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SUMMARY

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EU regulations on external rolling noise of passenger car tyres

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ABSTRACT

The acoustic and mechanical comfort in passenger cars is becoming more and more important. Whereas the number of cars is continuously increasing – which implicitly results in higher overall noise emission – the respective legal regulations are becoming more stringent. However, abiding by these objective limits does not necessarily imply a better interior noise performance, since the subjective perception of acoustic signals varies depending on their spectral composition. In this article, the main mechanisms of tyre/road noise are summarised, and the current EU regulations for road vehicles are presented, with special emphasis on C1 class tyres.

1. BACKGROUND

Traffic noise *has become* a major pollutant of the outdoor urban *environment* with direct implications on public health. Noise exposure can affect the individual's concentration and, depending on its level and dosage, can cause a temporary threshold shift. Acute noise effects may also develop into clinical symptoms like permanent threshold shift, tinnitus, sleep disturbance, or even insomnia [1]. This has led the responsible authorities to apply certain measures to mitigate traffic noise pollution.

In this regard, the EU tyre labelling regulation 1222/2009 [2] provides a first step towards reducing traffic noise. It stipulates that manufacturers comply with the limits for external rolling noise (along with fuel consumption and wet grip) of each tyre that is intended to be sold in the EU as of November 2012. Accordingly, tyres are classified by A (green, best performance) to G (red, worst performance) for the overall performance. Moreover, with the noise classification on the tyre label (schematic one to three sound waves emitted from a tyre), the customer gets a better overview of the acoustical tyre behaviour.

Now the question is: Are these EU regulations sufficient for ensuring a quiet and comfortable ride? In this report, we first recapitulate the main mechanisms of tyre/road noise and then shed some light on the advantages and limitations of the EU legal regulations concerning tyre noise.

2. TYRE NOISE GENERATION MECHANISMS

A schematic of a tyre on a surface is shown in Fig. 1, along with the main excitation mechanisms. For frequencies below about 300 Hz structure-borne noise, instigated by the tyre and suspension vibrations, is the dominant factor (relevant mainly for interior noise). Above 600 Hz air-borne noise dominates (relevant both for interior and exterior noise).

All these excitation mechanisms are caused by the interaction of the tyre tread pattern with the road surface. These vibrations are induced in the tyre structure (e.g., radial and tangential vibrations), in the air column within the tyre (cavity mode), and in the surrounding air that is "trapped" in the grooves (pipe and Helmholtz resonators). Table 1 shows an overview of the main noise generation mechanisms and their causes [3,4,5,6].

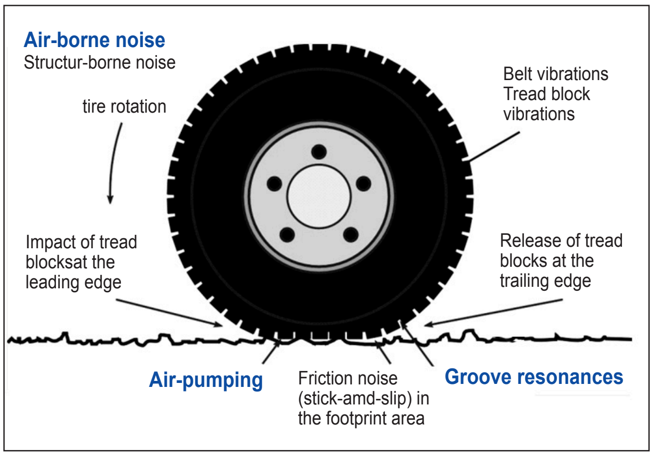

Figure 1. *Tyre schematic indicating the main excitation mechanisms upon the interaction of the tyre with the road surface.*

Table 1. *Overview on the main mechanisms of tyre/road noise [3,4,5,6].*

Tyre vibration	Cause
Radial tyre vibrations	Radial belt vibrations and pattern elements hitting (on the leading edge) and leaving (on the trailing edge) the contact patch.
Tangential tyre vibrations	Tangential forces in the contact patch.
Sidewall vibrations	Tread vibrations transported to the sidewall and radiated thereof.
Tangential stick/slip vibrations	Tangential displacements of the tyre on the road surface due to a reduced friction in the footprint area.
Adhesion stick/snap	Occurs on relatively clean road surface when the tyre tread surface gets sticky (e.g., due to hot asphalt). This may take place in winter tread compounds at high temperatures.
Cavity mode	Resonating air-column within the tyre (membrane filled with air). For a rolling tyre, two cavity modes of adjacent frequencies arise [3]: $f_{\text{cavity}} = c^2\left(\frac{ic}{\lambda}\right) \pm (s * i + \Delta f)$, where i = 1,…,n; c is speed of sound; λ wavelength; s: number of revolutions per second; $\Delta f \approx 0.5$ Hz (frequency shift)
Air-pumping	Air displacement into and out of groove cavities or between the tyre tread and the road surface due to entering and leaving the contact patch.
Pipe reso-nance	Air displacement in the grooves (λ/2 and λ/4 pipe resonators) upon the contact of the tread pattern with the road surface.
Helmholtz resonators	Air displacement into/out of the connected air cavities in the tyre tread pattern and the road surface.

3. LEGAL LIMITS FOR PASSENGER CAR TYRES

Regarding the acoustical tyre performance, the EU tyre label stipulates that tyre noise lies within well-defined limits when measured on certified ISO surface (ISO 10844:2011 [7]). The measured noise level [in dB(A)] is calculated in accordance with UNECE Reg. 117 [8] in an outdoor coast-by test.

For passenger car tyres of class C1 (tyre classification as defined in Article 8 of Regulation (EC) No 661/2009 [9]), the noise coast-by measurement is performed at a speed of 80 km/h with the engine switched off during recording (Fig. 2, left). To obtain the value exactly at this reference speed, at least 8 measurements (4 lower and 4 higher than 80 km/h) are carried out in the range of 70 to 90 km/h with an accuracy of ± 1 km/h. The level at 80 km/h is then determined by a regression analysis [10] and used for the tyre approval testing[1]. Other restrictions concerning meteorological conditions (wind speed: $v_{\text{wind}} < 5$ m/s, air temperature: $5\,°\text{C} \leq T_{\text{air}} \leq 40\,°\text{C}$; test surface temperature: $5\,°\text{C} \leq T_{\text{surface}} \leq 50\,°\text{C}$) must also be met for testing [10].

The tyre noise performance is schematically represented by sound waves depicted on the tyre label (Fig. 2, right), with:

- one black wave meaning that the tyre noise is at least 3 dB below the future limits of 661/2009 which will come into effect as of November 2016;
- two black waves meaning that the tyre noise lies between the future limit and 3 dB below, i.e., the tyre meets the imminent 661/2009 limits that will apply in the future.
- three black waves meaning that the tyre noise is above the future European limits of 2016 and, hence, this tyre cannot be used after that date.

All tyre classes (C1, C2, and C3) must meet the rolling noise requirements listed in Reg. No 661|2009 (Annex II [9]). While different countries may have different regulations, Table 2 shows the EU values (both old and new) for C1 class tyres, which are designed primarily for vehicles of categories M1, N1, O1 and O2.

In Figure 3, the current noise values (listed in Table 2) are shown as function of the tyre nominal width for lucidity. Whereas these legal requirements (objectively measured values) pave the way for a reduced overall

[1] Note that for class C3 tyres, measurements are performed in a speed range of 60 to 80 km/h, and the legal value is obtained by interpolation at 70 km/h.

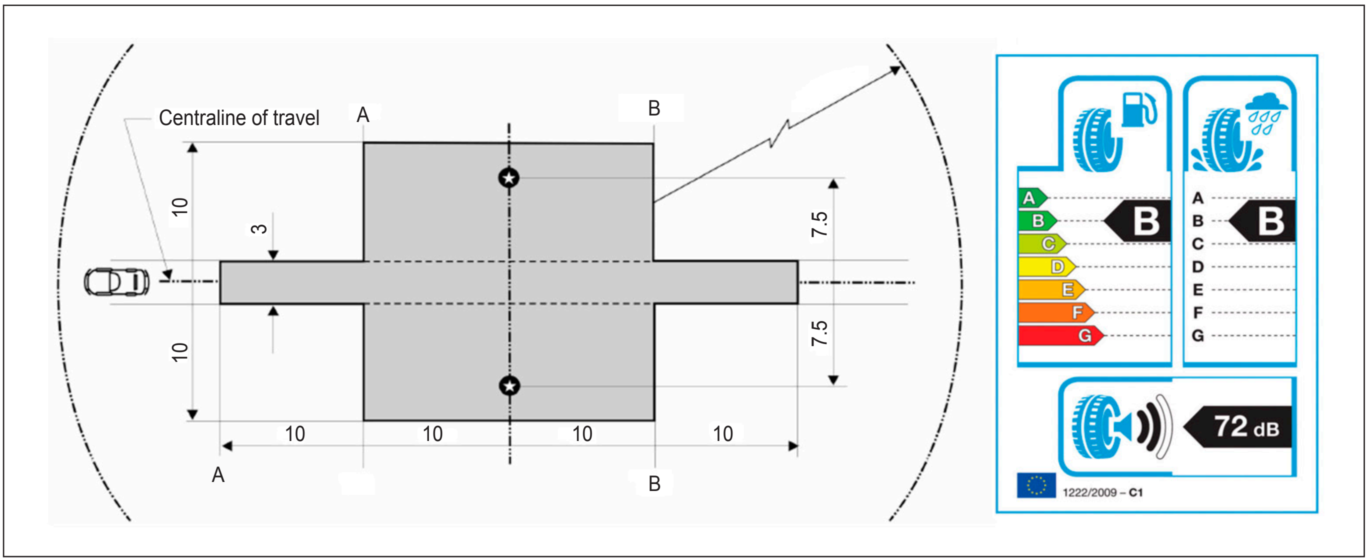

Figure 2. *Left: a highly schematic representation of the noise coast-by test [8]. The shaded part represents the test area that is passed by the test vehicle. Two microphones are mounted, each (7.5 ± 0.05) m away from the reference line (centre line of the test track) and (1.2 ± 0.02) m above the ground. Source: Directive 2001|43|EC [10]. Right: example of a label for a C1 class tyre. Source: Reg. 122|2009 [2].*

Table 2. *Legal values for class C1 tyres (old and new limits), depending on the nominal section width of the tyre [9]. Note that for reinforced (extra load) tyres, the limit values are 1 dB(A) higher.*

Tyre class	Nominal section width: w (mm)	Limit values in dB(A)	
		Old	New
C1A	$w \leq 185$	72-74	70
C1B	$185 < w \leq 215$	75	71
C1C	$215 < w \leq 245$	76	71
C1D	$245 < w \leq 275$	76	72
C1E	$w > 275$	76	74

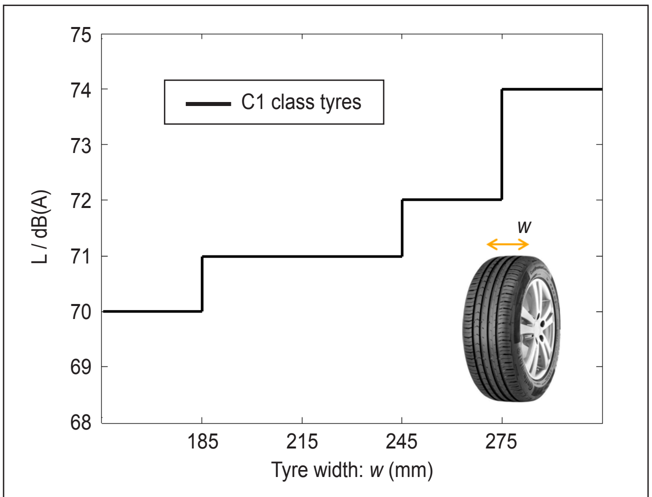

Figure 3. *Graphical representation of the legal values for class C1 tyres (valid since November 2012) as a function of the nominal tyre width. C1 tyres are primarily used for standard passenger cars (e.g., vehicle category M1 with ≤ 9 seats including driver's seat and a power-to-mass ratio ≤ 120 kW/ton). For more details on tyre classes C2 and C3, please refer to the EU tyre labelling regulation 1222/2009 [2].*

sound pressure level emitted from a certain tyre, they do not say much about the spectral composition of the emitted noise. Hence, the subjective comfort of the passengers in the car is not addressed by the legal limits. This is true especially for low-frequency sound and vibration (say below 50 Hz), which can adversely affect the psycho-physiological well-being of humans, as known from experiments using vibratory chairs (i.e., chairs equipped with a vibration accelerator).

4. OUTLOOK

The current legal requirements for tyre noise were presented for C1 class tyres. These requirements set the limits for exterior rolling noise (cf. tyre label). It can be anticipated that more strict limitations to further reduce these limits may be proposed in the future. The challenge will be to achieve this without resulting in target conflicts with other essential tyre performances. The utmost example is a slick tyre, which though represents the theoretical acoustical limit, results, however, in deteriorated wet grip (braking on wet or snow). Future revisions of tyre/road noise regulations may also include extending the test conditions for tyre approvals to lower speeds (e.g., 50 km/h) that affect the inner-city living areas to a larger extent.

The EU legal regulations provide a first step towards reducing traffic noise pollution and increasing the public awareness to noise aspects by encouraging the use of tyres that show better acoustical performance. However, in order to thoroughly address the problem of traffic noise, traffic road mitigation must be accompanied by a sustainable transport planning, taking also the influence of the road surfaces (e.g., ISO 10844 [7]) into account. Recall also that the legal limits do not directly tackle the tyre-induced noise in the interior of a vehicle (i.e., the subjective comfort of the driver and passengers). Bearing in mind that noise has a direct psycho-physiological health impact on humans, both criteria (exterior and interior noise) must be addressed for a calmer environment and for the comfort of the car passengers.

REFERENCES

[1] European environment agency (2010). "Good practice guide on noise exposure and potential health effects". EAA Technical report No. 11/2010.

[2] Regulation (EC) No 1222/2009 of the European Parliament and of the Council of 25 November 2009 on the labeling of tyres with respect to fuel efficiency and other essential parameters. Official Journal of the European Union.

[3] Bederna C., Saemann E.-U. (2009). Contributions to a better understanding of tire cavity noise. International Conference on Acoustics NAGA-DAGA, Fortschritte der Akustik 35; 502-505.

[4] Graf R.A.G., Kuo C.-Y., Dowling A.P., Graham W.R. (2002). "On the horn effect of tyre/road interface, Part 1: Experiment and Computation". Journal of Sound and Vibration 256, 417-431.

[5] Kuijpers A., van Blokland G. (2001). "Tyre/road noise models in the last two decades: a critical evaluation", internoise (The Hague).

[6] Sandberg U, Ejsmont J.A. (2002). Tyre/road noise reference book. Informex, Harg, SE-59040 Kisa, Sweden.

[7] ISO 10844: 2011 Acoustics – Specification of test tracks for measuring noise emitted by road vehicles and their tyres.

[8] Regulation No R117 of the Economic Commission for Europe of the United Nations (UN/ECE): Uniform provisions concerning the approval of tyres with regard to rolling sound emissions and to adhesion on wet surfaces and/or to rolling resistance.

[9] Regulation (EC) No 661/2009 of the European Parliament and of the council of 13 July 2009 concerning type-approval requirements for the general safety of motor vehicles, their trailers and systems, components and separate technical units intended therefor. Official Journal of the European Union.

[10] Directive 2001|43|EC of the European Parliament and of the Council of 27 June 2001 amending Council Directive 92|23|EEC relating to tyres for motor vehicles and their trailers and to their fitting. Official Journal of the European Communities.

Sonic Boom, Jet Noise and Doppler Effect

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ABSTRACT

In the literature dealing with supersonic sound sources, a frequent confusion is found between the shock waves induced by moving bodies and the sound waves induced by sound sources. Of course, only the sound waves are concerned by the Doppler effect. A review of the theory and of the present models is proposed, with examples concerning the sonic boom from aircraft and the jet noise generated by a launch vehicle in flight. The calculation results are compared with signals recorded from ground-based sensors.

1. INTRODUCTION

The ballistic waves from gun projectiles and the sonic boom from aircraft are phenomena due to the impact into the atmosphere of a solid body moving at supersonic speed: we are in the domain of aerodynamics and shock waves. In contrast, the hiss from an artillery shell and the jet noise from an aircraft or a launch vehicle flying at supersonic speed are acoustic phenomena, which spread inside the supersonic shock wake and become audible after the passage of the sonic boom only.

In the literature, these very dissimilar phenomena are subject to frequent confusion, because the Mach cone is often described as the resultant of spherical pressure waves generated by the nose of the moving body. That suggests that the sonic boom could be subject to the Doppler effect, a very questionable assertion obviously. Both aspects of that issue are presented below, as they follow totally dissimilar formalisms.

2. SONIC BOOM

2.1. Ballistic wave

The first studies carried out in the supersonic field, from the end of the 19th century [1-3], were as a matter of fact related to the ballistic wave generated by firearm projectiles (Fig. 1). The models formalizing the "N-wave", that corresponds to the pressure profile of the ballistic wave in far field (Fig. 2), are more recent [4-6]. Remember that the N-wave of any projectile moving at supersonic speed has two space bounds: a fore shock front or bow wave (overpressure), and a rear shock front or tail wave (underpressure). For an observer, the going past of this wave produces a crack, not a hiss. The amplitude ΔP and the duration ΔT of the N-wave are given by the equations below [6]:

$$\frac{\Delta P}{P_0}=2^{1/4}\gamma(\gamma+1)^{-1/2}(M^2-1)^{1/8}\left[\int_0^{y_0}F(y)dy\right]^{1/2}R^{-3/4} \qquad (1)$$

$$\Delta T=2\frac{\Delta P}{P_0}\frac{\gamma+1}{\gamma c_0}\frac{M}{\sqrt{M^2-1}}R \qquad (2)$$

where M is the Mach number, R is the distance between the observer and the projectile path, γ is the ratio of air specific heats, 0 is the subscript referring to ambient data (atmospheric pressure P_0, celerity of sound c_0), and F(y) is the "Whitham function" depending

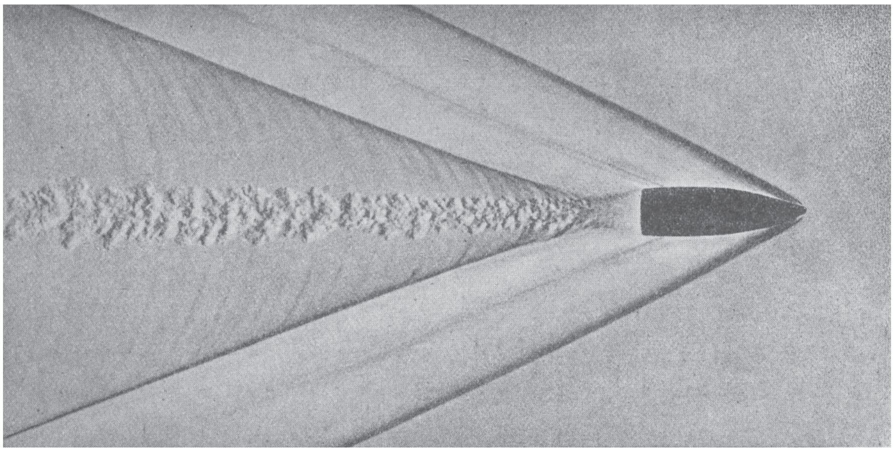

Figure 1. *Shock wake and turbulent wake of a rifle bullet. Picture from Ref. [3] (Germany, 1917).*

on the shape of the projectile. Note that the integral of F(y) may be replaced, for small solid bodies, by a ratio linking diameter and length of the body [7-8]. Fig. 1 shows the shock wake of a bullet, constrained by two shock fronts and easy to distinguish from the acoustic zone where swirls and acoustic waves are visible.

That zone, bounded by the "sound cone" [3], is developing inside the second shock cone. The front cone, usually called "Mach cone", has in fact an ogival shape. It is obvious that no spherical waves are developing between the shock fronts, where the pressure decreases more or less regularly, as shown by the ideal shape of the "N-wave" in Fig. 2.

Knowing that the apex half-angle α of the sound cone is in theory given by:

$$\sin\alpha = \frac{c_0}{V} = \frac{1}{M} \tag{3}$$

where c_0 is the speed of sound in the ambient environment, we can calculate the speed V of the bullet in Fig. 1 by measuring the half-angle of the second shock front, which bounds the sound cone of aerodynamic noise stemming from the turbulent wake.

We find V ≈ 900 m/s, M ≈ 2.7, which can correspond to a war rifle bullet. Note that this speed may be overestimated if the normal speed of the second shock front is subsonic because of the strong underpressure. On the contrary, the normal speed of the first shock front is supersonic and decreases from the tip of the bullet, hence the ogival shape of this front.

The model of ballistic wave developed at ONERA (France) for small bodies follows a simplified formalism close to the one described in Ref. [7-8]. That model was tested and validated from data

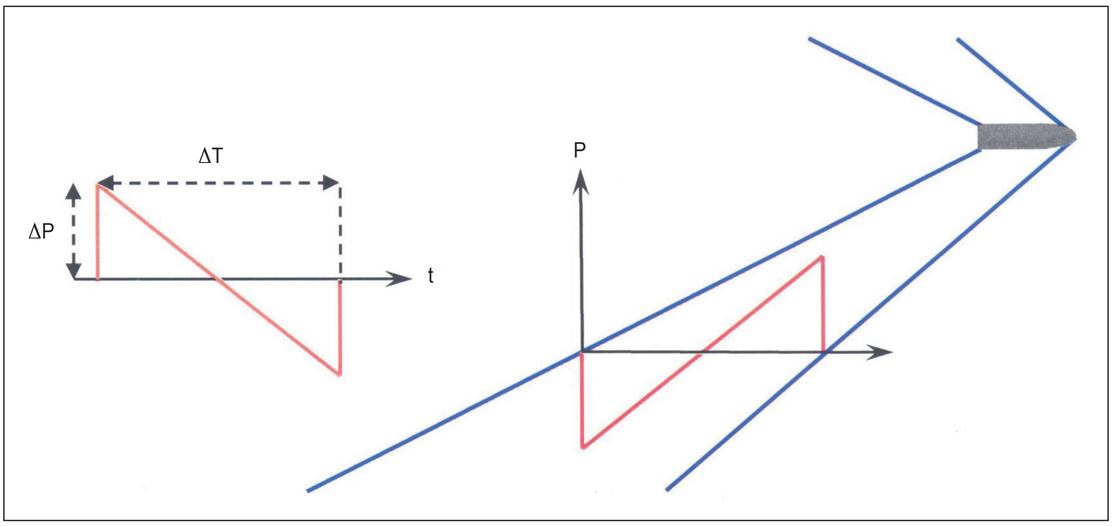

Figure 2. *Time and space pressure profiles of an ideal "N-wave".*

available in Ref. [5] concerning ballistic waves generated by firearm projectiles with calibres from 7.62 mm to 40 mm and with initial speeds generally close to 800 m/s ($2.2 < M < 2.6$). The ONERA's model calculates with small gaps by default (around -30 % for ΔP and -10 % for ΔT) the N-wave parameters such as they had been measured on the spot at various distances.

2.2. Sonic boom from aircraft

Because of a great similarity between the sonic boom from aircraft (Fig. 3) and the ballistic wave, the formalisms established for weapon projectiles flying at ground level were applied to sonic boom afterwards, sometimes by introducing a "lift coefficient" taking into account the geometric shape and the incidence of the airplane [9]. The lift function can cause asymmetry of the N-wave corresponding to the sonic boom (see Fig. 3), but formulas (1) and (2) can be used by considering the averaged amplitude of overpressure and underpressure recorded in the field [10-11]. For the simulation, the maximum diameter of the fuselage is the main parameter that is used to calculate the Whitham function of a given aircraft.

Another issue is how the parameters of the N-wave evolve at a long range and at varying altitudes, for instance the flight altitude and the ground level: indeed, Mach number and sound pressure depend on the local ambient conditions. For instance, the TRAPS computer code of NASA (USA) takes into account a non-linear propagation of the N-wave through the atmosphere [12]. The formalism developed at ONERA takes only into account the initial conditions of pressure and temperature (i.e. P_0, T_0 respectively) and the final ones (i.e. P'_0, T'_0). Simple physical considerations lead to the "transformation formulas" below:

$$\Delta P' = \Delta P \sqrt{\frac{P'_0}{P_0}} \tag{4}$$

$$\Delta T' = \Delta T \sqrt{\frac{T_0}{T'_0}} \tag{5}$$

where ΔP and ΔT are the amplitude and the duration of the N-wave calculated at the same distance as the listening point, but at the altitude of the airplane. In a practical way, expressions (1) to (5) enable us to simulate the measurements of aircraft sonic booms, knowing that the calculated amplitude $\Delta P'$ must be multiplied by two to take into account the acoustic reflection on the ground, since the sensors are generally put on the ground. For two French jet planes, a fighter *Dassault Mirage III* and a supersonic bomber *Dassault Mirage IV*, flying at a constant altitude and at a constant speed, the following ratios were obtained between calculated and measured parameters of the N-wave:

Flight altitude (m)	Mach number	ratio of ΔP	ratio of ΔT
600	1.03	1.14	1.23
11,000	1.18	0.83	0.96
8,800	1.50	1.05	1.00
13,000	1.50	0.98	1.00
11,000	1.70	0.95	1.06

We can see that the uncertainty of the simulation on the N-wave parameters is about 25 % for transonic speeds, but becomes smaller when the Mach number increases.

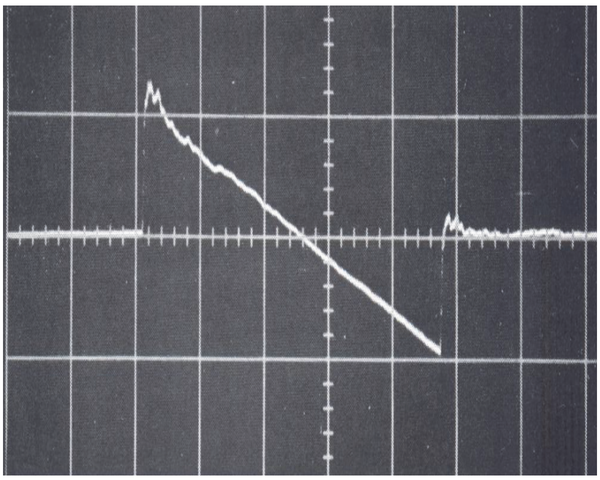

Figure 3. *Airliner "Concorde" in flight. Sonic boom recorded at ground level (CEV, Istres, France).*

That formalism was also tested on measurements performed by NASA during test flights of a *Lockheed SR-71 Blackbird*, a high-performance strategic reconnaissance jet plane which could reach Mach 3.4 at 26,000 m high [13-14]. Unfortunately, the speeds and flight altitudes which were tested did not exceed Mach 1.6 and 15,000 m respectively, i.e. flight conditions not very different from those of previous tests carried out in France in the 1960s (Operations “Jéricho” [10-11,15-16]).

2.3. Focused sonic boom

The overpressure of the N-wave may be strongly increased by the sonic boom focusing phenomenon (Fig. 4), which occurs when the airplane is accelerating or turning [15-16]. This phenomenon is caused by interferences of the shock fronts, knowing that the Mach cone aperture decreases when the Mach number increases (Fig. 5, on the left). In the case of a turning, the interferences occur on the concave side of the flight path (Fig. 5, on the right).

In both cases, the zone of focusing is narrow and can be calculated from geometrical considerations, by making the hypothesis of infinitesimal moving. For instance, one shows that the surface where occurs the focusing of the sonic boom of an aircraft flying at a constant altitude and subjected to a constant acceleration γ_x is given by the equation:

$$y^2+z^2=\frac{\gamma_x}{c^2}\left(\frac{2}{3}x\right)^3 \qquad (6)$$

with the following space references: the axis Ox is the flight path, the origin O of the focus surface is the nose of the aircraft at the very instant it passes through the sound barrier (M = 1).

One can see in Fig. 6 that the cross-section of this surface is a circle. The intersection with the ground is a fixed curve which can be detected with a sensor array. Our analytical model has been validated using flight data and measurements taken from References [15-16].

Consider the case of the focused sonic boom (Fig. 4): the amplitude of the N-wave is multiplied by a factor varying from 3 to 5, which can not be predicted by the classical modelling of the sonic boom. On earth, that strong overpressure can cause a temporary deafness among living beings and material damages (glass breakage, etc.).

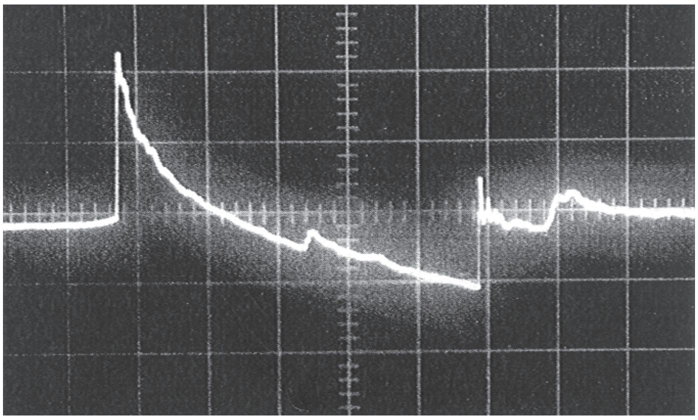

Figure 4. *Fighter Dassault Mirage III in flight. Recording of focused sonic boom, from Ref. [15].*

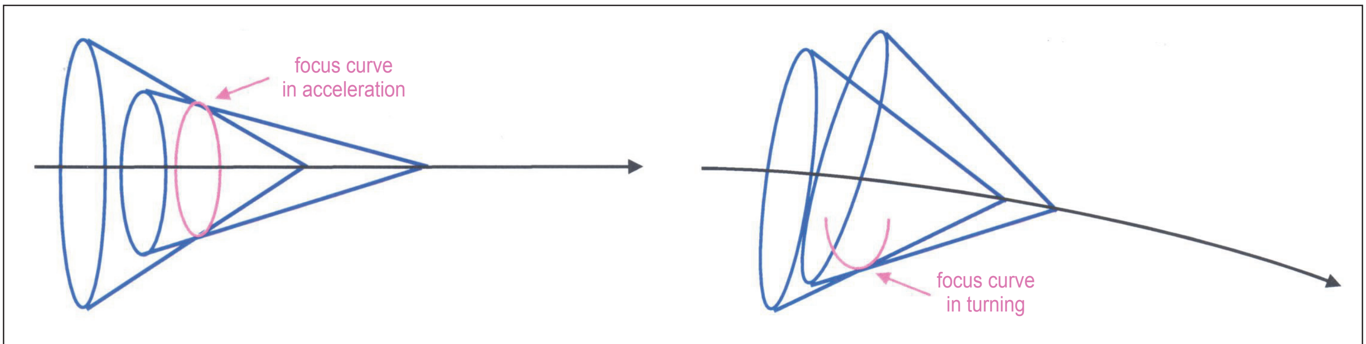

Figure 5. *Simplified representation of the focus phenomenon in acceleration and in turning.*

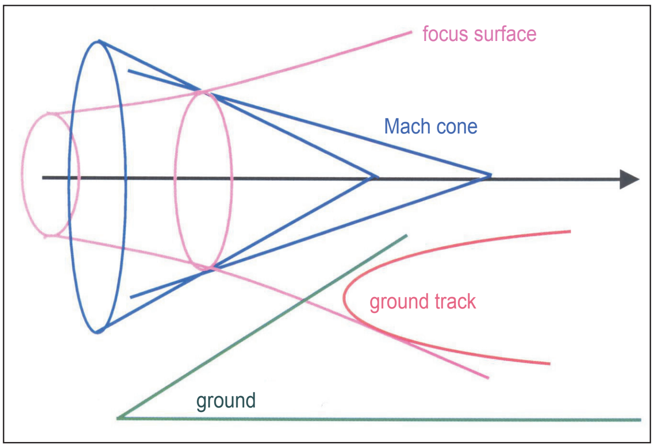

Figure 6. *Focus surface and ground track in the case of an accelerating airplane.*

Most recent studies are interested in the infrasound emission generated by a sonic boom [17-18], but this is outside the scope of our current subject.

3. NOISE EMITTED BY A SUPERSONIC SOURCE

3.1. Doppler effect

In the literature dealing with aeroacoustics, the Doppler effect is often represented by a series of spherical waves generated at equal time intervals, namely the period of a harmonic sound source moving at celerity V.

Fig. 7 gives such a representation in the case of a supersonic source S, the volume of which is equal to zero. As in Ref. [3], we call "sound cone" the envelope of the acoustic waves, the term "Mach cone" being rather reserved for the shock waves generated by a solid body, the cross-section area of which is not equal to zero.

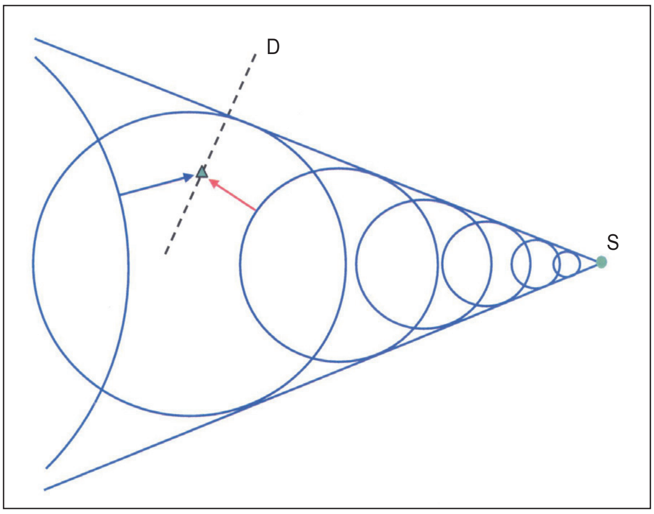

Figure 7. *Acoustic waves and sound cone in the case of a supersonic sound source.*

This distinction gets lost in many papers where a moving solid body is considered as a source of spherical wavelets or disturbances which focus on the Mach cone [19-22]. In fact, this conventional model is not suitable for the sonic boom: in particular, the N-wave and its second shock front are curiously omitted. In addition, by analogy with Fig. 7, such a model suggests that the sonic boom may be subject to the Doppler effect, which is patently false. Note that a similar model of circular waves was used by Whitham to describe a ship wake [23].

Fig. 8 shows the right representation of the shock wake generated by a solid body moving at supersonic speed (a jet airplane here), and of the acoustic zone linked up with the sound sources of the jet and bounded by the sound cone. See also Fig. 1, where the sound sources are of an aerodynamic nature (turbulent wake).

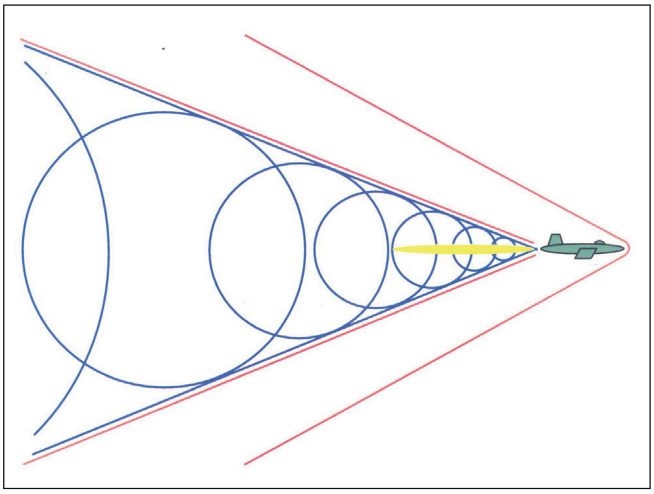

Figure 8. *Shock wake of a moving solid body (in red), sound cone of the noise sources (in blue).*

Fig. 7 suggests that a motionless observer being inside the sound cone (mark Δ) shall perceive two Doppler frequencies simultaneously, the one emitted from the source moving near ("direct frequency"), the other from the source moving away ("retrograde frequency"). In fact, the border between both modes is the direction D perpendicular to the sound cone.

Ernest Esclangon [3] noticed that an observer perceives one frequency only when an artillery shell is hissing, and he identified it as the "retrograde frequency".

Note that the "direct frequency" is negative, which means that the wave fronts reach the observer in the reverse order of their emission, because of the supersonic speed of the sound source. An analytical solution of this problem is given in Ref. [24].

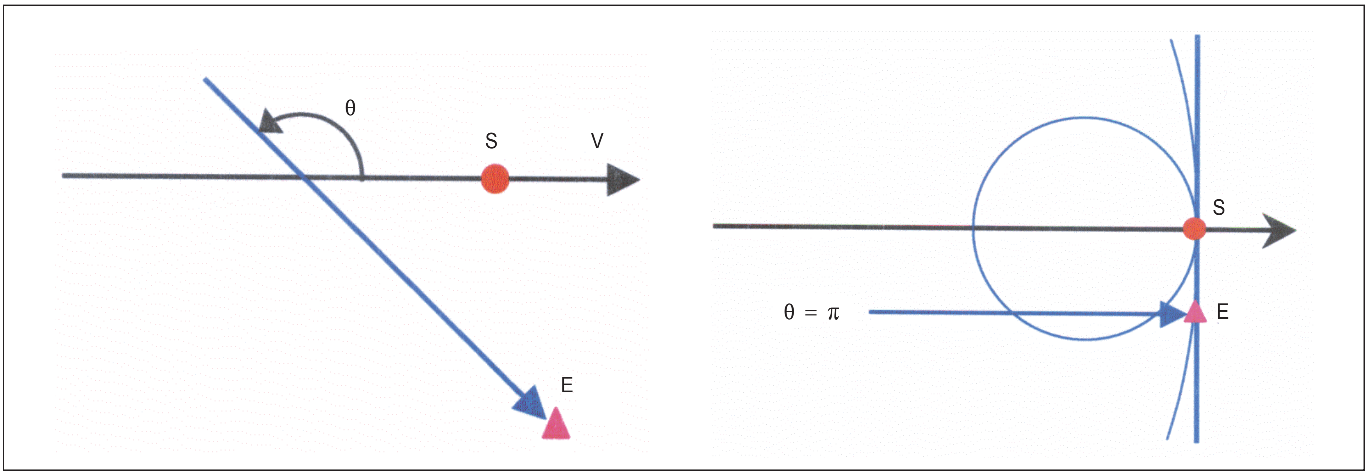

Figure 9. Geometrical conventions for the calculation of the Doppler effect, for M ≠ 1 and M = 1.

If the Doppler factor D.F. is defined as the ratio f/f_0 between the frequency f perceived at the listening point (linked to the fixed space coordinate basis) and the frequency f_0 emitted by the source, this factor is given by the well-known expression [25-26]:

$$D.F. = \frac{f}{f_0} = \frac{1}{1+M\cos\theta} \qquad (7)$$

where θ is the angle under which the observer E saw the source when the acoustic wave has been emitted (Fig. 9, on the left). That is why we have $\theta = \pi$ (and not $\theta = \pi / 2$) when the observer is reached by the sound barrier in the case M = 1 (Fig. 9, on the right). As a result, $1 + M\cos\theta = 0$ in equation (7), and the Doppler factor and the received frequency f are infinite in theory. Note that this result is also true when the observer is on the sound cone in general.

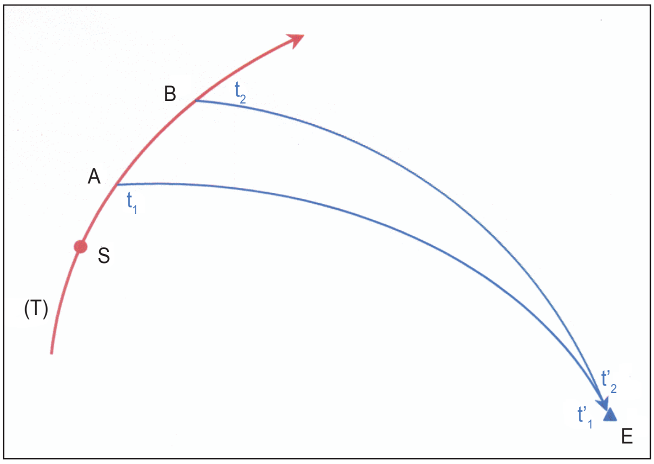

Figure 10. Time approach of the Doppler effect: trajectory of the sound source and propagation paths, from Ref. [27].

3.2. Time approach of the Doppler effect

It is shown in Ref. [27] that the Doppler factor is also equal to the ratio $\Delta t/\Delta t'$ between an emission duration Δt and the corresponding reception duration $\Delta t'$, which was not mentioned in the previous literature to our knowledge, at least under this form. In Fig. 10, the sound source S follows any trajectory (T) with or without acceleration, and the sound rays (in blue) propagate in an actual atmosphere.

For the part AB of the trajectory, we have for the listening point E the average value of the Doppler factor $D.F. = (t_2 - t_1) / (t_2' - t_1')$. As a direct consequence of the conservation of the acoustic energy, the corresponding frequency shift goes with a sound level variation given by:

$$\Delta L_{(dB)} = 10\log(|D.F.|) \qquad (8)$$

Thus, the sound cone where $D.F. \longrightarrow \infty$ also corresponds to a sound level peak: there is a “focusing” phenomenon linked up to the Doppler effect only. Such a phenomenon is perhaps visible in Fig. 4 (small peak following the N-wave, before the jet noise signal).

Note that the time-approach of the Doppler effect explains the focusing on the sound cone: indeed, two pulses emitted by the sound source in the direction θ_0 (like $1 + M\cos\theta_0 = 0$) at a short time interval Δt arrive almost simultaneously at a distant observer ($\Delta t' \approx 0$ s), the delay of the second pulse being exactly compensated by the speed of the source.

3.3. Application to the European launch vehicle Ariane 5

It would be interesting to test the model of Doppler effect on recordings of jet noise emitted from military aircraft, but that could not be done because of lack of experimental data. We know, however, that unlike the jet engines fitted on civilian airliners, the jet engines fitted on fight airplanes have a bypass ratio close to zero or very low, which brings the noise they emit closer to the noise from rocket engines.

So, it seems to be opportune to test the model on the jet noise emitted by a launch vehicle in flight, with the additional difficulty due to a variable speed on a near-vertical trajectory. For instance, the recordings performed by ONERA at Kourou (French Guiana) during the Flight 521 of Ariane 5 are available data, as well as the weather conditions of the day and the launch vehicle trajectory communicated by CNES/DLA, Evry (France).

The listening station TOUCAN was located 4 km away from the launch pad, the atmosphere was quiet. In a first step, we made the hypothesis of a sound propagation in straight line, which leads to negligible errors on the travel times for distances to the launch vehicle less than 15 km.

The spectral and time analyses of actual signals and the simulations of the jet noise reaching the station were performed by using jet plume aerodynamics and jet noise models tested with success from data of static firing of rocket motors at reduced scale (Fauga-Mauzac Test Center, ONERA).

Of course, the models also take into account the launch vehicle speed and the atmospheric conditions at the considered altitudes. Calculations are made by one-second steps along the launch vehicle trajectory (step $t_2 - t_1$ in Fig. 10), the calculated arrival times at the recording station allowing to estimate the successive values of the Doppler factor, and thus the shifts in frequency and in sound level of the spectra calculated without Doppler effect.

Without going into detail of the applied models, one can see on Fig. 11 (subsonic case on the left, supersonic case on the right) that the introduction of the Doppler factor improves, to a significant extent, the simulation of the sound pressure spectra recorded at ground level, whether the launch vehicle speed is subsonic or supersonic.

The scales of sound level have a dynamics of 50 dB, i.e. 2.5 dB per small graduation. On each figure, the upper sky blue curve shows the simulation of the noise spectrum without introducing the Doppler effect. The red and the orange curves show the simulation including the Doppler effect, with and without taking into account an acoustic reflection off the ground: the gap between these curves is 3 dB, knowing that the microphone of the station is fixed on a vertical pole over a planted ground.

Note that no sonic boom was recorded by the station TOUCAN, because it was already located inside the sound cone of the jet sources when the launch vehicle speed became supersonic.

Besides, there are not two Doppler frequencies with the time approach, since the two frequencies which reach together the listening point are not emitted simultaneously. Here, only the "retrograde frequency" can reach the listening station, which will not be the case with an aircraft flying past at supersonic speed.

4. CONCLUSION

We have shown that the sonic boom and the sound wave emission at supersonic speed are two phenomena of totally different nature, the former being linked up to the size and the geometric shape of the mobile, the latter being of an acoustic nature and

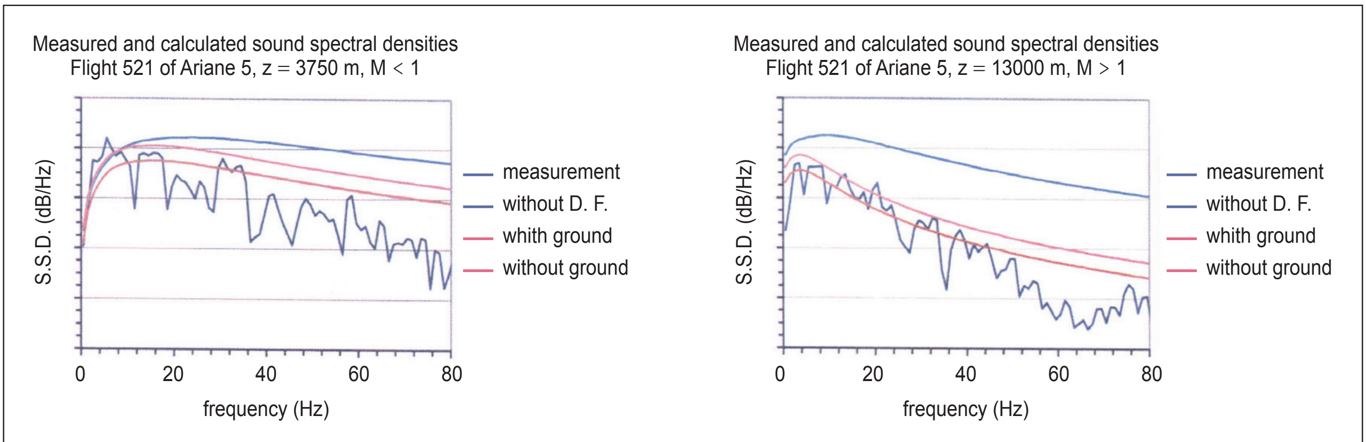

Figure 11. Recorded and measured spectral densities of the sound pressure received at ground level during Flight 521 of Ariane 5, from Ref. [27]

subject to the Doppler effect which modifies the reception characteristics to a considerable extent.

In brief, the first phenomenon depends on the physics of shocks, the second phenomenon depends on the geometrical acoustics. A common feature may be the focusing which occurs on a given surface in the cases of acceleration or turning on the one hand, on the sound cone which follows the shock wake immediately on the other hand.

Despite the frequent confusion or inaccuracy found in the later literature (Mach cone generated by spherical waves), these phenomena have been very well described in Ref. [3] as early as in 1925, except for the theoretical focusing on the sound cone which is actually difficult to detect.

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REFERENCES

[1] Mach E., *Photographische Fixierung der durch Projektile in der Luft eingeleiten Vorgange*, Akademie der Künste und Wissenschaften, Vienna, 1887..

[2] Becker R., *Stosswellen und Detonationen*, Zeitung für Physik 8, pp. 321-347, 1921.

[3] Charbonnier P., Esclangon E., *Etude cinématique du champ acoustique d'un projectile. L'acoustique des canons et des projectiles*, Mémorial de l'Artillerie Française, Vol. IV, Part 3, 1925.

[4] Landau L.D., *On shock waves*, J. Phys. Acad. Sciences USSR 6, pp. 229-301, 1942.

[5] Du Mond J.W.M., Cohen E.R., Panofsky W.K.H., and Deeds E., *A determination of the wave forms and laws of propagation and dissipation of ballistic shock waves*, J. Acoust. Soc. Am., Vol. 18, No. 1, pp. 97-118, July 1946.

[6] Whitham G.B., *The flow pattern of a supersonic projectile*, Communications on pure and applied mathematics, Vol. V, No. 3, pp. 301-348, John Wiley and Sons, Inc., New-York, August 1952.

[7] Stoughton R., *Measurements of small-caliber ballistic shock waves in air*, J. Acoust. Soc. Am., Vol. 102, No. 2, Part 1, pp. 781-787, August 1997.

[8] Sadler B.M., Pham T., Sadler L.C., *Optimal and wavelet-based shock wave detection and estimation*, J. Acoust. Soc. Am., Vol. 104, No. 2, Part 1, pp. 955-963, August 1998.

[9] Ribner H.S., *The noise of aircraft,* ICAS Paper No 64245, 4th ICAS Congress, Paris, 1964 .

[10] Froböse M., *Kopfwellenknalle einer Mirage III im Überschallflug. Teil V: Ergänzungsflüge zur Versuchsreihe "Jéricho Marina"*, ISL Report N 30/64, November 1964 .

[11] Froböse M., *Flugzeugknalle einer Mirage III beim Überschallflug. "Jéricho Instrumentation" in Istres, 7.-11. Februar 1966*, ISL Report T 38/66, November 1966 .

[12] Taylor A.D., *The TRAPS sonic boom program*, NOAA Technical Memorandum ERL ARL-87, Air Resources Laboratories, July 1980 .

[13] Norris R.N., Haering Jr. E.A., and Murray J.E., *Ground-based sensors for the SR-71 sonic boom propagation experiment,* NASA Technical Memorandum 104310, September 1995.

[14] Ivanteyeva L.G., Rackl R.G., et al, *Validation of sonic boom propagation codes using SR-71 flight test data,* J. Acoust. Soc. Am., Vol. 111, No. 1, Pt. 2, pp. 554-561, January 2002.

[15] Vallée J., *Mesure de l'intensité des bangs soniques engendrés par un avion volant en palier accéléré supersonique. Opération « Jéricho-Focalisation »*, CEV, Annexe d'Istres, Report No. 272, October 1967.

[16] Vallée J., *Etude expérimentale des focalisations de bangs soniques engendrées par le vol supersonique en accélération rectiligne ou en virage d'un avion Mirage IV à l'altitude 11000 m. Opération « Jéricho-Virage »*, CEV, Annexe d'Istres, Report No. 277, May 1969.

[17] Le Pichon A., Garcés M., Blanc E., Barthélémy M., and Drob D.P., *Acoustic propagation and atmosphere characteristics derived from infrasound waves generated by the Concorde,* J. Acoust. Soc. Am., Vol. 111, No. 1, Pt. 2, pp. 629-641, January 2002.

[18] Ménéxiadis G., Varnier J., *Long-range propagation of sonic boom from the Concorde airliner: analyses and simulations*, Journal of Aircraft, Vol. 45, No. 5, pp. 1612-1618, September 2008.

[19] Hubbard H.H., et al, *Proceedings of the sonic boom symposium*, St Louis (Missouri), November 3, 1965, J. Acoust. Soc. Am., Vol. 39, No. 5, Part 2, pp. S1-S80, 1966.

[20] Hubbard H.H., *Sonic boom*, Physics Today, pp. 31-37, February 1968.

[21] Pierce A.D., *Atmospheric propagation of sonic booms*, 15th AIAA Aeroacoustics Conference, Long Beach, California, October 27, 1993.

[22] Coulouvrat F., *Le bang sonique*, Le Monde des Sons, magazine "Pour la Science", special issue, pp. 24-29, July/October 2001.

[23] Whitham G.B., *Linear and non-linear waves*, Pure and applied mathematics, Chapter 12-4 Ship waves, pp. 409-414, John Wiley and Sons, Inc., New-York, 1974.

[24] Ménéxiadis G., *Détection à grande distance et localisation du supersonique "Concorde" à partir de signaux infrasonores*, thèse de l'Université d'Aix-Marseille, December 2008.

[25] Morse P.M., Ingard K.U., *Theoretical Acoustics*, Sound emission from moving sound sources, pp. 717-736, McGraw-Hill Book Co., New York, 1968.

[26] Gill T.P., *"The Doppler effect – An introduction to the theory of the effect"*, Logos Press Ltd., Academic Press Inc., London, 1965.

[27] Varnier J., *Calcul des jets d'Ariane 5, simulation des écoutes au sol compte tenu de l'effet Doppler*, 42ème Colloque d'Aérodynamique Appliquée, Sophia-Antipolis, France, 19-21 March 2007.

Acoustic Simulation of Renaissance Venetian Churches

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ABSTRACT

The large churches of the Venetian Renaissance have very long reverberation times and provide poor clarity for appreciating the complex polyphonic music composed for these spaces. Geometric acoustic simulation techniques have been used to provide insights into the acoustics of two large Venetian churches, the Redentore and San Marco, as they would have existed during the Renaissance. Using the ODEON® acoustic simulation programme, virtual models were constructed that accurately matched recently measured acoustic data at a number of source-receiver combinations. In consultation with architectural historians, evidence has been assembled on the structure and layout of the Redentore and San Marco on festal occasions, when large crowds, extra seating and wall tapestries would have provided extra absorption. The models were then adjusted to reflect these changes. The simulations demonstrate that under festal conditions these churches would have had significant improvements in T_{30}, EDT and C_{80}, making them suitable for the performance of polyphonic music. The Doge's position in the chancel of San Marco has particularly good clarity for sources in the galleries, or *pergoli*, supporting Moretti's conjecture that these galleries were installed by architect Jacopo Sansovino for enhanced appreciation of polyphonic split-choir music.

1. INTRODUCTION

This study of the acoustics of Renaissance churches in Venice is a follow-up to a research project carried out at the University of Cambridge, UK. The Centre for Acoustic and Musical Experiments in Renaissance Architecture (CAMERA) is an interdisciplinary project investigating the connections between architecture, acoustics and musical composition in the Renaissance, and has involved architectural historical and musicological research, *in situ* choral experiments and the quantitative acoustic characterisation of eleven Venetian churches [1]. 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?

The first three questions were discussed in detail in the book *Sound and Space in Renaissance Venice* by Howard and Moretti [1] and in the studies by Bonsi *et al.* [2, 3]. This paper concerns the virtual reconstruction of the acoustics of two of the great churches studied by Howard and Moretti in order to discuss the fourth question and to cast further light on the first three.

2. BACKGROUND

During the sixteenth century, there were remarkable developments in architecture and music in Venice. At the church of San Marco, *cori spezzati*, or split choirs, were probably introduced into Venice by composer Adriaan Willaert and later exploited by Andrea and Giovanni Gabrieli and Claudio Monteverdi. 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. Howard and Moretti's comprehensive survey of the many different aspects of the interactions between music, architecture and acoustics addressed all the issues listed above and at the same time raised questions about how the complexities of innovative polyphonic music could be fully appreciated in the large acoustic volumes of the great celebratory churches for which some of the greatest music was written.

Howard, Moretti and their colleagues carried out an extensive programme of acoustic measurements of 11 surviving Venetian churches: 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 details of the programme of measurements are described in Appendix 1 of Howard and Moretti [1]. The combinations of source and microphone positions were chosen on the basis of architectural historical and musicological research. Sufficient measurements were taken to provide an excellent quantitative characterisation of the acoustic properties of the various spaces within each church. This paper describes how these acoustic data were used to create virtual acoustic models of four of the churches studied, the emphasis being upon the results for the Redentore and San Marco. Once these models were calibrated by providing satisfactory agreement with the measured acoustic data at the present day, they could be modified to recreate the acoustic conditions in the 16th century, using the evidence of architectural and musicological history.

3. THE MODELLING PROCEDURES - THE CHURCH OF SANTA MARIA DEI DERELITTI (THE OSPEDALETTO)

This project uses an approach developed to reduce the speculation involved in 'archaeo-acoustic' research. It involves first developing models for spaces that still exist and for which acoustic measurements are available. Assumptions about geometrical relationships, coupling effects and material content can then be tested against quantitative data. Once a virtual model has been obtained that accurately reflects the present state of a space, the simulation may then be adjusted to reflect its earlier form [4].

The modelling approach was tested through an analysis of the orphanage church of Santa Maria dei Derelitti, commonly known as the Ospedaletto, which has a simple geometric 'shoe-box' form and which had the best acoustics properties of all the churches studied. Acoustic data were secured for it as part of the CAMERA project by Bonsi and Moretti [2]. Construction of the church began in 1570 with some design input by Palladio. It was modified in the 17th and 18th centuries and was renowned throughout Europe for the girls' choir and its excellent acoustics.

The modelling was carried out using Odeon® v.10.0 Combined Edition [5, 6]. We benefited greatly from the advice of the originators of the Odeon® programme, Jens Rindel and Claus Christensen. In summary, the Odeon® software uses image-source modelling for first- and second-order specular reflections. For diffuse reflections, it uses a ray-tracing approach with oblique Lambert scattering. Diffraction effects are also taken into account [5]. The virtual acoustic space was built using the programme's parametric editor and then materials, sources and receivers assigned in the main window of the programme.

In the modelling procedures, we sought to create a good model, not an alternative reality. Some of the materials assignments were straightforward - the floors and columns were marble and the ceiling lath and plaster. The walls were a mixture of paintings, ornamentation and damp plastered brick. We adopted an empirical approach to the average absorption, reflection and scattering properties of the walls, starting with an absorption coefficient of 0.1-0.2 as a reasonable initial guess. The parameters only needed to be mildly adjusted to obtain values of EDT and T_{30} that were in satisfactory agreement with the acoustic measurements. A similar approach was adopted for the Redentore and San Marco.

Since the primary interest was in the perception of the music as experienced by period audiences, auditory just-noticeable differences (JNDs) were used to assess the agreement of the simulations with the measured values. The accepted JND for T_{30} and EDT is 5% [7]. The JND for C_{80} has been shown to be 1 dB or greater for reverberant spaces [8]. In principle, a perfect simulation should be within 1 JND of measured values, but since the most accurate blind modelling attempts yield results with an accuracy of about 5 JNDs, it was considered that the calibrated model had attained a satisfactory level of accuracy when the simulations were within 3 JNDs of the measured data [6].

A number of anechoic recordings were made of choral pieces composed in the 16th century, and these were used in auralisation experiments for the virtual model of the Ospedaletto. Listening tests convincingly demonstrated the excellence of the acoustics of the Ospedaletto for the performance of complex polyphonic music with excellent clarity and reverberance of about 2 seconds. Among the interesting results was the demonstration of the origin of an effect noted by the audience who responded to the questionnaires that accompanied the live choral experiments [3]. Several listeners remarked on the fact that the sound seemed to 'come down from on high', providing an ethereal effect. The acoustic modelling showed that this is a real effect associated with reflections of the sound within the organ gallery. The resulting wavefronts arrived at an angle of about 45° to the audience in the nave.

The fourth church studied was San Francesco della Vigna, the objective being to study the effect of different roof types and heights on the preaching of sermons. The results of that study are discussed in a companion paper [3].

4. THE CHURCH OF THE REDENTORE

4.1. Background

Palladio's Redentore, like the other large churches, exhibited long reverberation times that reduced complex polyphonic music to a muddied wash of sound. In his study of the decoration of Venetian churches on great festive occasions, Hopkins inferred that the spaces would have sounded very different on these occasions, when 'ephemeral ornament increasingly transformed church interiors … during feast-day celebrations and processions.' [9]

As a votive church funded by the Republic, the Redentore was built for the city's annual festival of the same name. For the rest of the year, the austere Capuchin friars who lived there would have experienced the acoustics of the empty church. The Capuchins disapproved of the extravagance of the church's main body, prompting Palladio to design a plain friars' choir behind the high altar (see Fig. 1), more in keeping with the Capuchin order's life of simplicity [1].

4.2. Modelling the Current Church

The Redentore's internal acoustic volume was modelled in Odeon®. The church is composed of marble floors and altars, some high clerestory glass windows, stone columns and plastered brick walls and ceiling. While the absorption data for marble and glass windows are fairly uniform, plastered brick is more variable. Since the latter constituted a large fraction of the church's interior surface area, absorption coefficients were selected within measured ranges to match the model's simulated data to the physical acoustic measurements.

Fig. 1 shows the source and receiver locations in the Redentore, as well as the listening locations of audience members who participated in the choral experiments.

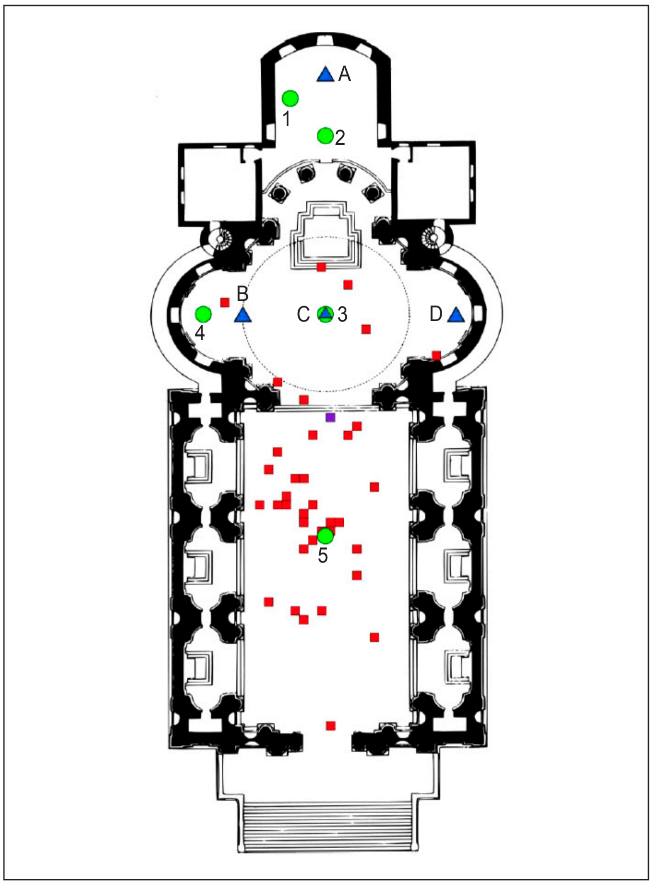

Figure 1. *A plan of the church of the Redentore showing: red squares - positions of audience members; blue triangle - location of acoustic measurement source, identified by letters; green circle - position of acoustic measurement microphone, identified by numbers. The source A and listening positions 1 and 2 are within the friars' choir.*

Figs. 2(a) and (b) compare the simulations with measurements of T_{30} for source A within the friars' choir to receivers 3 and 5 in the main body of the church. The simulations are within 3 JNDs of the measurements at every frequency except 8000 Hz, where the shorter T30 value decreases the JND significantly. The decrease in T_{30} is caused by the extreme lowpass filtering effect of air absorption in this band, making T_{30} less dependent on the material composition of the space. Since T_{30} is less salient at high frequencies, it was decided that this level of precision was acceptable for the 8000 Hz band. The model estimates of EDT and C_{80} were also found to provide a satisfactory match to the measured values at receiver positions 3-5 in the main body of the church.

The friars' choir is separated from the chancel by a colonnaded screen, consisting of a curved wall about 3 meters high and four large columns extending to the ceiling (see Fig. 1). This screen acted as a 'semi-permeable barrier' with the friars' choir acting as a 'church within a church', but still coupled to the main acoustic volume. The acoustic measurements supported this conclusion. With the source at A and the receivers at positions 1 and 2 in the choir, very

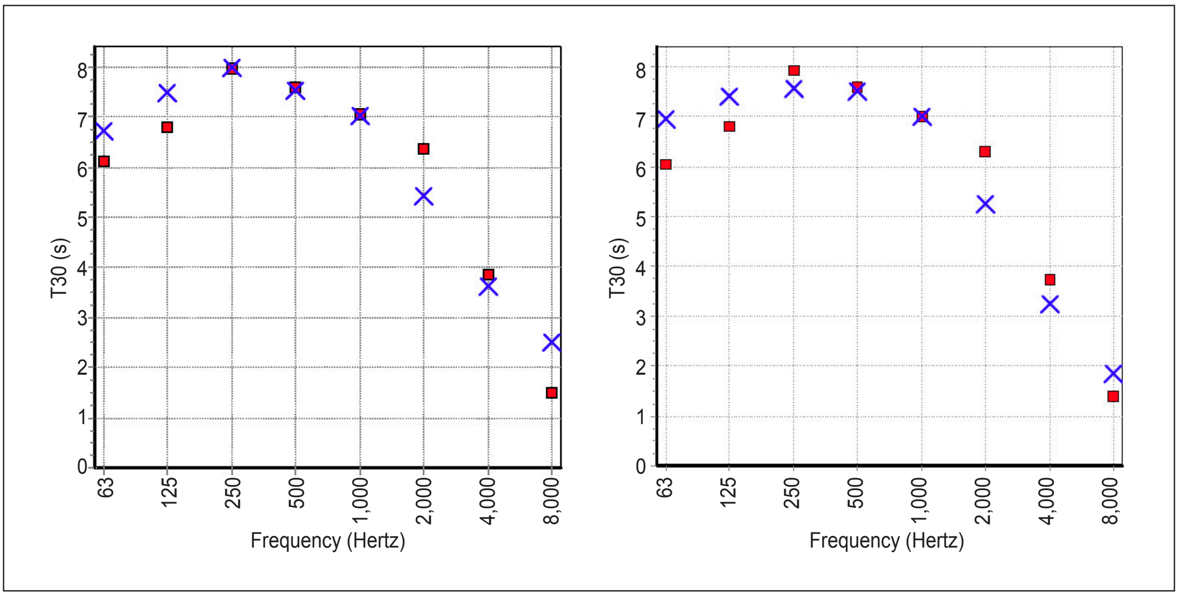

Figure 2. *Comparison of the measured and simulated values of T_{30} for the combination of source and receiver positions (a) A3 and (b) A5. The (blue) crosses are the measured values and the (red) squares the simulated values.*

significantly lower average values for the EDT of 1.6 seconds and of T_{30} of 3.7 seconds were found, as well as values of C_{80} greater than 2 dB. Thus, the friars had excellent acoustics for the performance of plainchant within their choir.

The coupling of the acoustic volumes of the choir and nave resulted in a double-slope decay within the choir (Fig. 3) - the early part of the decay is determined by the acoustic volume of the friars' choir while the later part is associated with the much longer decay constant of the main acoustic volume of the church [10, 11]. Because of this coupling effect, single-slope quantifiers such as T_{30} are inadequate to characterize these decay curves, although the EDT is well matched to the early decay. Odeon® recommended using a larger number of rays for coupled volumes, but increasing the number of rays used in the simulation by a factor of 5 did not affect the result. Thus, care is needed in interpreting the parameters derived from geometrical acoustical simulation algorithms. The long decay tail seen in Fig. 3 matched well the values of T_{30} for the main body of the church, and it was therefore concluded that the model gave a satisfactory account of all the acoustic volumes of the Redentore.

4.3. Sound Visualisation

Computer modelling also allows a visual analysis of sound propagation within the church by showing a spherical sound wave that gradually expands and reflects from surfaces in its path. The most striking geometrical feature of the acoustic volume is the extreme height of the dome above the chancel, as can be seen in Fig. 4. Previous Venetian churches had a tradition of false outer cupolas supported by wooden trussing, as was the case at San Marco. Palladio broke with this custom by instead using a cradle of thin wooden ribs to support the dome, allowing the inner curvature to be much greater, nearly matching the outer dome of the church's roof [12].

Visualizing the propagation of sound with a source at location C in the centre of the chancel (see Fig. 1), the effect of the dome on the acoustics of the church can be assessed. As expected and demonstrated by the model, the almost spherical dome causes focusing effects above the radial centre of the dome (Fig. 4(a)). After the wavefront spreads out from the first focusing point, there is a concentration of secondary focusing farther down resulting from reflections within the cylindrical drum supporting the dome (Fig. 4(b)). Because of the height of the drum, these secondary focal points are still many meters above the floor. Had Palladio constructed a shallower dome at a lower height, the secondary focal point could have reached the floor level causing unpleasant comb filtering effects in the chancel. Although Palladio probably had no acoustical effect in mind when he designed the dome, the immense cylindrical acoustic volume acts as a diffuser spreading the sound uniformly through the main volume after passing out of the dome.

4.4. Modelling Festive Occasions

Once a year, the Doge and his entourage would take part in a formal procession across the canal between the main island of Venice and the Giudecca on a bridge of boats to celebrate the delivery of the city from the devastating

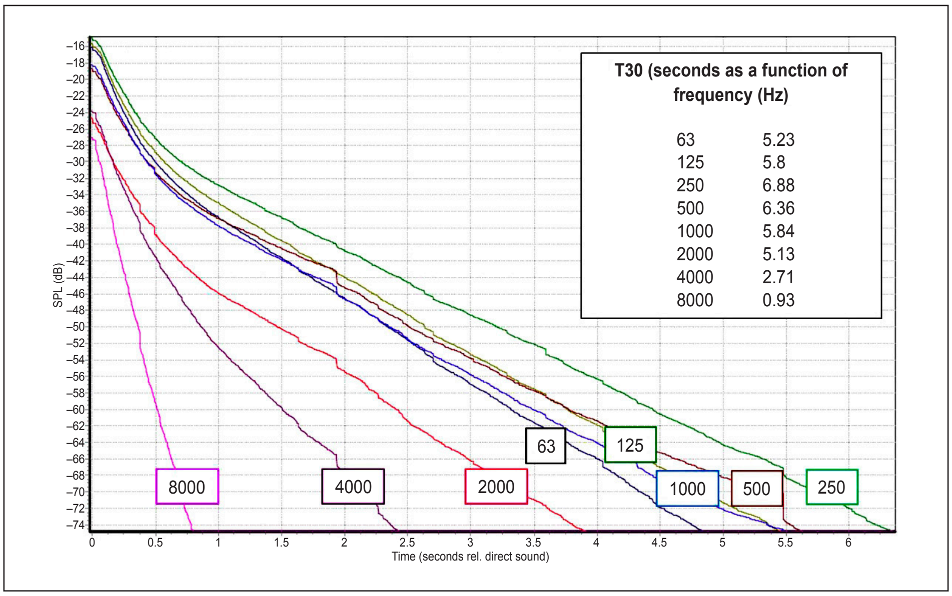

Figure 3. *Typical model decay curves by frequency band for source-receiver combinations A1 and A2 in the Redentore in dB-SPL for a source with sound power level L_W = 0 dB. The labels on the diagrams are the frequencies of each curve in Hz.*

plague of 1575-6 which caused the deaths of one third of the population of the city. On these major celebratory occasions, the Redentore would have been packed with the citizens of Venice. Hopkins has suggested three ways in which the acoustics would have been significantly modified on these occasions [9]. On the basis of his studies of similar celebrations in the church of Santa Maria della Salute [13], there would have been wall hangings and tapestries covering the columns in the nave and most of the sanctuary, the congregation would have been in their heavy robes, and temporary wooden bleacher-like seating called *palchi* would have been placed in the chancel for the Doge and his entourage. It has been recorded that on the great festive occasions, thousands of Venetians were present in the Redentore, filling the floor area of most of the acoustic volume.

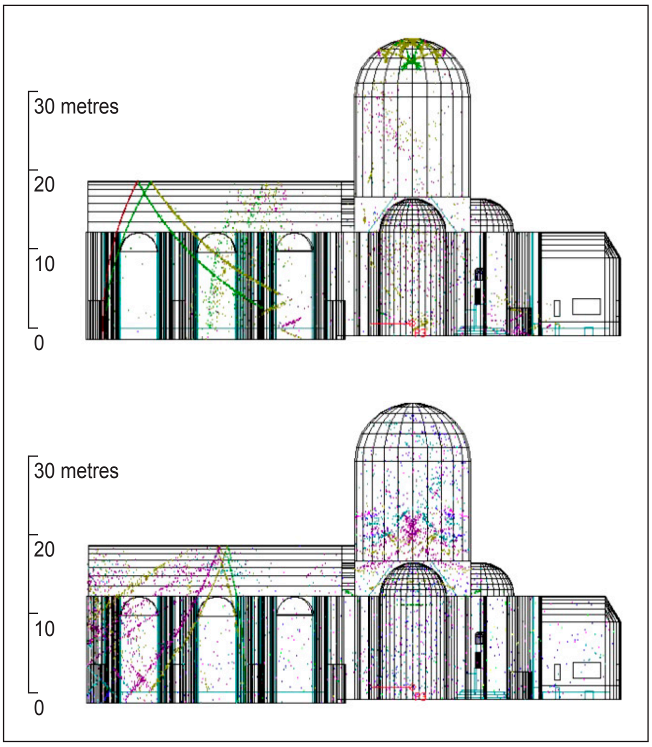

Figure 4. *(a) Primary focusing of sound waves within the dome of the Redentore from a source at C, 114 milliseconds after the sound was emitted. (b) Secondary focusing from the dome, 179 milliseconds after the sound was emitted.*

In modifying the virtual Redentore, we aimed to produce the largest reasonable acoustic change using the properties of measured materials in order to understand how significantly the acoustic parameters might have changed on the great festal occasions. The absorption coefficients for Renaissance tapestries and wall hangings were taken to be those of heavy drapes, which are very absorbent at high frequencies but less so at lower frequencies.

One of the most absorbent materials was the audience itself. Based on the descriptions of the massive crowds flocking to the church, we modelled a large congregation in the church. The nave floor was covered by a 'surface' of people 2 meters above the ground, though the side chapels were left empty. The chancel would have been occupied by the clergy, the Doge, and his entourage. This area would probably have been less crowded and so was less densely populated in the model. Since the database included different absorption coefficients for individuals based on the thickness of their clothes, this was incorporated into the model: the audience in the nave were given slightly less absorbent clothing, while the nobility in the rear of the chancel were given higher absorption coefficients corresponding to their heavy ceremonial robes.

The original high altar was less tall than that in the church today. Although the marble altar provides almost no absorption and was not found to contribute to the coupling of the friars' choir, the original altar was incorporated into the virtual festal church. In addition, two *palchi* were added to the model's chancel and were filled with the same heavily-robed nobility as at the rear of the chancel. Virtual images of the festal Redentore from the Odeon® simulations are available on line [14].

The four changes to the virtual church were added separately to ascertain the impact of each. As expected, the shortened altar had no effect on any acoustic parameter. The addition of an audience gave significant damping at mid-frequencies. The tapestries provided additional absorption at high frequencies. While the wooden parts of the *palchi* added low-frequency absorption, their surface area was too small to affect the overall reverberation time, though the *palchi* did slightly affect EDT at nearby receivers in the chancel.

When these changes were combined into a single model, the overall changes were considerable. Figs. 5(a) and (b) show the averaged T_{30} across all receivers from source B in the left chancel apse. Low frequencies are dampened somewhat, since the audience (absorption coefficient 0.15 at 62.5 Hz) is still much less reflective than the marble floor (absorption coefficient 0.01 at 62.5 Hz). T_{30} at mid and high frequencies is, however, decreased to roughly half of that of the empty church. As would be expected based on the earlier analysis of the friars' choir, while the EDT decreased for the receivers in the main body of the church, receivers in the choir were unaffected since absorption behind the screen was unchanged.

Reducing the reverberance of the main body of the church also increased significantly the C_{80} values. For a source under the dome in the chancel, the C_{80} value for a listener in the centre of the nave was very low for the empty church (Figs. 6(a)). But in the virtual festal church (Figs. 6(b)), C_{80} was significantly increased in

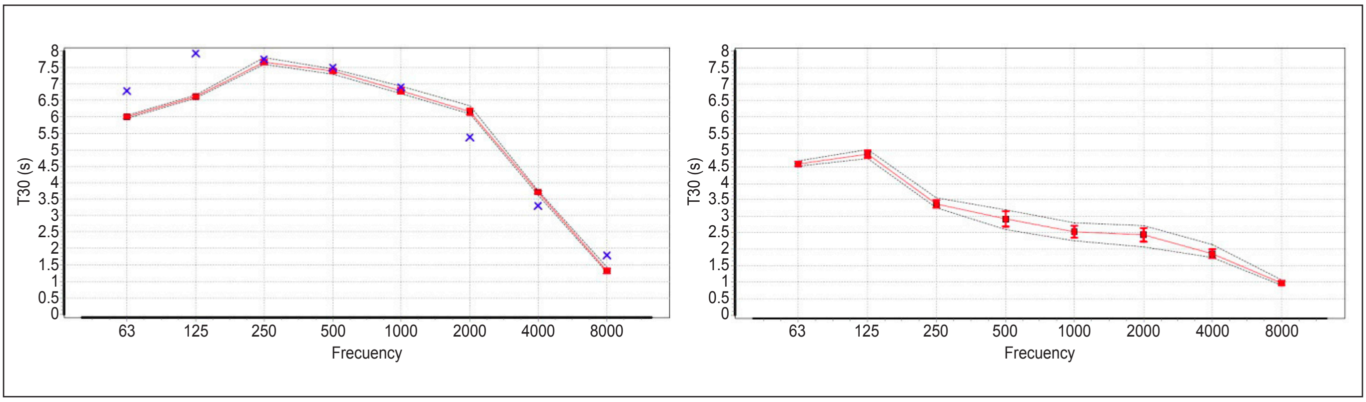

Figure 5. *(a) Comparison of the simulations for T_{30} averaged over all receivers with the source at B in the left chancel apse for the empty Redentore. (b) The averaged T_{30} simulations as in (a) for the festal Redentore.*

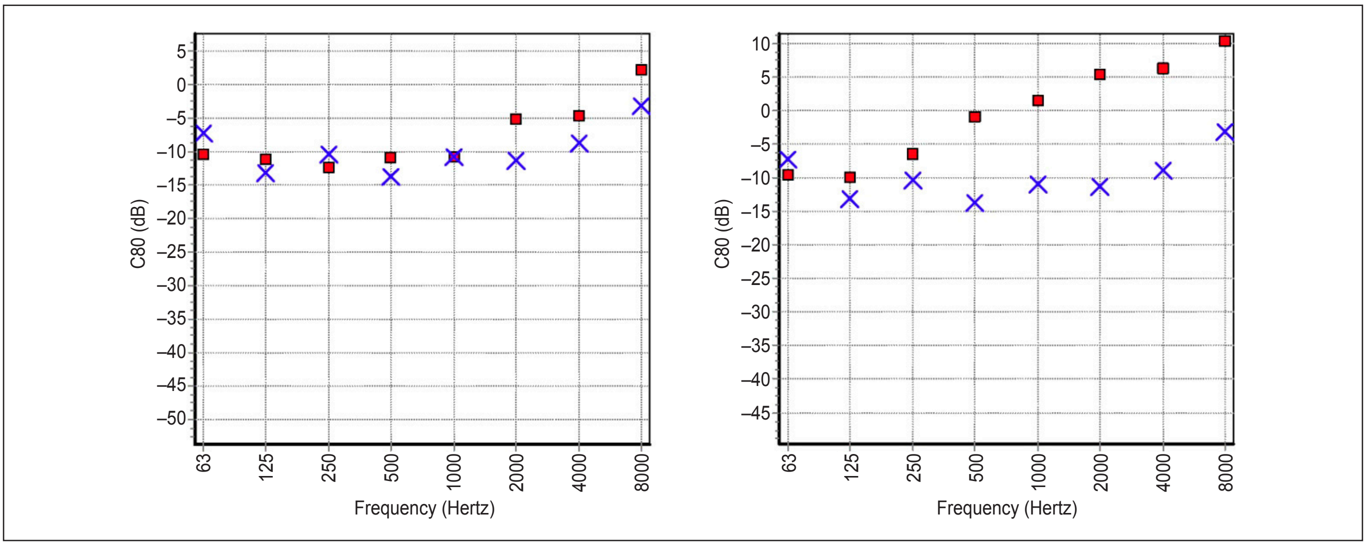

Figure 6. *(a) Comparison of the C_{80} simulations (red boxes) with the acoustic measurements at C5 (blue crosses) for the empty Redentore. (b) C_{80} simulations for C5 in the festal Redentore (red boxes) compared with measurements of C5 for the empty Redentore (blue crosses).*

the mid- and high-frequency bands. Reaching values greater than 0 dB, this region of the spectrum experienced a dramatic increase in clarity. The added clarity of the festal church does not come without cost, however - there is a decrease in overall sound intensity. The simulated impulse response for C5 in the empty church is 4-8 dB louder than that of the festal church from 250-8000 Hz, the frequency bands in which C_{80} increased the most.

These conclusions were substantiated by auralisations of the anechoic recordings made by the choir of complex polyphonic music. Whilst the empty church was unsuited for such music, the festal church would have provided all listeners wherever they were located with a clear and satisfying musical experience.

5. THE CHURCH OF SAN MARCO

5.1. Background: The Doge's Chapel

Until 1807, the church of San Marco was the private chapel of the doge. As a state church, it developed its own liturgy, distinct from that of the Roman Church. This ceremonial independence was highly prized by the Venetian Republic, which resisted papal efforts to impose the Roman liturgy in Venice.

During the Renaissance many distinguished composers, such as Willaert (1527-1562) and Monteverdi (1613-1643), occupied the post of *maestro di cappella* at San Marco, writing new music for the chapel and conducting the choir. In this same period Andrea and Giovanni Gabrieli served as the church's chief organists and composed works for the choir as well. During Willaert's 35 year tenure, the split-choir, or *coro spezzato*, style for which San Marco would become famous, was introduced. The Doge had previously occupied the hexagonal pulpit, known as the *bigonzo* (location A,1 in Fig. 7) outside the chancel. Doge Andrea Gritti became so overweight that he could no longer climb the stairs into the *bigonzo* and so moved his location to a throne in the chancel [15], to location 2 in Fig. 7.

Moretti proposed that during Willaert's tenure the split choirs occupied the twin singing galleries known as *pergoli* within the chancel [16]. Willaert's student, and subsequently *maestro di capello* at San Marco, Gioseffo Zarlino, asserted that the split choirs were 'placed rather far apart' [1]. Jacopo Sansovino, appointed as chief architect, or *proto*, of San Marco two years after Willaert's arrival, erected the two *pergoli* in the chancel following Gritti's relocation of the Doge's position. The first was built to replace a previous *pergolo*, but at a significantly higher level because the ground level was now fully occupied by stalls for the Doge's retinue. Moretti suggested that the second *pergolo*, added about five years later, was constructed for the performance of *coro spezzato* on either side of the Doge's new position. The south, or right, *pergolo* is labelled C in Fig. 7 and there is a corresponding north, or left, *pergolo* on the opposite side of the chancel.

The CAMERA experiments found that performances from the *pergolo* had excellent clarity and low EDT at the Doge's position and throughout the chancel [1,3] but these values were considerably inferior in the nave where the congregation was located. As in the case of the Redentore, it was anticipated that the acoustics would be significantly improved on the great festal occasions. The church was therefore modelled in Odeon® with the goal of reconstructing the performance of complex polyphonic music as it would have been heard during Willaert's lifetime.

5.2. Modelling the Current Church

The church of San Marco has a Greek-cross plan, complicated by vast series of arches and apertures beneath its five mosaic domes. The structure of the church was traced as an extrusion model, and the many

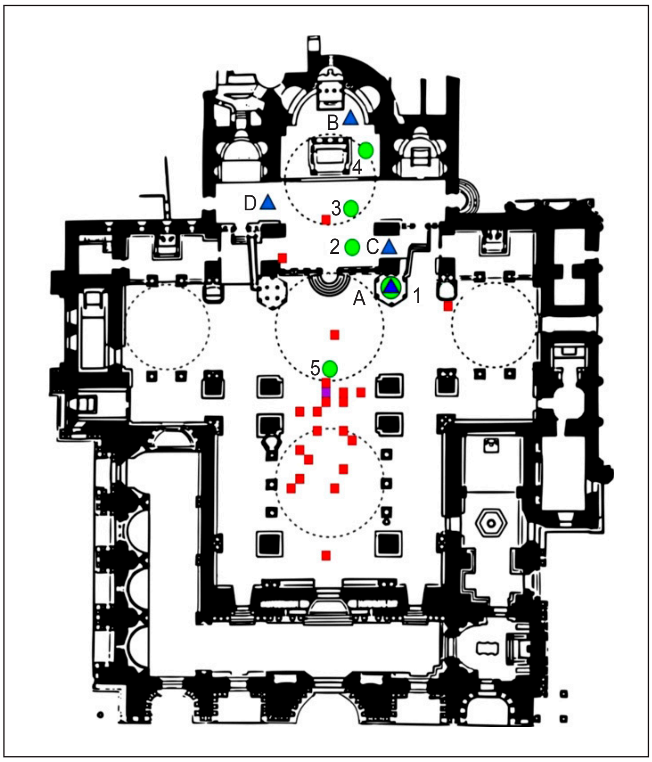

Figure 7. *A plan of the church of San Marco showing: red squares - positions of audience members; blue triangle - location of acoustic measurement source, identified by letters; green circle - position of acoustic measurement microphone, identified by numbers. Positions A and 1 are in the bigonzo, slightly raised, position C is in the right pergolo in the chancel and position D is the organ gallery, high above the left side of the chapel.*

arches, apses, columns and domes were added parametrically in Odeon® (Fig. 8). The many pendentives were modelled as triangles, as in the Redentore.

The only surfaces with unknown acoustic properties in San Marco were the gilded glass mosaics that cover large portions of the walls and ceiling. The mosaics were intentionally not laid smoothly, to give the church a golden glittering appearance. Using measured values of the acoustic parameters, we worked backwards as in the case of the walls of the Ospedaletto and the Redentore. The mosaics were found to have average absorption coefficients of up to 0.1, depending on frequency band. These surfaces were assigned a mid-frequency scattering coefficient of 0.2, corresponding to a surface roughness depth of about 10 mm. The CAMERA data used four source and five receiver positions (Fig. 7), but the present analysis focused mainly on sources at A (in the *bigonzo*) and C (in the south *pergolo*).

The model was able to reproduce correctly the variation of T_{30} with frequency in the nave (receiver position 5) from sources at A and C. In addition, the model correctly simulated the high measured values for EDT in the nave, a simple exponential decay.

The Doge's position in the chancel (position 2) proved to be more complex acoustically than had been expected from the CAMERA measurements. With the source located centrally in the south *pergolo* and the receiver at the Doge's position (C2), the model resulted in poor agreement with the measured values of EDT, T_{30} and C_{80}. As with measurements in the friars' choir at the Redentore, the T_{30} simulations deviated from measured values, but in San Marco the simulated values were too high rather than too low (Fig. 9(a)). When the source was moved one metre forward to the front centre of the *pergolo*, agreement with the measured values of EDT, T_{30} and C_{80} was recovered (Fig. 9(b). The origin of the relative clarity of the sound at the Doge's position is the direct line of sight to the choir in the *pergola* [17].

The reason for this is illustrated by the decay curve for C2 (Fig. 10), which shows a remarkable double-slope

Figure 8. *Odeon® model of San Marco, looking towards the rood screen and chancel.*

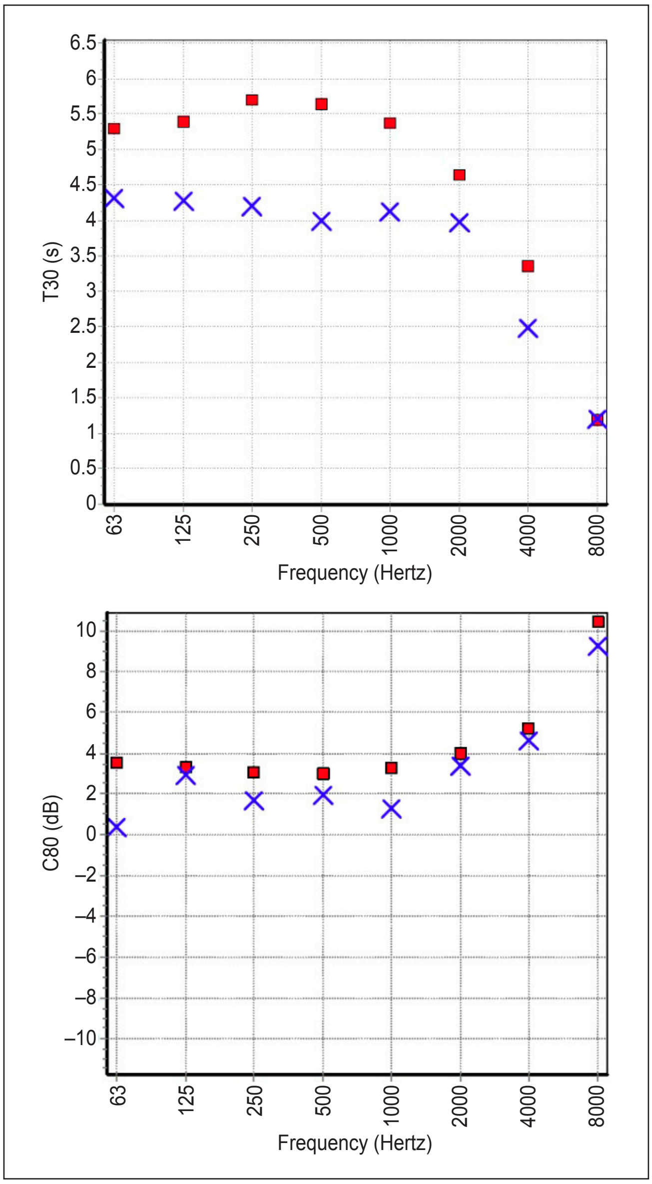

Figure 9. *(a) Model simulations of the values of T_{30} as a function of frequency (red boxes) compared with the acoustic measurements for the source-receiver combination C2 (blue crosses) for San Marco with the source centrally located in the south pergolo. (b) Model simulations of the values of C_{80} as a function of frequency (red boxes) compared with the acoustic measurements for the source-receiver combination C2 (blue crosses), after moving source C one metre forward to the front centre of the south pergolo.*

decay: the first 4-5 dB was nearly instantaneous, followed by the longer decay profile of the larger acoustic volume of the church as a whole. Although double-slope decay usually results in the T_{30} prediction being shorter than the actual reverberation time, in this case, since the estimate of T_{30} begins at -5 dB, the T_{30} value represents the longer decay time for the nave and thus overestimates the actual time for an extrapolated 60 dB decay for T_{30} at the Doge's position. While most double-slope decays are the result of a smaller acoustic volume coupled to a much large volume of the church as a whole, the modelling of the chancel of San Marco illustrates a more extreme type of behaviour. Because of the cavernous nature of the acoustic volume, the chancel exhibits almost complete 'open-window' absorption as the sound escapes into the larger volume of the church.

The clarity experienced at the Doge's position depended critically upon the location of the sound source within the south *pergolo*. During the modelling process, it was found that moving the choir's position by as little as 1 metre towards the back of the south *pergolo* drastically changed the simulated impulse response at the Doge's position: the earliest sound path to reach the Doge was a second-order reflection, delayed by about 45 ms from the previous arrival time and attenuated by 14 dB more than the direct path from the previous position (Fig. 11). From this altered position, the decay curve at the Doge's position was purely exponential, matching that of the nave, with clarity reduced accordingly.

Sansovino's elevated, slightly projecting *pergolo* resulted in a direct line of sight to the Doge and his entourage in the chancel, ensuring much higher musical clarity than that experienced by the rest of the congregation.

5.3. Modelling Festive Occasions

Like the Redentore, San Marco was filled with the people of Venice, tapestries and extra seating on the numerous great festal occasions, which were a very important part of the Venetian calendar. An anonymous painting from the 17th century entitled *Consignment of the Sword to Doge Francesco Morosini by Pope Alexander VIII in San Marco in 1690*, now in the *Museo Correr*, Venice, shows in great detail the stalls and tapestries in the chancel on one such occasion. The virtual chancel was altered to reflect the absorbent materials shown in this painting and the nave was filled by a large congregation and hangings were placed on the columns and walls. Virtual images of the festal San Marco from the Odeon® simulations are available on line [14].

These changes had a modest impact at low frequencies but resulted in much more substantial differences at mid frequencies because of absorption by the audience members. For combination A5, from the *bigonzo* to the centre of the nave, T_{30} (Fig. 12(a)) and the EDT decreased by up to 3.5 seconds in the middle frequency bands, while C_{80} (Fig. 12(b)) increased by up to 5 dB in that same range. This increase in clarity came at the expense of average loudness, which was nearly 6 dB lower in the festal church. A comparison of auralisations using anechoic input signals for the combination A5 in the empty and festal churches confirmed that the festal church sounded very much clearer but significantly quieter in intensity.

For source C in the south *pergolo* and receiver 2 in the Doge's position, the changes were also significant. T_{30} decreased by up to 4 seconds relative to the empty

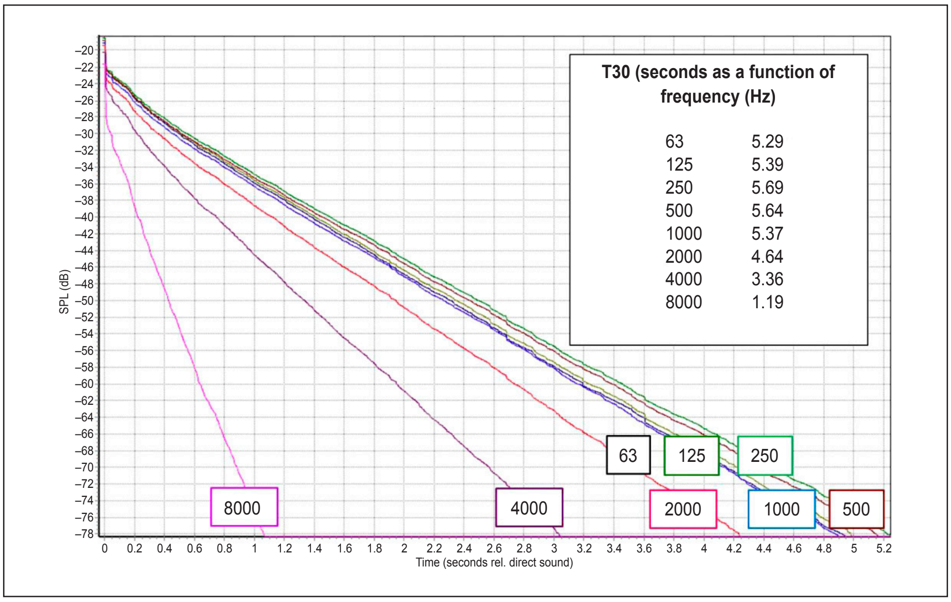

Figure 10. *Model decay curves by frequency band for source-receiver combinations C2 in San Marco in dB-SPL for a source with sound power level L_W = 0 dB. Note the very rapid decrease in intensity in the first 50 milliseconds.*

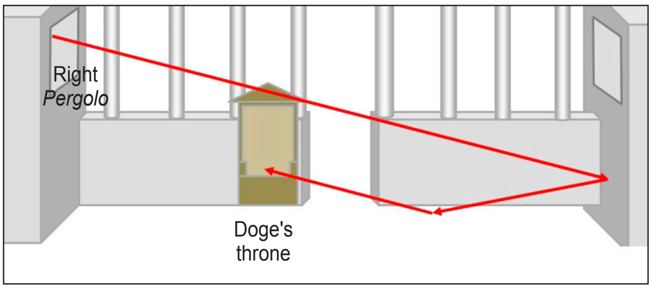

Figure 11. A schematic diagram illustrating the earliest sound path from recessed location C (right pergolo) to 2 (Doge's position) when source was moved 1 metre back in the centre of the right pergolo.

church (Fig. 13(a)), while the chancel's EDT was only shortened by about 2 seconds in the middle frequency bands. C_{80} increased by 2-3 dB (Fig. 13(b)). The average loudness for the combination C2 only decreased about 2.5 dB, remaining louder in the festal chancel than in the empty nave. Because of the problems of estimating T_{30} for decay curves such as that in Fig. 10, the differences between the empty and festal churches are regarded as indicative rather than absolute figures.

6. CONCLUSIONS

Most modern measurement campaigns of historic churches focus on their suitability for performance today. Geometric acoustical modelling is also an important tool for analysing historically significant performance spaces. In conjunction with quantitative acoustic measurements for existing buildings, it provides many ways of understanding the acoustics of complex volumes such as the churches in this study. When the accuracy of the models can be calibrated using such data, the models provide insights into past soundscapes of acoustic volumes for which architectural features and/or the acoustic properties of the materials of the building have changed significantly over time.

Acoustical modelling of the highly-reverberant Redentore has clarified how the added absorption would improve the acoustics, both by showing how sound propagates within the space and by quantifying how much difference a reasonable amount of absorbent material could have made. The sound diffuses so effectively those additional

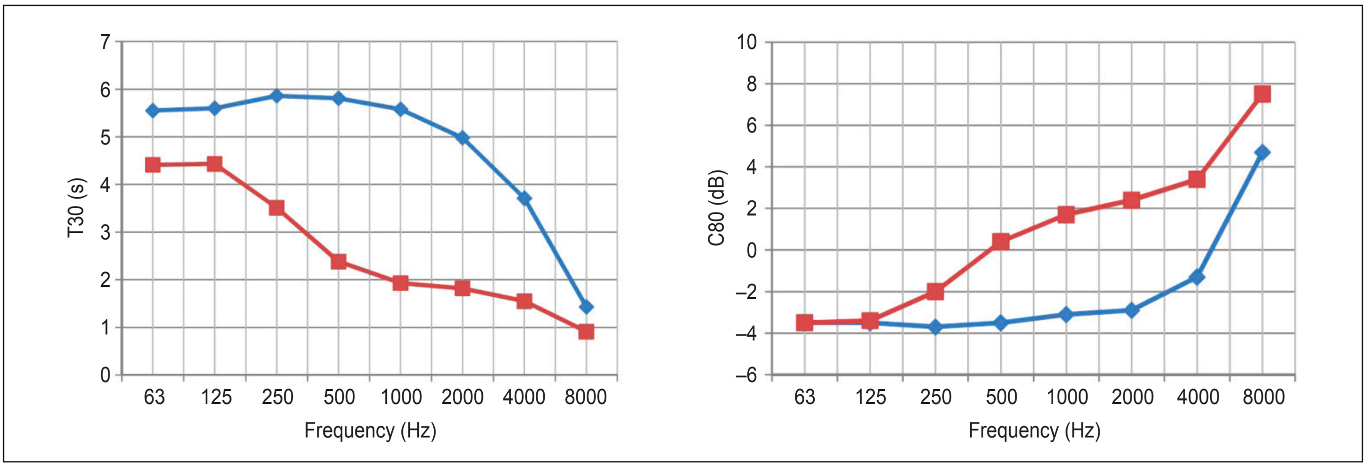

Figure 12. (a) Comparison of T_{30} for the empty church of San Marco (blue diamonds) and the festal church (red boxes), A5. (b) C_{80} comparisons for both versions of San Marco, A5 with the same notation as (a).

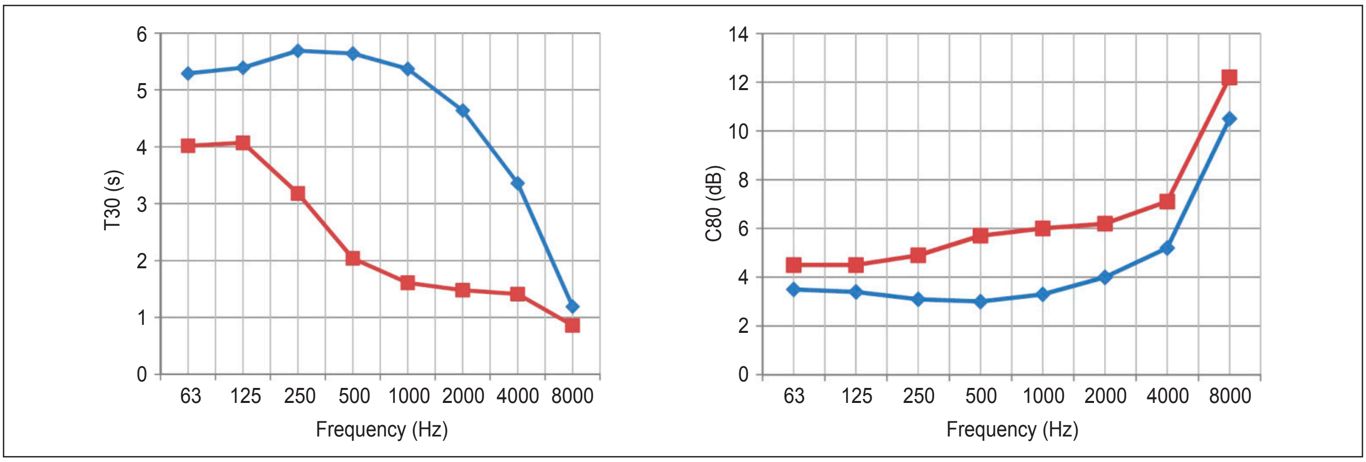

Figure 13. (a) Comparison of T_{30} for the empty church of San Marco (blue diamonds) and the festal church (red boxes) for the combination C2. (b) C_{80} comparisons for both versions of San Marco, with the same notation as (a) for the combination C2.

absorptive materials reduced significantly the space's very long reverberation time - T_{30} could be decreased at mid-frequencies by half or more [17]. Even if the audience was smaller than our estimates, each person's body would gain more equivalent absorption as the audience density decreased. As a result, the church's reverberation time would still have been significantly reduced at mid and high frequencies, and possibly reduced somewhat at low frequencies as well. For *a cappella* choral music, which has little energy in low frequency bands, the clarity would have significantly improved, although the overall loudness would have decreased. We can only speculate as to how Palladio's experience may have informed his intentions for the acoustics of the Redentore, but it is clear that it would have sounded best on the single day of the year, the annual *Festa del Redentore*, for which it was built.

The virtual model of the church of San Marco shows that, because of the drastic double slope decay in the chancel, a direct line of sight from the choir to the listeners would have been essential to achieve the favourable acoustics found in the CAMERA measurements. Whether Sansovino built the first *pergolo* to ensure a direct sound path is unknown - it had to be added because the earlier gallery on the ground floor had been concealed by the wooden stalls for the Doge's entourage. Sansovino's higher projecting galleries would have allowed direct sound from the choir to reach the entire chancel. Moretti's hypothesis that the *pergoli* were built to improve the clarity of complex polyphonic music and *coro spezzato* seems entirely plausible. The reconstruction of the festal interior demonstrated a significant drop in T_{30} and an increase in clarity, mostly at mid frequencies and mostly due to the presence of the large virtual audience.

The historical connection between architecture and music is a complex topic, spanning multiple disciplines and posing difficult questions [1]. Though computer modelling cannot establish definite proof of any particular historical hypothesis, it can provide valuable quantitative evidence to inform the historical discussion and also answers to specific questions about soundscapes that no longer exist.

ACKNOWLEDGMENTS

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REFERENCES

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

[2] Bonsi, D., Longair, M., Garsed, P. and Orlowski, R. Acoustic and audience response analyses of eleven Venetian churches. *Acoustics '08,* Paris, 3087-3092 (2008).

[3] Bonsi, D., Boren, B., Howard, D., Longair, M., Moretti, L. and Orlowski, R. Acoustic and audience response analyses of eleven Venetian churches . *Acoustics in Practice*, **1(1)**, 39-52 (2013).

[4] Boren, B. and Longair, M. A Method for Acoustic Modelling of Past Soundscapes. *The Acoustics of Ancient Theatres Conference*. Patras (2011).

[5] Christensen, C. and Rindel, J. A new scattering method that combines roughness and diffraction effects. *Forum Acousticum. Budapest* (2005).

[6] Christensen, C., Nielsen, G. and Rindel, J. *Danish Acoustical Society Round Robin on Room Acoustic Computer Modelling.* Odeon A/S: Lyngby, Denmark (2008).

[7] Vorlander, M. *International Round Robin on Room Acoustical Computer Simulations. 15th International Congress on Acoustics.* Trondheim (1995).

[8] Martellotta, F. The Just Noticeable Difference of Center Time and Clarity Index in Large Reverberant Spaces . *Journal of the Acoustical Society of America*, **128(2)**, 654-663 (2010).

[9] Hopkins, A. Ceremony, Singing and Seating in San Giorgio Maggiore. In *Architettura e musica nella Venezia del Rinascimento* (eds. Howard, D. and Moretti, L.), 147-159, (Milan: Bruno Mondadori), (2008).

[10] Bradley, D.T. and Wang, L.M. The effects of simple coupled volume geometry on the objective and subjective results from nonexponential decay. *Journal of the Acoustical Society of America*, **118(3)**, 1480-1490 (2005).

[11] Bradley, D.T. and Wang, L.M. Quantifying the double slope effect in coupled volume room systems. *Journal of Building Acoustics*, **16(2)**, 105-123 (2009).

[12] Piana, M. San Giorgio Maggiore e le cupole lignee lagunari. *Annali di architettura* **21**, 79-90. Rivista del

Centro Internazionale di Studi di Architettur Andrea Palladio di Vicenza (2009).

[13] Hopkins, A. *Santa Maria Della Salute: Architecture and Ceremony in Baroque Venice*, (Cambridge: Cambridge University Press), (2000).

[14] Boren, B. *Music, Architecture and Acoustics in Renaissance Venice: Recreating Lost Soundscapes*, (University of Cambridge: M.Phil. Dissertation, 2010). Online at: https://files.nyu.edu/bbb259/public/braxtonboren/MPhil_Thesis_Braxton_Boren.pdf

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

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

[17] Meyer, J. *Acoustics and the Performance of Music (5th ed.)*, (Berlin: Springer-Verlag), (2009).

Influence of the audio rendering on 3D audiovisual experience

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ABSTRACT

3D movies provide an improved immersion in terms of visual perception. As for the associate audio content, most of them are mixed for the conventional format of "multichannel 5.1". It should be considered that today there are various ways of listening to 5.1 audio content, either over loudspeaker arrays (for instance ITU standard 5.1 set-up), or over headphones. Recently, sound projectors were introduced in order to render surround sound with compact equipments. The choice of the solution to render multichannel audio has obviously an impact on the perception of the sound, but not only. Indeed, this choice could potentially impact the visual perception of audiovisual contents. This paper re-examine these issues in the new context of 3D video. The perception of the audiovisual scenes (audio, video and cross-modal perception) is assessed by a listening test for a set of audiovisual excerpts of a 3D movie. To do so, assessments are based on various criteria: degree of visual depth, sound spatialization, viewing comfort, listening comfort, immersion and consistency. The potential influence of audio rendering technology over these criteria is investigated.

1. INTRODUCTION

The digital entertainment industry is undergoing major changes with the recent generalisation of 3D video technologies (movies, TV, smartphones). In this context, video catches most of the attention and the question of a suitable audio is poorly investigated. Today, 5.1 surround system is the most often used sound spatialization technology for TV applications. But the 5.1 format is far from being the only solution. There is a wide range of alternative 3D audio technologies like binaural technologies [1, 2], Wave Field Synthesis [3, 4] or Higher Order Ambisonic [5] for example. The last two are suitable for home cinema, but not for handheld devices. For these latters, binaural technology provides a compact solution for 3D audio rendering. Now, it is well-known that all sound spatialization technologies are not equivalent, in terms of rendering of each dimension of the sound space (azimuth, elevation, distance), and particularly in terms of depth rendering. More precisely, WFS is known to render the depth of sound sources and parallax effect without sweet-spot constraints [6, 7].

The issue of interaction between the audio and video rendering already arose with 2D video (either for psychological approaches [8], or quality assessment [9]) but it deserves to be re-assessed for stereo display. Indeed, disparities between right and left images provide depth reproduction which is the new element brought by the 3DTV technique.

When putting together 3D video and 3D audio, it is clearly of considerable interest to compare the audiovisual perception as a function of the sound spatialization technology.

As a first step, this paper will focus on spatial sound systems which are commonly used to reproduce 5.1 audio contents. The most straightforward solution is a loudspeaker array, based for instance on the ITU standard 5.1 set-up [10]. An alternative is sound reproduction over headphones with a down-mix processing [10]. Recently, sound projectors were introduced in order to render surround sound with compact equipments. It is intended here to measure the impact of the solution chosen to render multichannel audio, on the perception of 3D audiovisual content. Among these existing systems, is there a solution more suitable than the other ones? Can the visual perception of stereoscopic images be influenced by a particular sound reproduction system? To answer these questions, subjective test should be performed, but first a proper methodology must be defined.

Indeed, most of the recommended 2D subjective assessment methodologies address only one single modality (ITU-R BT.500 and BT.1788 for video quality [11, 12], or ITU-R BS.1284, BS.1534 and BS.1116 for audio quality [13, 14, 15]). Some recommendations make suggestions for evaluating one modality in an audiovisual context or in the presence of an accompanying signal in the other modality (ITU-R BS.775 for multichannel audio with accompanying picture [10], ITU-R BS.1286 for the testing of audio systems with accompanying image [16], and ITU-T P.910 for evaluating the one-way overall video quality for multimedia applications such as videoconferencing [17]). Only P.911 and P.920 recommendations [18, 19] applied to audiovisual subjective assessment, in a non-interactive context or in an interactive one. But, if visual depth is added to the initial 2D video, these latter should be potentially rethought [20]. For example, Wei Chen suggested taking into account additional assessment attributes such as depth sensation, or visual comfort [21]. These considerations on the subjective assessment of stereoscopic 3DTV systems recently led to a specific ITU recommendation [22]. Similar issues are encountered with spatial sound: there is a lack of methods for the assessment of spatial audio quality. Indeed, standard methods [14, 15] do not take into account specific features of spatial sound and assessments are most of the time limited to the overall sound quality. That is why many studies are focused on the development of new methodologies for quality assessment of sound spatialization [23, 24, 25, 26]. Anyway, it should be noticed that, up to now, audio and video assessments remain independent: 3D video assessment is studied on one side, and spatial sound on another. We will consider the recent work on both sides to design our experimental test for the subjective assessment of 3D audiovisual contents.

This paper will describe a subjective test in which 15 excerpts of a 3D movie are presented to assessors. The 3D movie is mixed in 5.1 surround audio format. The aim is to present audiovisual sequences with 3 sound reproduction systems (5.1 surround system, sound projector and headphones). For each sound reproduction system, spectators have to evaluate the fifteen audiovisual sequences through six criteria focusing either on video, or audio, or the combination of audio and video. First, the experimental protocol is given in part 2. Then, the results are presented and discussed in part 3.

2. TEST DESIGN

2.1. Environment

Video excerpts are displayed on a LG 47LW5500 47” stereoscopic LCD screen with a 1920 x 1080 resolution. Spectators need to wear polarized glasses to see stereoscopic effects throughout the test duration. The passive technology is chosen because it appears more comfortable for the audience in comparison to active stereoscopic technology due to the weight of glasses.

Regarding to sound reproduction, three systems are used for the play-black of 5.1 sounds: Genelec 8040A Bi-amplified 5.1 multichannel system, Yamaha YSP-1 sound projector and AudioTechnica ATH-AD700 open headphones. All the sound reproduction systems are upstream controlled by a Terratec Phase 26 USB external sound card.

The test is performed in an acoustically treated room at Orange Labs. In this room, the background noise level is less than 30 dB(A) and the background room illumination is less than 20 lux as recommended in ITU-T P.911 [18]. The recommended viewing distance is about three times the height of the screen for HDTV [11, 22]. According to the monitor dimensions, the spectator sits at 1.85 meter from the 3DTV. The sound projector is placed under the TV and the multichannel audio system is placed around the listener. The 5 loudspeakers are located in accordance with the ITU BS.775 recommendation [10] and are 1.90 meter distant from the sweet spot.

2.2. Stimuli

Fifteen audiovisual sequences are extracted from a 3D documentary about the boxer Jean-Marc Mormeck [27]. Each excerpt lasts between 11 and 17 sec. The sequences were selected in order to illustrate the various combinations between audio content (speech, dialogue, environmental sounds, background music, etc.) and video content (indoor/outdoor, number of characters, object and camera motion speed, etc.). Sequences characteristics are presented in Table 1. Depth budget describe the amount of stereoscopic depth in an image. This value is defined as the difference between the disparity of the farthest and closest objects and is measured with a StereoLabs PURE system.

Surround sound effects have been added in post-production and are annotated (*) in Table 1.

Video files are encoded using H264 codec with an average bit rate of 30 Mbps (25 frames/s). All audio files are uncompressed PCM files with an original bit rate of 6912 kbps for 6 channels files and 1536 kbps for down-mixed 2 channels files. In both cases the sampling frequency is 48 kHz.

Table 1. Description of selected sequences.

Seq. number	Place	Motion	Music	Speech	Sound effects	Depth budget (px)	Description
1	Outdoor	Dynamic	Yes	–	Birds*	43	jogging (hand-held camera)
2	Outdoor	Dynamic	Yes	Breath	Birds* Footstep	16	jogging (travelling)
3	Outdoor	Dynamic	Yes	Breath	Birds* Footstep	41	title and jogging
4	Indoor	Dynamic	Yes	–	Applause* Punch	34	punchbags installation
5	Indoor	Static	Yes	Yes	–	33	interview
6	Indoor	Static	Yes	–	Punch	34	speed bag training
7	Indoor	Static	Yes	Voiceover	–	37	barbell training
8	Indoor	Static	Yes	Voiceover	–	40	warm-up walking
9	Indoor	Static	Yes	Voiceover	–	30	coach briefing
10	Indoor	Dynamic	Yes	–	–	37	training fight
11	Indoor	Dynamic	–	–	Applause* Punch	48	Fight (close up)
12	Indoor	Dynamic	Yes	–	–	39	cool-down period
13	Indoor	Static	Yes	Voiceover	–	21	cool-down (slowmotion)
14	Indoor	Dynamic	Yes	–	Applause*	54	punchbags installation, credits
15	Indoor	Static	Yes	Voiceover	–	51	end credits

2.3. Panel composition

The panel consists of 30 participants (21 women and 9 men) whose average age is 32.7 years. Among them, 28 spectators have experience in listening tests, but none of them took part to a subjective test with audiovisual content.

The number of participants is deliberately higher than recommended by the BT-500 (at least 15 observers). Indeed, in the context of 3D video, Chen highlights the need to increase the number of observers because of the instability of viewers' opinion [21], which is in agreement with the recent ITU recommendation BT.2021 [22].

2.4. Test procedure

The test is divided into three sessions. Each session is dedicated to one system of sound reproduction, either the 5.1 multichannel system, or the headphones, or the sound projector. The order of presentation of rendering systems changes every five spectators in order to present each possible combination to the same number of participants. The order of sequences is randomly varied for each spectator but keeps unchanged during the three sessions.

For each session, audiovisual excerpts are presented three times to spectators so they can focus successively on video, audio and audiovisual properties:

- During the first presentation, spectators have to assess the following video characteristics: **degree of visual depth** and **viewing comfort**.
- During the second presentation, participants have to assess the following audio properties: **degree of sound spatialization** and **listening comfort**.
- Finally, at the third presentation, the audiovisual scene should be assessed as a whole. Criteria are: **degree of consistency** between sound and image and the **degree of immersion** in the audiovisual scene.

After each presentation, participants rate the two corresponding criteria on 5-point scales of which extremes are labelled: “uncomfortable/comfortable” for comfort relating criteria and “low/high” for others. Each rating is then converted between 0 for “uncomfortable” (or “low”) and 4 for “comfortable” (or “high”).

Prior to the test, participants perform a short training task with 4 excerpts selected from the same 3D documentary. With this training, assessors can familiarize themselves with the stimuli and the test procedure. The average total test duration is 92 min (including pauses).

3. RESULTS

For each criterion, a variance analysis (ANOVA) is performed on individual scores considering two between-group factors: “Sound reproduction system” (three levels) and “Sequences” (fifteen levels). Then correlations between the six criteria are also studied.

3.1. *Video criteria*

Regarding the **degree of visual depth**, Figure 1 shows mean scores and associated 95% confidence intervals, obtained for each sound reproduction system and each sequence. It should be noticed that spectators perceived depth difference between sequences ($F(14,406)=11.27$, $p<0.001$). The sound reproduction system seems to not influence the visual depth perception ($F(2,58)=0.48$, $p=0.62$), whatever the sequence considered (no interaction, $F(28,812)=0.69$, $p=0.88$).

Figure 2 is a representation of mean scores obtained for perceived visual depth as a function of the depth budget measured among sequences (Table 1).

The perceived visual depth score is linearly correlated to the depth budget for 11 sequences with a R^2 factor of 0.89 (blue dots on Figure 2). The perceived amount of visual depth is greater than predicted for sequences number 3, 4 and 6 (red dots on Figure 2). A possible explanation is that additional visual cues can enhance depth perception. Monocular cues like linear perspective or relative size of objects could explain this phenomenon for sequences 3, 4 and 6. In addition, for sequence number 3, the title appearance in front of the screen is potentially responsible of the enhancement of visual depth

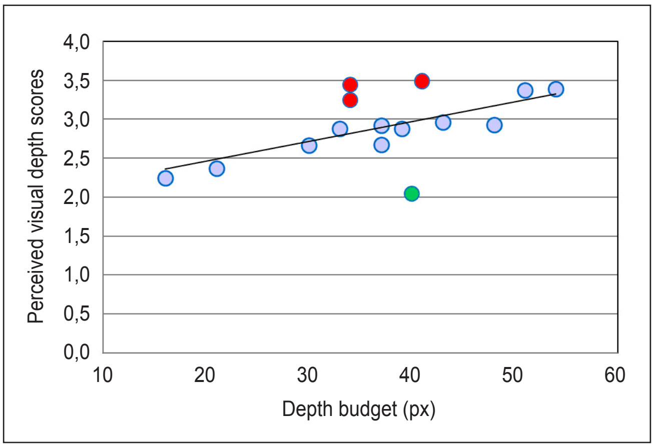

Figure 2. *Perceived degree of visual depth and objective depth budget of all sequences.*

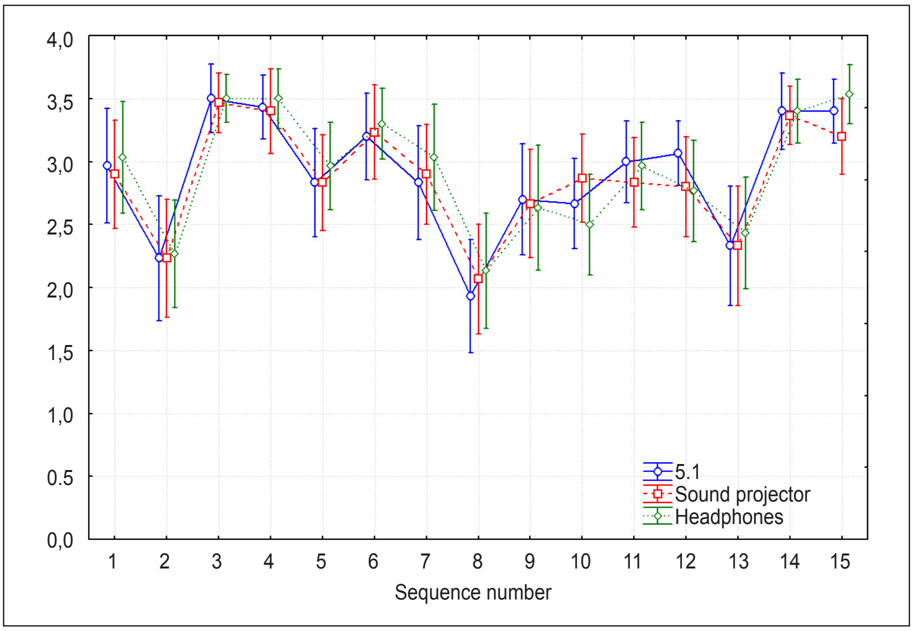

Figure 1. *Means and 95% confidence intervals for degree of visual depth criterion. The degree of visual depth is rated on a 5-point scale within 0 for “low” and 4 for “high”.*

perception. In order to illustrate these hypotheses, snapshots taken from sequences 3 and 4 are presented in Figure 3. Nevertheless, visual depth perception can also be reduced: the sequence number 8 is a case in point (green dot on Figure 2). In this particular case, it can be hypothesized that assessments are lower because some participants perceived visual depth as artificial.

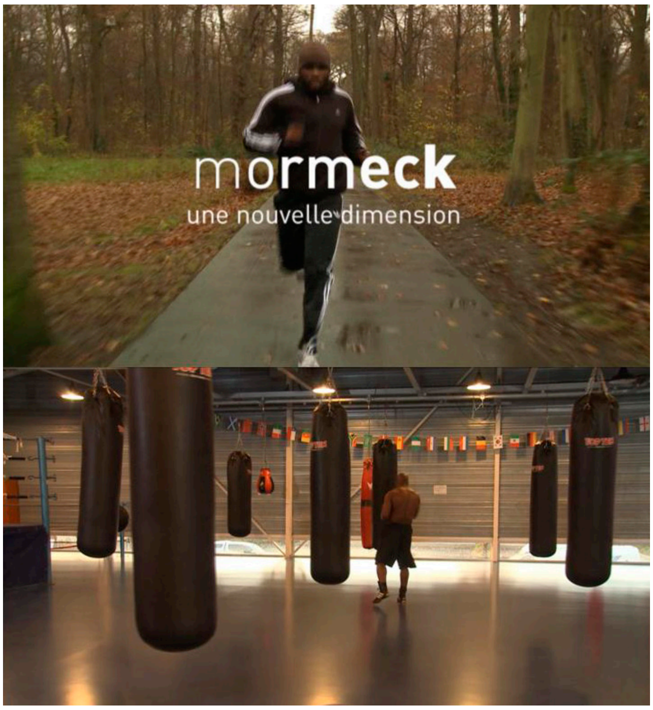

Figure 3. Snapshot of sequences 3 (top) and 4 (bottom) where various visual cues could enhance visual depth perception.

As to the **comfort of visualization**, Figure 4 shows mean scores and associated 95% confidence intervals, obtained for each sound reproduction system and each sequence.

As for the degree of visual depth, the only significant effect concerns sequences ($F(14,406) = 10.21$, $p < 0.001$). This effect is mainly due to the first sequence, which is perceived as uncomfortable for all sound reproduction technologies ($F(2,58) = 0.24$, $p = 0.78$). Assessors probably judged this particular excerpt as uncomfortable because of fast camera motions coupled with an important parallax for the nearest object.

3.2. Audio criteria

During the second presentation, participants have to assess audiovisual excerpts following its audio properties: **degree of sound spatialization** and **listening comfort**. Figure 5 depicts the mean scores concerning the **degree of sound spatialization.** Apart from a weak effect of the sequence on the impression of sound spatialization ($F(14,406) = 3.29$, $p < 0.001$), it appears that the perception of spatialization essentially depends on the sound reproduction system ($F(2,58) = 9.88$, $p < 0.001$). Figure 5 shows that spatialization is generally perceived as more noticeable with headphones than with a 5.1 system and that the sound projector is judged lower than the two other technologies, whatever the sequence ($F(28,812) = 0.88$, $p = 0.64$).

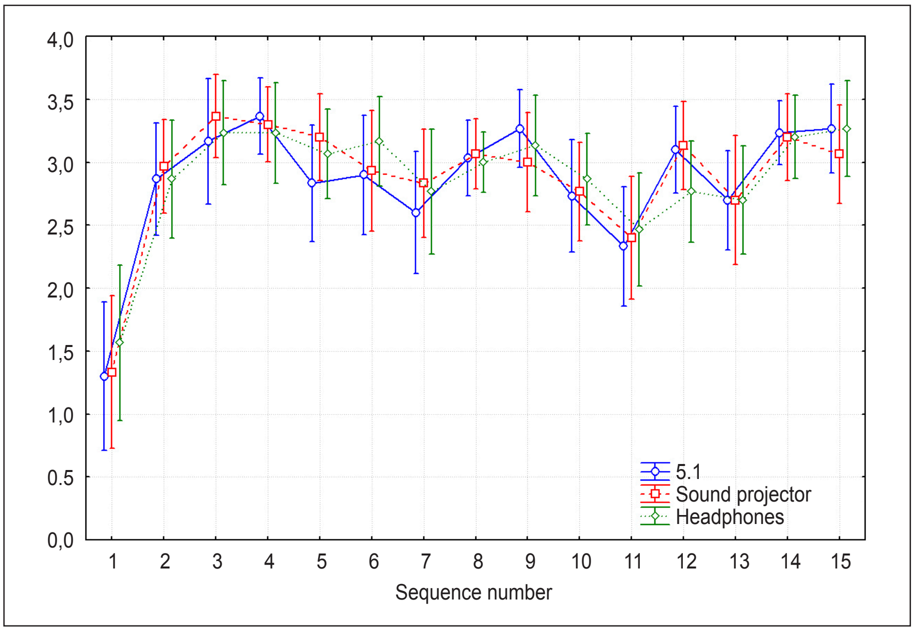

Figure 4. Means and 95% confidence intervals for comfort of visualization criterion. The degree of visual depth is rated on a 5-point scale within 0 for "uncomfortable" and 4 for "comfortable".

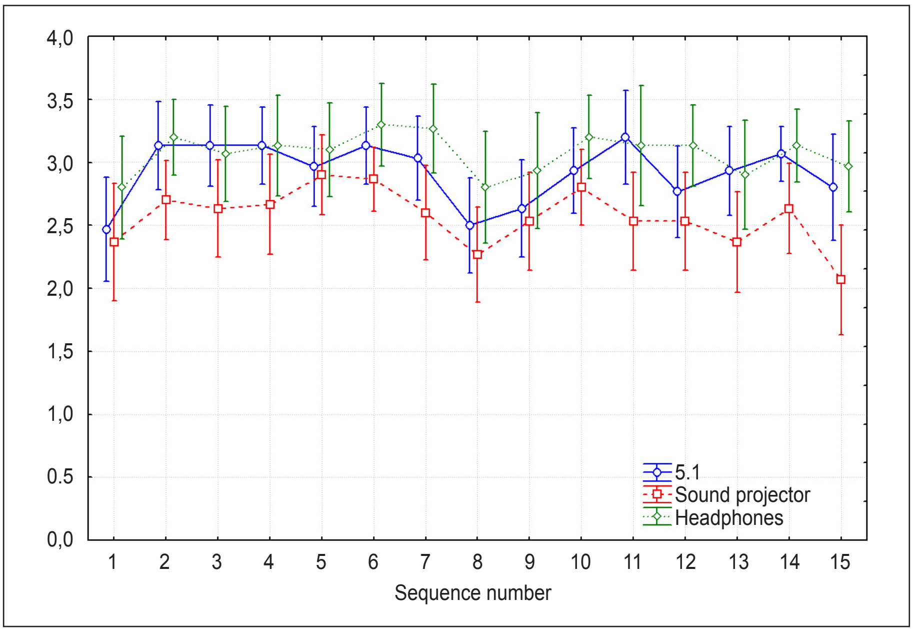

Figure 5. *Means and 95% confidence intervals for degree of sound spatialization criterion. The degree of visual depth is rated on a 5-point scale within 0 for "low" and 4 for "high".*

Nevertheless, this strong effect of sound reproduction system is not found for the **listening comfort** criterion ($F(2,58) = 2.54$, $p = 0.09$). It is observed on Figure 6 that all sound technologies are perceived as quite comfortable: most of mean scores are between 3.0 and 3.5.

Moreover, there is an effect of sequence on listening comfort ($F(14,406) = 4.76$, $p < 0.001$). Sequences 4 and 11 are perceived as the less comfortable. It can be remarked that these sequences have been post-processed to enhance surround sounds (Table 1).

3.3 Audiovisual criteria

During the final presentation, participants should consider the audiovisual scene as a whole. Regarding the **degree of consistency** between sound and image, the ANOVA shows a little but significant effect of sound

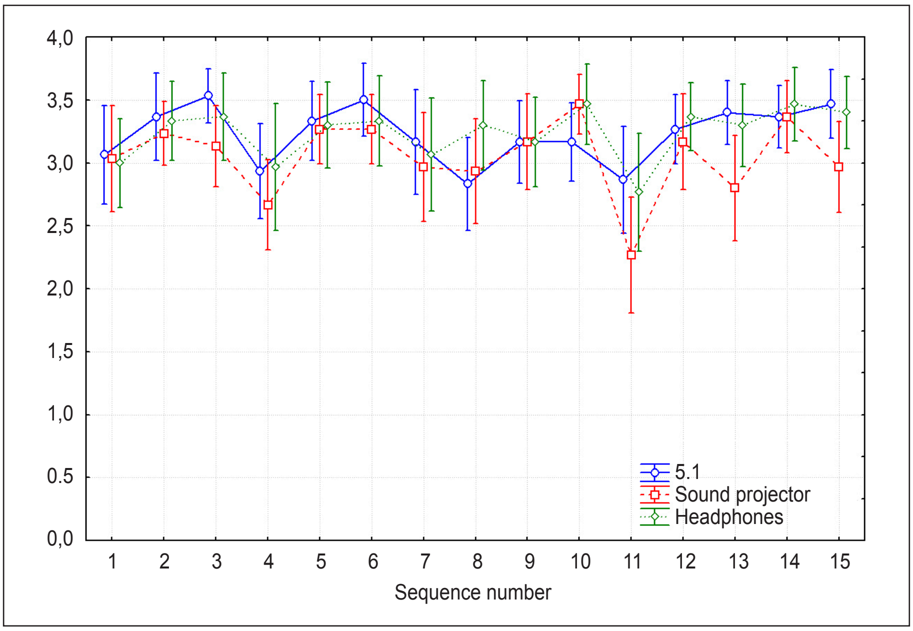

Figure 6. *Means and 95% confidence intervals for listening comfort criterion. The degree of visual depth is rated on a 5-point scale within 0 for "uncomfortable" and 4 for "comfortable".*

reproduction system ($F(2,58)=44.41$, $p<0.05$). According to these results, it seems that sound reproduction over headphones is slightly more consistent than other technologies. The ANOVA also reveals a significant effect of sequence ($F(14,406)=4.44$, $p<0.001$) but there is no interaction between these two factors ($F(28, 812)=0.66$, $p=0.91$).

As for the **degree of immersion**, the only significant effect concerns sequences ($F(14,406)=4.28$, $p<0.001$). There is no significant effect of the sound reproduction technology ($F(2,58)=2.69$, $p<0.08$) on the assessment of this attribute.

When these judgments are compared to the previous results (Sections 3.1 and 3.2), it appears that degrees of consistency and immersion are not explained in a trivial way by either visual depth or sound spatialization or visual/listening comfort criteria. Therefore, a correlation analysis is performed and the results are presented in Table 2. V1 and V2 are the video criteria **visual depth** and **comfort of visualization**. A1 and A2 are respectively the **sound spatialization** and **listening comfort** criteria. AV1 is the **consistency** criterion and AV2 is related to **immersion**.

Table 2. *Results of correlation analysis over assessment criteria.*

Criterion		Video		Audio		AudioVisual	
		V1	V2	A1	A2	AV1	AV2
Video	V1	1	0.41	0.23	0.19	0.36	0.46
	V2	–	1	0.20	0.25	0.38	0.46
Audio	A1	–	–	1	0.62	0.46	0.43
	A2	–	–	–	1	0.57	0.49
AudioVisual	AV1	–	–	–	–	1	0.67
	AV2	–	–	–	–	–	1

This analysis confirms the lack of clear correlation between criteria. The degree of audiovisual immersion would be more related to the consistency between sound and image (0.67) than to the degree of visual depth or sound spatialization.

4. CONCLUSION

In this paper, a subjective test is carried out in order to compare the 3D audiovisual perception as a function of the audio rendering. The aim is to measure the impact of three sound reproduction systems chosen to render multichannel audio (5.1 surround system, sound projector and headphones), on the perception of 3D audiovisual content. For each sound reproduction system, spectators have to evaluate audio, video and audiovisual criteria.

Degree of visual depth and comfort of visualization are the criteria for the video part. The possible influence of sound reproduction system on visual depth or on comfort of visualization hasn't be proved in this experiment. But the participants have judged those two criteria as independent. Assessors are able to discriminate different degrees of visual depth between sequences. Their judgments are probably influenced by the depth budget but not exclusively. Indeed, visual depth perception can be attenuated or enhanced by various visual cues like linear perspective or relative size of objects for instance. Nevertheless, visual depth perception does not impact the comfort of visualization for selected sequences.

The analysis of audio criteria results shows that, in terms of degree of sound spatialization, headphones listening is rated higher than 5.1, which is itself preferred to the sound bar. Regarding to the listening comfort, all systems are quite equivalent.

Assessment also covers audiovisual criteria (degree of consistency and degree of immersion). There is a slight but significant effect of sound reproduction systems on the degree of consistency but not strong enough to be statistically significant in the case of immersion criterion. A correlation analysis shows that all criteria are independent. Immersion seems to be more correlated to audiovisual consistency than to other criteria.

Further work should explore alternatives 3D audio technologies. The future MPEG-H standard which is under development is taking these technologies into consideration with the creation of a specific "3D audio" group. Channel-based, Object-based, and HOA-based input formats are subject of interest. In this context, Wave Field Synthesis is an attractive solution for further work since it potentially impacts the consistency perception by adding audio depth rendering. With this in mind, experiments are currently conducted in order to estimate to which extent the audio depth can be efficiently simulated by WFS.

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REFERENCES

[1] H. Møller, "Fundamentals of binaural technology", *Applied Acoustics,* 36, 171–218 (1992).

[2] R. Nicol, "Binaural Technology", *AES Monograph* (2010).

[3] A. J. Berkhout, D. de Vries, and P. Vogel, "Acoustic control by Wave Field Synthesis", *Journal of the Acoustical Society of America*, 93(5), 2764–2778 (1993).

[4] G. Theile, and H. Wittek, "Wave Field Synthesis: A promising spatial audio rendering concept", *Acoustical Science & Technology,* 25(6), 393–399 (2004).

[5] J. Daniel, R. Nicol, S. Moreau, "Further Investigations of High Order Ambisonics and Wavefield Synthesis for Holophonic Sound Imaging", *Proceedings of the 114th AES Convention,*Amsterdam, The Netherlands (2003).

[6] M. Rébillat, X. Boutillon, E. Corteel, and B. F. G. Katz, "Audio, Visual, and Audio-Visual Egocentric Distance Perception by Moving Subjects in Virtuals Envrionments", *ACM Transactions on Applied Perception*, 9(4), 19:1–19:17, (2012).

[7] C. Renard, "Analyse objective et subjective d'une technique de rendu sonore 2D sur une zone d'écoute étendue, l'holophonie, en vue de réaliser un mur de téléprésence", *Master Thesis Report*, Université du Maine (2000).

[8] S. Komiyama, "Subjective evaluation of angular displacement between picture and sound directions for HDTV sound systems", *Journal of the Audio Engineering Society*, 37(4), 210–214 (1989).

[9] J. G. Beerends, and F. E. De Caluwe, "The influence of video quality on perceived audio quality and vice versa", *Journal of the Audio Engineering Society*, 47(5), 355–362 (1999).

[10] ITU-Recommendation BS.775-3: "Multichannel stereophonic sound system with and without accompanying picture", *International Telecommunications Union, Radio-communication Assembly* (2012).

[11] ITU-Recommendation BT.500-13: "Methodology for the subjective assessment of the quality of television pictures", *International Telecommunications Union, Radio-communication Assembly* (2012).

[12] ITU-Recommendation BT.1788: "Methodology for the subjective assessment of video quality in multimedia applications", *International Telecommunications Union, Radio-communication Assembly* (2007).

[13] ITU-Recommendation BS.1284-1: "General methods for the subjective assessment of sound quality", *International Telecommunications Union, Radio-communication Assembly* (2003).

[14] ITU-Recommendation BS.1534-1: "Method for the subjective assessment of intermediate quality level of coding systems", *International Telecommunications Union, Radio-communication Assembly* (2003).

[15] ITU-Recommendation BS.1116-1: "Methods for the subjective assessment of small impairments in audio systems including multichannel sound systems", *International Telecommunications Union, Radio-communication Assembly* (1997).

[16] ITU-Recommendation BS.1286: "Methods for the subjective assessment of audio systems with accompanying picture", *International Telecommunications Union, Radio-communication Assembly* (1997).

[17] ITU-Recommendation P.910-3: "Subjective video quality assessment methods for multimedia applications", *International Telecommunications Union, Radio-communication Assembly* (2008).

[18] ITU-Recommendation P.911: "Subjective audiovisual quality for multimedia applications", *International Telecommunications Union, Radio-communication Assembly* (1998).

[19] ITU-Recommendation P.920-2: "Interactive test methods for audiovisual communications", *International Telecommunications Union, Radio-communication Assembly* (2000).

[20] S. Pastoor, "Human factors of 3DTV: an overview of current research at Heinrich-Hertz-Institute Berlin", *Stereoscopic Television IEE Colloquium, 11/1-11/4* (1992).

[21] W.Chen, J. Fournier, M. Barkowsky, and P. Le Callet, "New requirements of subjective video quality assessment methodologies for 3DTV", *Fifth International Workshop on Video Processing and Quality Metrics – VPQM 2010*, Scottsdale, Arizona, U.S.A (2010).

[22] ITU-Recommendation BT.2021: "Subjective methods for the assessment of stereoscopic 3DTV systems", *International Telecommunications Union, Radio-communication Assembly* (2012).

[23] J. Berg, and F. Rumsey, "Systematic evaluation of perceived spatial quality", *Proceedings of the 24th AES International Conference on Multichannel Audio* (2003).

[24] J. Berg, "Evaluation of perceived spatial audio quality", *Proceedings of the 9th World Multi-Conference on Systemics, Cybernetics and Informatics*, 4(2), 10–14 (2005).

[25] G. Lorho, "Evaluation of spatial enhancement systems for stereo headphone reproduction by preference and attribute rating", *Presented at* the *118th AES Convention*, Barcelona, Spain (2005).

[26] S. Le Bagousse, C. Colomes, M. Paquier, and S. Moulin, "Sound quality evaluation based on attributes – application to binaural contents", *Presented at* the *131st AES Convention*, New-York, NY, U.S.A. (2011).

[27] *Mormeck, une nouvelle dimension* (2009), A. Drhey, prod. Orange Sport.

The IOA Diploma in Acoustics and Noise Control

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ABSTRACT

The IOA Diploma was started in 1975 to satisfy the educational requirements for Associate membership of the Institute. Since then over 2000 candidates have gained the Diploma and have gone on to become corporate members of the Institute. The Diploma is offered currently at six Higher Education Institutions in the UK and through tutored distance learning supported by extensive course materials. The author has a long experience of teaching the IOA Diploma course, is the current Project Examiner and has contributed to the distance learning notes.

The main pedagogical features of the course, particularly of the tutored Distance learning version, which relies on printed teaching materials, supplemented by compulsory laboratory sessions (4 days) and a programme of (optional) tutorials, are described. Statistics will be presented to demonstrate the effectiveness of the course, together with examples taken from course materials, assignments, laboratory exercises, examinations and project investigations.

1. INTRODUCTION AND HISTORY

The 1970s in the UK saw an increase in public concern about noise in the environment and in the workplace. There were very few degree and postgraduate course in acoustics and noise control in UK Universities, and there was growing demand for further education and training in this area. Many higher education colleges and Universities were attempting to meet this demand by providing a range of introductory short courses (typically three afternoons or evenings over about 6 weeks).

In 1974 the Control of Pollution Act was issued containing a section on the control of noise pollution in the environment, and the Health and Safety at Work Act produced guidance for controlling the noise exposure of employees in the Workplace, based on the earlier 1972 Department of Employment Code of Practice for reducing the exposure of employed persons to noise. The introduction of these two pieces of legislation saw a further increase in demand for information and training about noise from those required to deal with them.

The Institute of Acoustics developed the Diploma course in the mid-1970s in response to these developments. The first cohort of students sat their examinations in June 1978.

The curriculum at that time consisted of the study of a compulsory General Principles of Acoustic (GPA) module (60 hours of study) and any two from four specialist modules (30 hours of study for each module): architectural and building acoustics (ABA), noise control engineering (NCE), law and administration (LA), and transportation noise (TN). The award of the Diploma required the achievement of passes in the GPA examination and in two of the four specialist modules, together with the successful completion of a Project, which comprised 60 hours of study. Laboratory work made up a significant part of study of these modules (up to 50% for the GPA), but there was no assessed coursework. In later years three additional (optional) special modules were added in Vibration Control, Measurement and Instrumentation, and Sound Reproduction, and coursework assignments were included in the assessment of the modules. These arrangements persisted until a major restructuring of the Diploma in 2008, which will be described later.

1.1. Responding to Change

Although the laws of physics and acoustics have not changed since 1978 there have been very many changes in other aspects of noise control: in the instrumentation available for the measurement of noise and vibration (in particular the introduction of digital signal processing); in methods of noise control (e.g. active noise and vibration control); in computerised noise prediction methods; in legislation, regulations, standards, and codes of practice relating to the control of noise. The Diploma course has developed to respond to all of these changes.

Since its introduction over 2000 candidates have gained the Diploma and have gone on to become corporate members of the Institute. The course is aimed at all who are, or wish to wish to be professionally employed in the fields of acoustics and noise control and has attracted students from a wide range of backgrounds including engineers and technicians (particularly mechanical, production and building services engineers), mathematicians, physicists and other scientists, architects, builders, acoustic and environmental consultancies and local authority environmental health practitioners, audio and sound reproduction technologists and engineers.

1.2. The revised Diploma 2008

The Diploma was restructured in 2008 to respond to changes in the national assessment and rating requirements of higher education in the UK, to ensure a postgraduate status that might provide better opportunities for Diploma holders, and also to rationalise the delivery of the modules. The Vibration Control, Measurement and Instrumentation, and Sound Reproduction special modules, which had attracted only a small minority of candidates, were discontinued and their content incorporated into four new specialist modules: Architectural and Building Acoustics (ABA), Environmental Noise - measurement, prediction and control (EN), Noise and Vibration Control engineering (NVCE), and the Regulation and Assessment of Noise (RAN). The content of the GPA module was revised and extended, and the extensive programme of laboratory exercises were built into a Laboratory Module, and the Project arrangements were revised. In addition, the format of the examinations was revised to include a short section of compulsory short questions as well as the usual selection of optional longer questions.

1.3. Credit Rating of the revised Diploma

It is considered by the IOA Education committee that following the restructuring in 2008 the Diploma has a credit transfer rating of 90 credits (at level M) with the nominal ratings of individual components as follows:

Principles of Acoustics	30
Laboratory Module	10
Each Specialist Module	15
Project	20

Students may be able use their Diploma to gain entry into various MSc courses in acoustics, with exemptions from some a parts of the programme amounting in some cases to direct entry into the second year of a two years part time Masters programme.

1.4. The Diploma approach

The Diploma course aims to teach the practical application of acoustic principles to the control of noise. Most of the course members are working in this area for example in local authority environmental health departments, or with acoustic consultancy practices, and so the course is able to connect directly with their day to day activities, and in turn they are able to enrich the course by sharing these experiences during class discussions. Therefore it is the applications of theory which are emphasised rather than the detailed derivation of formulae, although such derivations are always available to those students who wish to explore them. Emphasis is also placed on the assumptions of various theories and formulae because it is these that set the limitations of their validity when applied to practical situations. The course teaches various noise level prediction methods based on simplified and idealised models of noise propagation (free field, inverse square law, diffuse sound fields for example) which are the basis of current practice and the limitations of these assumptions in practice are discussed. This emphasis on the practical applications underlies all aspects of the Diploma course: teaching, assignments, examinations and project.

2. MODULE CONTENT

2.1. The General Principles of Acoustics Module (GPA)

This introductory module is the compulsory foundation for the Diploma study. The syllabus includes: the nature and behaviour of sound; frequency wavelength and sound velocity; sound pressure; intensity and power. The decibel scale: sound power level, sound intensity level and sound pressure level. Sound propagation: the inverse square law and prediction of free field sound propagation. The behaviour of sound waves: interference, reflection, refraction, and application to sound propagation outdoors and indoors. Near and far fields of sound sources and directivity.

The behaviour of sound in rooms and other enclosed spaces: wave, ray and statistical approaches to room acoustics. Sabine acoustics, direct and reverberant sound and reverberation time, Sabine's equation. Sound transmission between enclosed spaces, and between inside and outside: sound reduction index; mass law; panel resonances and coincidence; double leaf partitions; airborne and impact sound insulation.

Vibration and structure borne sound transmission: vibration displacement, velocity and acceleration. The theory of a one degree of freedom mass-spring-damper vibrating system; free and forced vibration; natural frequency; resonance; and the effects of damping. The application of simple theory of vibration isolation and transmissibility.

The measurement of sound and vibration: microphones and sound level meters; their construction, properties and performance criteria; sensitivity; frequency response; linearity dynamic range. Calibration. The use of sound level meters, and principles of good sound measurement technique. Frequency weightings and frequency analysis; time weightings F and S. The measurement of time varying noise: L_{Aeq}, L_{max}, L_{A10} and L_{A90}. The measurement of noise in the environment, workplace and indoors. Building acoustics measurement: reverberation time and airborne and impact sound insulation. Uncertainty in measurements. Measurement of vibration: accelerometers and vibration meters and principles of use, calibration, attachment of accelerometers to vibrating surfaces.

Human response to sound and vibration, The ear and hearing, loudness, equal loudness contours, frequency weighting curves, phons. Hearing disorders, conductive and sensory-neural hearing loss, presbycusis, noise induced hearing loss. Audiometry. Control of noise exposure in the workplace: Action Values and Exposure Limits, use of hearing protectors.

2.2. The Architectural and Building Acoustics Module (ABA).

This module builds upon the GPA and offers more detailed consideration of the theory and practice of room acoustics and sound insulation. The specific acoustics requirements of different types of space are considered, for example background noise level, reverberation time, speech intelligibility and privacy and the establishment of suitable criteria in each case, and how these criteria might be achieved through design of the space including shape, volume, and distribution of sound reflecting, absorbing or diffusing materials and surfaces, and separation and /or insulation from other spaces and noise sources.

The types of different spaces considered might include, for example: homes (living rooms and bedrooms), offices, school classrooms, performance spaces (theatres, concert halls, etc.), workplaces, rooms for public and private meetings, places of religious worship, restaurants, cinemas, specialist acoustic test rooms (anechoic, reverberant, audiometric), recording studios for radio and TV.

Other topics include: special acoustic parameters for evaluating acoustic of performance spaces, acoustic modelling of spaces (ray and beam tracing methods), noise from building services, remedial design to achieve improved sound insulation: isolated walls, floating floors, suspended ceilings and box-in-box spaces, use of electroacoustic techniques.

2.3. The Noise and Vibration Control Engineering Module (NVCE)

This module also builds on the material covered in GPA to consider methods of noise control relating to the source, transmission path, and receiver. Consideration of the mechanisms by which sound may be generated from vibrating surfaces, from impacts and from aerodynamic sources leads to a review of ways in which noise control at source may be achieved. The principles of sound absorption, insulation and isolation, introduced in the GPA are reviewed, studied in further detail and applied to the design of standard noise control measures such as enclosures silencers and barriers. The ability to diagnose sound sources and transmission paths, and to predict noise levels from various sources are important aspects of noise control and are discussed in this module. Other aspects covered include noise from fans and ducts in ventilation systems, noise from jets and exhausts, reactive silencers and active noise control. Specification and measurement of noise emission from machinery and of performance of noise control measures.

2.4. The Environmental Noise Module (EN)

This is an expansion of the previous Transportation Noise module to include all types of environmental noise. It covers noise from: road rail and air transport; noise from industry and commerce; from mineral, landfill and construction and demolition sites; wind turbines; entertainment and other leisure activities. In all cases the prediction, measurement, assessment and control of various types of noise are reviewed. The module includes a review of standards, codes and regulations governing control of environmental noise, of the various measures of environmental noise exposure and of current guidance on impacts on human health of exposure to environmental noise; the Environmental Noise Directive, environmental noise regulations, noise mapping, action plans.

2.5. The Regulation and Assessment of Noise Module (RAN)

Overview of the European and UK National Policy on environmental noise; review of neighbour and neighbourhood noise; impact of planning and Building Control legislation on environmental noise; overview of legal and administrative frameworks; the role of noise prediction and mapping for the control and assessment of environmental noise; introduction to environmental impact assessment (EIA); Integrated Pollution Prevention Control (IPPC); Control of Noise and Vibration at Work Regulations; vibration.

Full details of all these syllabuses including learning outcomes, learning objectives, acquired / transferable skills and indicative content may be found on the IOA website, which also includes a list of standards, codes and regulatory documents applicable to the study of each module.

2.6. Project Module

The purpose of the Project is to enable the student to demonstrate the use of the skills and knowledge gained during the course in successfully carrying out an investigation to solve and report an acoustics related problem, within a specified time scale.

Since the student will spend considerable time and effort in their project investigation the choice of topic is usually left to him / her, guided by his / her tutor.

Most projects are practically based and will involve some or all of the following stages: selection of topic area, research and literature survey, definition of aims and objectives, formulation of a methodology and time schedule for execution, gathering of data (noise and /or vibration measurements), analysis of data, formulation of proposals, implementation, testing and report writing.

A list of titles of successfully completed projects is printed each year in the Acoustics Bulletin (the bi-monthly IOA members magazine), and also in the current edition of the Diploma Handbook for students.

An example list of project titles for one academic year is given at the end of this presentation, to demonstrate the wide variety of topics which have been investigated.

2.7. Laboratory Module

Although there will be some variation between different Diploma Centres the programme of lab work will include a core of common experiments including: use of sound level meter to measure spectral based noise indices, NC, dBA, dBC and environmental noise parameters for time varying noise; building acoustics measurements: reverberation time, absorption coefficient, field measurement of airborne and impact sound insulation of walls and floors, measurement of sound power levels, measurement of vibration levels, evaluation of loudness and plotting of equal loudness contours, audiometry, performance of barriers and enclosures, standing waves and room modes, speech intelligibility, FFT analysis, sound propagation (level v distance from source) indoors and outdoors.

Students are required to keep a log book recording details of all experiments undertaken, and to formally write a report of four selected experiments for assessment purposes.

Modern sound measurement equipment is complex and although it is important to be able to use such equipment competently there are the even more important underlying skills of good measurement procedure such as calibration where when and what (noise parameter) etc. Emphasis in the laboratory module is therefore placed on good measurement techniques rather than just the ability to programme and press the right sequence of buttons.

3. ASSESSMENT OF THE MODULES

Each of the taught modules is assessed by a combination of examination (60%) and assignments (40%). The assessment of the laboratory module is based on the quality of three written lab reports (90%) and of the lab notebook (10%), and for the project on the quality of the final report (80%) and of the project logbook (10%) and the initial project proposal (10%). Copies of the past three years examination papers are made available to all students. Each candidate is informed privately of his/her module results at the beginning of September each year. A Chief Examiner's report containing an overview of the results for all centres is published each year in the Acoustics Bulletin.

A course handbook (separate versions for centre based and distance learning study) is issued to all students which contains information about all aspects of studying the Diploma including details of the assessment procedures.

3.1. Assignments

Students are required to complete two written assignments as part of the GPA module and one for each special module completed. These assignments although part of the course assessment process are designed to add to the quality of the students learning experience.

One of the GPA assignments usually involves an extended exercise involving a design calculation on some aspect of the syllabus, and the other assignment requires the student to research some aspect of acoustics which encourages reading and understanding beyond their course notes (including the distance learning notes described later). In the past, students have been required to investigate: the calculation of noise radiation from a process plant installation, acoustics issues in schools, noise from glass bottle handling, underwater sound exposure of marine mammals, building acoustics, non-auditory effects of noise on human health, environmental noise and its assessment, noise from a small wind turbine, outdoor sound propagation, and the acoustics of woodwind musical instruments.

The special module assignments are written by specialists in their fields. Subjects have included:

ABA Module: aspects of concert hall design, design of sound insulation of building conversions to meet Building Regulations requirements, acoustic design of a building and of a housing estate, measurement of sound insulation requirements to satisfy ISO 140, the acoustic design of the Wimbledon Centre Court roof.

NVC Module: performance of acoustic enclosures, noise impact assessment from a pumping station, assessment of noise from a sewage treatment plant, assessment of noise impact from Widget engineering, helicopter noise transmission, control of noise and vibration from a floor mounted machine, verification of noise predictions.

EN Module: noise from a new tramway system (airborne noise impact assessment), noise from minerals extraction (code of practice), the assessment of construction noise, assessment of vibration from railways, wind farm noise.

RAN Module: assessment of vibration from railways, environmental noise directive and noise action plans, wind farm noise, regulation of construction noise, dose effect relationships for night-time noise, EU Physical Agents Directive and the Control of Noise and Vibration at Work 2005 Regulations, the National Planning Policy Framework.

4. THE TUTOR SUPPORTED DISTANCE LEARNING MODE OF STUDY

For prospective candidates in regions where centre-based courses are not available or, in principle, for any candidate who can show due reason why he or she is unable to make use of an Accredited Centre in the usual way, there is a Tutored Distance Learning Scheme.

Distance learning students are provided with a comprehensive set of printed notes for each module that they study and are allocated a course tutor with whom they may have contact with by email, phone, or face to face at tutorial sessions. As well as presenting the tutorials the tutor will be responsible for marking their GPA assignments and examination, will provide guidance where necessary with choice of specialist modules and act as tutor for their project work i.e. provide guidance with selection of project topic, continued support throughout including feedback on draft and final assessment of final report.

The GPA notes are divided into 10 study units: 1 Basic concepts and principles, 2 measurement of time varying noise and calculation of noise indices, 3 the ear and hearing, 4 sound propagation, 5 sound absorbers and room acoustics, 6 sound insulation, 7 vibration, 8 measurement and instrumentation, 9 noise control and 10 review and revision. A programme of 10 days of tutorial support is provided each year (October to May) consisting of 5 days for the GPA Module, so that two units are covered in each tutorial session, two days for each specialist module and a revision tutorial before the examinations in May.

The Distance learning notes for the specialist modules also provide comprehensive coverage of the syllabus material and each contains a reference to material for further detailed study if required and, in the case of the building acoustics and noise control modules, several case studies are included.

Although they are optional, the tutorials are usually well attended. As well as receiving help and advice from the tutor these sessions also provide an invaluable opportunity for the students to meet each other, to discuss the course and exchange experiences, and this process is encouraged so that the class may set up their own self support groups. This process continues at the laboratory sessions. There is much invaluable learning material available on line at various websites which can greatly enhance the material in the printed notes and the distance learning students are encouraged to use this as a learning source. They are also provided with past examination papers which they are encourages to use as a learning resource throughout the year, and not just as an aid to examination revision.

Distance learning students must attend a total of four days laboratory classes at Liverpool (usually two sessions of two days each in November/ December and January / February). During this period they complete eight laboratory exercises and must keep a log book of all and write a full report on four of them.

Students from outside the UK may also study for the diploma by distance learning provided that they are also able to attend the 4 days of laboratory sessions (or where in exceptional cases arrangements can be made to do the laboratory work in their own country). They may join the tutorial sessions via the internet and have contact with their tutor by email and by telephone. Students from Dubai, Malaysia, Hong Kong, New Zealand, South Africa, Greece, India and the USA have studied the Diploma in this way.

The requirements for the award of the Diploma are exactly the same for distance learning candidates as for all other students attending week by week at recognised diploma centres, i.e. the same examinations assignments and laboratory work and project requirements.

5. COURSE RESULTS

Table 1 presents results (% pass rates) for each module for the last ten years, taken from the Chief Examiner's or Education Manager's report published each year in the Acoustics Bulletin. Also shown ( ) are the number of candidates each year sitting the GPA examination.

Table 1. *Module Pass rates (%) for years 2003 to 2013, with numbers of candidates taking the GPA Module examination ( ) also shown. (Project module results not available until January 2014).*

	GPA	PROJ	ABA	RAN/LA	NCE	EN/TN
2013	94 (108)		81	83	75	92
2012	80 (104)	83	79	77	81	91
2011	83 (110)	70	89	73	76	81
2010	68 (134)	64	72	72	66	86
2009	78 (144)	75	76	72	82	77
2008	90 (153)	85	87	86	85	80
2007	82 (137)	81	74	79	85	91
2006	79 (172)	79	74	84	75	84
2005	74 (145)	66	80	76	79	77
2004	83 (150)	82	83	74	76	74
2003	80 (138)	76	80	72	66	78

6. OPPORTUNITIES PROVIDED BY THE DIPLOMA COURSE

Many students study the Diploma whilst working in acoustics to improve their skills and knowledge as a form of career enhancement and to become corporate members of the IOA. Many job vacancies in acoustics specify the holding of a Diploma as a necessary condition of application. Other candidates not working in the field join the course to gain employment in acoustics as a career change and are successful. Others have used the Diploma as a pathway to further study for an MSc degree, and in a few cases for PhD study.

Diploma graduates who obtain three Merits (including a merit in the GPA module) may be considered to have met the M-level educational requirements for achieving Chartered Engineer (CEng) status through the IOA. This will require also that candidates have an accredited three year degree in a relevant subject (or equivalent qualification).

7. ACCESS AND RECRUITMENT

The normal minimum requirement for admission to the Diploma in Acoustics and Noise Control is a degree in a science, engineering or construction-related subject or an Environmental Health Officer's Diploma. However, as part of the Institute's policy of open access alternative qualifications, with related professional experience, may be acceptable and will be considered on a case-by-case basis.

Although the course is promoted by the IOA and the individual centres in the usual ways, much recruitment is by word of mouth recommendation. Many past students have studied the Diploma whilst at a junior level in their careers and have as their careers progressed subsequently over several years have sent colleagues to study the course.

8. COURSE ADMINISTRATION AND QUALITY CONTROL

The responsibility for maintaining the quality of the Diploma lies with the Education Committee of the IOA, which is ultimately responsible to Council. The day to day administration is carried out by full time staff at IOA headquarters with academic support from the IOA Education Manager. A board of examiners consisting of a Chief Examiner, Deputy Chief Examiner and specialist module examiners supported by the Education Manager is appointed by the Education Committed to directly oversee the assessment of the Diploma. The course syllabuses and the distance learning notes are reviewed and updated at regular intervals.

9. CONCLUSIONS

Over more than 35 years the Diploma course has successfully responded to many changes in the practice of acoustics and noise control, but still fulfils essentially the purpose for which it was introduced, to provide basic education and training in for those seeking a career in acoustics and noise control, and a route towards corporate membership of the IOA. It has also served as a route into employment in acoustics and noise control for many seeking a change of career opportunity as well as a pathway to study for MSc and in some cases PhD studies. The Institute's commitment to open access and the introduction of the distance learning option have significantly increased access to these opportunities.

DISCLAIMER

The views expressed in this paper are entirely those of the author, and not necessarily those of the Institute of Acoustics.

ACKNOWLEDGEMENTS

The author is grateful to the Institute of Acoustic for permission to publish this paper and for permission to include material from the IOA website and Student Handbook.

REFERENCES

IOA Diploma Course Handbook 2012/13.

IOA website: www.ioa.org.uk.

IOA Bulletin (Examiners annual presentations of course results).

EXAMPLE LIST OF PROJECT TITLES (PUBLISHED JANUARY 2013, FOR 2011-2012 YEAR)

- Hearing protection in the live event industry.
- Movable walls: production methodology.
- Noise levels from Kerbside glass collection.
- Drive-by test at Donington Race track A.
- Suitability of BB93 to assess existing school buildings.
- Critical assessment of noise impact of bird scarers.
- Friction modifiers and acoustic roughness of rails.
- Tonal correction feature of BS4142.
- Classroom acoustics and BB93.
- Comparison of predicted and measured reverberation time.
- Airborne noise and impact testing.
- Measurement of low level noise.
- Drifting at Santa Pod raceway.
- Assessment of perception of movable walls.
- Speech intelligibility in masonic temples.
- Relationship between music type and annoyance.
- Noise impact of night time deliveries.
- Impact Sound Insulations: Direct to Joist Solutions.
- Application of Noise Act 1996 to Licensed Premises.
- Sound Insulation investigation of a Recording Studio.
- Effects of placing Acoustic Weather Louvres within near field of a plant room sources.
- Evaluation of noise generation at Children's outdoor play areas.
- Comparison between an EBM-Papst RadiCal and a Standard centrifugal fan.
- Determination of Transmission Loss performance of Elastomeric materials.
- Review of Strategies to abate Noise Nuisance caused by Licensed Premises.
- Railway Noise and Annoyance from a London Overground railway line.
- Noise Exposure and Small Scale Agriculture.
- Assessment of effect of wind on Road Traffic Noise at a site for housing development.
- Sound Control of Noise from a Church.
- Measurement of Train Wheel Screech affecting a block of flats.
- Review of the Microgeneration Certification Scheme & protection against noise disturbance.
- Real Noise in an average home and its annoyance factor.
- An Investigation into noise from Power Shower Pumps.

- Measurement and analysis of Noise and Vibration impacts of Speed Humps.
- Evaluation of Mobile Phone Acoustic measurement app technology.
- Investigation into sound propagation from an outdoor concert.
- An Exploration and definition of the purpose of music in shops.
- How the edges of a material affect the measured absorption coefficient.
- Alternative noise mapping using measured noise and GPS points.
- Influence of topography on commercial aircraft noise in the Calder valley.
- The sound insulation properties of music teaching and recording facilities.
- Acoustic assessment of a huddle-hub.
- A study of acoustic characteristics of commercial extraction systems.
- Hand-arm vibration assessment of grounds maintenance equipment.
- Comparison of methods for calculating wind turbine noise levels.
- Assessment of ETSU Averaging Periods.
- Urban and rural environmental noise exposure.
- A comparison of BS 5228-1 measurement data with real life noise levels.
- An assessment of predicted noise associated with a residential development in a remote rural environment and the use of PAN1/2011's Technical Advice Note as appropriate qualitative planning assessment.
- Wind Turbine Directivity.
- The effect of noise exposure from regular attendance at music entertainment venues on noise induced hearing loss among young adults.
- An investigation into the potential risks to pedestrian health and safety caused by 'silent running' electric vehicles.
- Sound Transmission through varying apertures of sash windows.
- Performance of Noise Barriers of Different Designs.
- Audibility of a Domestic Smoke Alarm in a Single Level Property.
- The effectiveness of Wooden Clapper Boards as an Impulsive Source.
- Effect of resilient mounting of a light switch on impact sound through a wall.
- Accuracy of SLM phone Apps compared with B&K 2250.
- Comparison of Measured and Predicted Wind Turbine Noise.
- Multi-cellular Array Technology in Modern Concert Systems.
- Effectiveness of a Barrier in Attenuating Petrol Generator Noise.
- Sound Reduction through an Open Window.
- The Variability of Bus Noise Levels.
- Assessment of the acoustics of a room to be used as both a Cinema and a Lecture Theatre.
- Improving the concentration, productivity and staff satisfaction in an open plan call-centre through better acoustics.
- Using a Head and Torso Simulator (HATS) to measure speech intelligibility.
- Reducing noise from a high output data projector.
- Comparison of attenuation provided by communication ear plugs (CEP) in Combination with a Mk4B4L Flying Helmet, and CEP alone.
- Evaluation of novel sound attenuation measures for rifle fire.
- A comparison of noise generated in Watford town centre by two methods of street cleaning.
- Likelihood of annoyance from gas utilisation plant derived low frequency noise.
- Investigation into the effectiveness of a range of outdoor microphone windshield protection systems and their effect on noise levels obtained when in use.
- An exploration of alternate methods of acoustical analysis.
- What is good quality acoustics: Objective and subjective assessments of smartphone audio playback.
- Noise control of basement supply fans.
- An investigation into noise from whole house ventilation and heat recovery system and its effect on background noise in an open plan office.
- An Assessment of a low frequency noise complaint.
- Calculating the sound power of an engine.
- Skateboard noise in relation to noise nuisance.
- Evaluation and comparison of low cost IPhone noise meter Apps for use in initial assessments of noise problems.

- Project for the live music Act 2012.
- Noise in Open-plan office.
- Performance of a partial enclosure: A CNC router case study.
- Amplitude modulation in large wind turbines.
- A study of reverberation time and speech intelligibility in a reverberation room used for conferencing devices.
- A noise assessment after relocation and redesigned office layout.

The members of the initial editorial board are shown in the table below. New members will be added to the board to provide expertise in topic areas not sufficiently represented by the current members of the board. It is also hoped to widen the geographical spread of the board to include members form more EAA societies.

Editorial board

European Acoustics Association – EAA

Comprising 32 national acoustical associations:

• Austria (AAA) • Belgium (ABAV) • Bulgaria (NSA) • Croatia (HAD) • Czech Republic (CAS) • Denmark (DAS) • Finland (ASF) • France (SFA) • FYROM (MAA) • Germany (DEGA) • Greece (HELINA) • Hungary (OPAKFI) • Iceland (IAA) • Italy (AIA) • Latvia (LAA) • Lithuania (LAS) • Morocco (MSA) • Norway (NAS) • Poland (PTA) • Portugal (SPA) • Romania (SRA) • Russia (PAO) • Serbia (ASY) • Slovakia (SKAS) • Slovenia (SDA) • Spain (SEA) • Sweden (SAS) • Switzerland (SGA-SSA) • The Netherlands (NAG) • Turkey (TAS) • Ukraine (UGA) • United Kingdom (IoA)

Serving more than 8500 individual members in Europe and beyond

The European Acoustics Association (EAA) is a non-profit entity established in 1992 that includes in its membership national acoustical societies interested in to promote development and progress of acoustics in its different aspects, its technologies and applications. The main objectives of the EAA are to:

- promote and spread the science of acoustics, its technologies and applications, throughout Europe and the entire world
- interface with associations whose activities are related to acoustics
- establish contacts across member associations and other public and private bodies
- promote the formation of national acoustical societies in European countries where these do not exist, and to support and strengthen activities of existing national associations, respecting the principle of subsidiarity
- publish a European journal on acoustics, in printed as well as in electronic format
- organize and promote congresses, publish books and monographs, and engage in all those activities that are connected with the diffusion, promotion and development of acoustics
- establish agreements for collaboration with European and international entities in order to better serve the objectives of EAA
- stimulate education activities and platforms in acoustics at all educational levels, both academic and professional
- promote and divulge the establishment and implementation of norms and recommendations in the various fields of acoustics

EAA is democratically organized (one vote per country) with a general assembly, a board and an executive council.

EAA web

www.euracoustics.org

EAA contact (General Secretary)

secretary@european-acoustics.net

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EAA Board 2010-2013

President: *Jean Kergomard*
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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)

Initiative for Science in Europe

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.

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