (1974).

G. Soulodre and J. Bradley, Subjective evaluation of new room acoustic measures, *The Journal of the Acoustical Society of America*, **98**, 294–301 (1995).

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Treasurer: *J. Salvador Santiago*

Technical Committees

EAA has 7 technical committees which, at different level, are in charge of organizing specific activities (technical reports, round robin tests, structured session organization at congresses, symposia, etc.). They are open to all individual members of EAA member societies and are coordinated by a Chairman:

• CA, Computational Acoustics • HYD, Hydroacoustics • MUS, Musical Acoustics • NOI, Noise • PPA, Psychological and Physiological Acoustics • RBA, Room and Building Acoustics • ULT, Ultrasound

EAA is an Affiliate Member of the International Commission for Acoustics (ICA)

INTERNATIONAL COMMISSION FOR ACOUSTICS

and Member of the Initiative of Science in Europe (ISE)

EAA Products

ACTA ACUSTICA united with ACUSTICA
Product Manager and Editor in chief: *Dick Botteldooren*
Acta Acustica united with Acustica is an international, peer-reviewed journal on acoustics. It is the journal of the EAA. It is published by S. Hirzel Verlag • Stuttgart.
See www.acta-acustica-united-with-acustica.com for more information.
EAA members receive Acta Acustica united with Acustica online as part of their membership.

NUNTIUS ACUSTICUS
Product Manager: *Brigitte Schulte-Fortkamp (Kristian Jambrošić from September 2013)*
Nuntius Acusticus is the “acoustic messenger” of EAA to vitalize communication between and in the European acoustical societies on a variety of topics. It is published monthly in electronic format and distributed via e-mail to all EAA members.

DOCUMENTA ACUSTICA
Product Manager: *Sergio Luzzi*
Documenta Acustica is the literature distribution system of the EAA. It distributes conference and symposia proceedings as well as books, reports and theses.

FENESTRA
Product Manager: *Olivier Dazel*
Fenestra Acustica is the website of EAA. Fenestra provides information on the association and its members (products, technical committees, organisational structure and policies, contact information), up-to-date news, upcoming events, links to other no-profit organisations in acoustics, a job market and much more.

SCHOLA
Product manager: *Malte Kob*
Schola is an online platform for education in acoustics in Europe: https://www.euracoustics.org/activities/schola. Through Fenestra, it offers information on university acoustics courses in Europe at different levels (Bachelor, Master, Ph.D.).

ACOUSTICS IN PRACTICE
Product manager: *Colin English*
This new technical journal will be written by practitioners for practitioners and other professions: a new link between all members of all EAA societies. The journal will be published four times a year in electronic form only. The first issue is planned for 1st July 2013.

YOUNG ACOUSTICIANS NETWORK
Contact person: *Elena Ascari and Xavier Valero*
This network is a non-profit student initiative within the EAA with the primary goal to establish a community for Mater and PhD students and researchers in the field of acoustics. It organises student events at scientific conferences and provides services that contribute to the community, including a monthly newsletter.

FORUM ACUSTICUM
Forum Acusticum is the triennial international convention organised by a national acoustical society on behalf of EAA. It is, in effect, a forum comprising a variety of different activities: high-quality scientific congress with invited plenary lectures, structured sessions, invited and contributed papers, an exhibition that includes commercial firms, laboratories and agencies, social meetings of acousticians with receptions, visits and awards.

EURONOISE
Euronoise is the European Conference and Exhibition on Noise Control, coordinated by the EAA Technical Committee Noise and organised by a national acoustical society on behalf of EAA.

EUROREGIO
Euroregio is an expression of EAA support for traditional regional events organized by groups of countries. Where and when appropriate, the regional events can be extended towards a full European and international scale.

EAA SYMPOSIA
EAA symposia are scientific meetings under the aegis of the EAA with a focus on specialised fields. They are typically organized by one or more member societies
of EAA in conjunction with the Technical Committee of EAA.

YOUNG RESEARCHER AND STUDENT PROGRAM
EAA supports with grants and best paper and presentation awards the active participation of students and young researchers at EAA major events (Forum Acusticum, Euronoise, Euroregio).

EAA SUMMER AND WINTER SCHOOLS
The EAA Summer and Winter Schools are conceptualized as events where Master and PhD students of acoustics, as well as other young acousticians, can learn about a variety of new accomplishments in the field of acoustics in half day or full day courses.

European Acoustics Association (EAA)
secretary@european-acoustics.net
office@european-acoustics.net

www.euracoustics.org