Characterising the Acoustic Attenuation of Selected Naturally Ventilated Double Skin Façades in non-domestic buildings within the UK

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Knowledge is proud that he knows so much:

Wisdom is humble that he knows no more.

William Cowper (1731-1800)

ABSTRACT

Acoustics within the field of façade engineering is considered to be something of 'a dark art'. It is certainly the element of building physics within the façade industry where the knowledge base is lower than the other elements.

When the advantages of Double Skin Façades are listed by most researchers, invariably, better acoustic attenuation is in the top three. However, the fundamental research to support and back-up to these statements is uncertain.

This study attempts to characterise the acoustic attenuation of naturally ventilated double skin façades in the UK. Some of the proposed hypotheses are taken from other fields of acoustic attenuation and applied to DSF technology. As part of this study, field testing has been undertaken and analysed in conjunction with current methods of predictive modelling.

The results concluded that there is potential for the design of a simple acoustic calculation methodology for early stage design and a solution method is proposed. Predictive parametric analysis has been validated by onsite testing to within an acceptable error suggesting that further research is worthwhile.

This research has relevance to the Industry in a number of ways. It is clear that there is insufficient research in the field of acoustics and natural ventilation within a DSF. This study concludes that current standards for acoustic testing and calculation need to be revised to consider functional performance of double skin facades. There is a commercial need for simple, dedicated acoustic predictive software in the façade industry.

The development of sustainable building using natural ventilation as a key element is an important driver for research in the field of acoustics applied to façades. The intention of this study was to start a process of this examination within a defined set of controlled parameters. The objective has been met but requires further research and validation.

As an Industry, there is need for an integrated and systematic approach to the research of acoustics in natural ventilation design with Double Skin Facades.

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Thank You All.

DECLARATION

I hereby declare that the following dissertation, '***Characterising the Acoustic Attenuation of Selected Naturally Ventilated Double Skin Façades in non-domestic buildings within the UK'***, is the outcome of my own personal work and research except where mentioned and referenced within the body of the text.

A complete list of references has been developed and included.

John Downes,
MSc Façade Engineering Candidate, 2013

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6 FIELD TESTING

ABBREVIATIONS

BBRI	**Belgian Building Research Institute**
BEA	**Boundary Elemental Analysis**
BREEAM	**Building Research Establishment Environmental Assessment Method**
BRIR	**Binaural Room Impulse Response**
BS	**British Standard**
CADNA	**Computer Aided Noise Abatement**
CATT	**Computer Aided Theatre Technique**
CW	**Curtain Wall**
CWCT	**Centre for Window and Cladding Technology**
dB	**Decibel**
dBA	**Weighted Decibel Level**
DEFRA	**Department for Environment, Food and Rural Affairs**
DGU	**Double Glazed Unit**
DSF	**Double Skin Facade**
DVGF	**Double Ventilated Glazed Façade *(Blasco 2003)***
FEA	**Finite Elemental Analysis**
FFL	**Finished Floor Level**
HRTF	**Head Related Transfer Function**
ISO	**International Organisation for Standardisation**
LEED	**Leadership in Energy and Environmental Design**
NGB	**National Governing Body**
NV	**Naturally Ventilated**
NV DSF	**Naturally Ventilated Double Skin Façade**
PDE	**Partial Differential Equation**
RH	**Relative Humidity**
RHS	**Rolled Hollow Section**
RT	**Reverberation Time**

SEA	**Statistical Elemental Analysis**
SEHM	**Semi Empirical Hybrid Method**
SPL	**Sound Pressure Level**
SRI	**Sound Reduction Index**
VACS	**Ventilated Acoustic Cavity Solver**

SYMBOLS

π	=	**Pi**
ρ	=	**Mean density of gas (air)**
β	=	**Reflection coefficient of a material**
$\propto$	=	**Absorption coefficient of the room boundaries**
δ	=	**Effective screening attenuation** ***(Chapter 5)***

NOMENCLATURE

a	**=**	**Distance between two reflecting planes *(Chapters 3,5and 7)***
A	**=**	**Equivalent absorption area**
A	**=**	**Distance from source to screening *(Chapter 5)***
B	**=**	**Distance from screening to receiver *(Chapter 5)***
c	**=**	**Speed of sound**
d	**=**	**Direct distance between source and receiver *(Chapter 5)***
dB	**=**	**Decibel**
dBA	**=**	**Weighted Decibel Level**
D_w	**=**	**Weighted on-site level difference**
L_p	**=**	**Sound Pressure Level (direct)**
L_w	**=**	**Sound Pressure Level (source)**
L_{sb}	**=**	**Level of signal and background noise combined in dB**
L_b	**=**	**Background noise level in dB**
p	**=**	**acoustic pressure**
ms	**=**	**millisecond**
Q	**=**	**Surface Directivity Factor**
r	**=**	**Radius**
R	**=**	**Room Constant**
R_w	**=**	**Weighted laboratory level difference**
S	**=**	**Surface area of the receiving room**
T	**=**	**Reverberation time in the receiving rooms**
V	**=**	**Receiving room volume**
W	**=**	**Radiated sound power**

EQUATIONS

$L_p = Lw + 10\log_{10}\frac{Q}{4\pi r^2}\ dB$ Equation 1.1

$D_{n,e,i}\ =\ -10Log_{10}\ \left[\frac{1}{10}S10^{\left(-\frac{R\,facade}{10}\right)} - S_{wall}\ \ 10^{\left(-\frac{R\,wall}{10}\right)}\right]$ Equation 2.1

$D_{2m,nT} =\ Log_{10}\ (f)x\ \lfloor 2.2 - 0.8\ x\ Log_{10}(S_{op})\rfloor - 3.2\ x\ Log_{10}\left(S_{op}\right) + 8.1\ dB$

Equation 2.2

$R' =\ D_{2m,nT} - 10xLog_{10}\left(\frac{V}{6T_oS}\right)\ dB$ Equation 2.3

$R'_w\ =\ -5.8\ Log_{10}\ (x) + 13.2.$ Equation 2.4

$10\ Log_{10}\left(\frac{area1}{area2}\right)$ Equation 2.5

$L = 10\ log(\ 10^{Lsb/10} -\ 10^{Lb/10}\ )\ dB$ Equation 4.1

$D_2m, nT = D_2m + 10\log(\frac{T}{T_0})dB$ Equation 4.2

$A =\ \frac{0.16V}{T}$ Equation 4.3

$Lp = Lw - 20log10 * r - 11dB$ Equation 4.4

$1.07\left(\frac{P}{S}\right) \propto^{1.4}\ dB/metre$ Equation 4.5

$p^2 =\ \frac{W\rho c}{4\pi}\left[\frac{1}{r^2} +\ \frac{2\pi^2}{3a^2}\right]db$ Equation 4.6

$p^2\ (r) =\ \frac{W\rho c}{4\pi r^2}\left[1 +\ \frac{\beta_1 + \beta_2\ + 2\beta_1\beta_2}{1 - \ \beta_1\beta_2}\right]$ Equation 4.7

$$Lp\ (reflected) = Lw + 10\log_{10}\left(\frac{4}{R}\right) dB$$ Equation 5.1

$$Lp\ (total) = Lw + 10\log_{10}\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right) dB$$ Equation 5.2

$$\delta = A + B - d$$ Equation 5.3

$$r = \left(2\sqrt{3/\pi}\right) a \simeq 1.95a$$ Equation 5.4

$$Lp = Lw + 10\log(5.6/_{4\pi})$$ Equation 5.5

$$p^2(r) = W\frac{\rho c}{4\pi}\left[\frac{1}{r^2} + \sum_{k=1}^{\infty}\left(\frac{1/\beta_1 + 1/\beta_2}{r_{2k-1}^2} + \frac{2}{r_{2k}^2}\right)(\beta_1\beta_2)^k\right]$$ Equation 5.6

$$L_p = L_w + 10\ Log\left(\frac{19}{4\pi r^2}\right)$$ Equation 5.7

$$RT = \frac{0.163V}{S\propto} seconds$$ Equation 6.1

$$RT = \frac{0.163\ V}{-S\ loge(1-\propto)}\ seconds$$ Equation 6.2

$$Lp\ (direct) = Lw + 10\ logT - 10logV + 14dB$$ Equation 6.3

$$Lp\ (direct) = Lw + 10\ logT - 10logV + 14dB + K,\ K\ being\ 0.9dB$$ Equation 6.4

$$y = -5.8\ Log_{10}(x) + 13.2$$ Equation 7.1

$$y = -8.6\ Log_{10}(x) + 93.3$$ (25mm opening) Equation 7.2

$$y = -10.5\ Log_{10}(x) + 97$$ (50mm opening) Equation 7.3

$$y = -10.2\ Log_{10}(x) + 96.5$$ (100mm opening) Equation 7.4

$$y = -8.0\ Log_{10}(x) + 90.9$$ (200mm opening) Equation 7.5

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CHAPTER 1
INTRODUCTION TO DISSERTATION

1.1 INTRODUCTION

The primary aim of this study is to investigate whether field testing can support and validate parametric models to enable the façade industry to characterise DSFs more accurately. This dissertation presents the findings from a series of field tests and parametric modelling of a selected project, supported by empirical calculation, to characterise the acoustic attenuation and performance of selected naturally ventilated double skin façades (NV DSF).

When the contributing elements of good sustainable and environmental design and construction are considered, there is a conflict between the optimal performance of acoustics and the airflow required for adequate natural ventilation.

Natural ventilation is generally accepted as a sustainable design strategy because of the benefits it provides such as reduced energy consumption, lower running costs, and improved indoor air quality. However, the use of natural ventilation conflicts with the controlled of ingress of external noise (Fields, Digerness 2008)

This conflict is a design challenge to be met by designers in the quest for a sustainable future in project design. National regulation of noise in design also poses challenges for natural ventilation design. These challenges should derive innovative solutions from designers that consider sustainable design as a core principle of a holistic approach to Engineering and Architectural design.

This study focuses on NV DSF's and the acoustic design challenges that it is perceived to bring. The DSF will be characterised in later chapters and the benefits will be examined in detail. The NV DSF is particularly suited to the Northern Maritime climate where external air temperature rarely exceeds design indoor temperatures (STW, AI 223).

The benefits of a DSF in an urban environment are even more substantial where other design solutions may not be suitable or possible. Some examples of this may be due to limitations of space for horizontal or vertical shading, planning restrictions on glass types to reduce solar gain and glare, insufficient plantroom area for mechanical plant etc (STW, AI 223a). The Belgian Building Research Institute (BBRI) was given funding in 1999 to research DSFs, recognising the possible positive influence that DSFs would have on urban design and development. According to Dr. Marcello Blasco, ‘the end of this research led to an overview of the performances’ of the various elements of building physics associated with this type of construction (Blasco, 2012)

Following the BBRI research, Dr Blasco states that it was in 2003 when the façade industry became involved and began to concentrate research into the different building physics elements associated with DSF. Dr Blasco has continued the BBRI research with the support of industry and has researched DSFs predominantly in the closed cavity condition (i.e. with the outer and inner skins sealed and with a mechanical or hybrid mode of ventilation) (Blasco 2012a)

This research is all so recent that it is important that the NV DSF is researched in more detail in relation to the perceived acoustic challenge. Results, analysis and conclusions drawn from this research will make an important contribution to the industry knowledge-capital in the field.

1.2 PROPOSALS AND AIMS

This study will concentrate on the field testing of selected NV DSFs and, in particular, will investigate the propagation of sound through the DSF cavity and opening windows on the inner skin.

The benefits of this research will be of interest to many groups across the industry:-

1.2.1 **Architects / Engineers** will be interested in the resultant acoustic data from predictive modelling. The results of this research may lead to more accurate predictive modelling and give confidence to more use of NV DSFs.

1.2.2 **National Governing Bodies** (NGB) will be interested in data produced that will increase the body of knowledge in relation to the combination of acoustics and natural ventilation.

1.2.3 **Manufacturers and contractors** will benefit because, to date, most research has concentrated on closed cavity systems.

1.2.4 **National and Global Rating Agencies** and Schemes, such as LEED, BREAAM and Greenstar will have an interest as this research may result in the investigation of a favourable rating for more holistic natural ventilation and acoustic design solutions.

The selected projects will be modelled using current acoustic modelling techniques. The resultant data will be analysed and used to validate the functional modelling capability of existing software to more accurately simulate DSF geometries.

The study will investigate sound pressure levels (SPL) at three stages along the sound path (see figure 1.2) and attempt to characterize their contribution to the overall acoustic attenuation of DSFs.

The scope of this dissertation is very broad so clear boundaries are established in section 1.4.2. The overall classification of DSFs in figure 1.1 shows that this research is a small part of many parameters that characterise DSF permutations and their performance. This work seeks to devise a research methodology capable of reliably characterising the acoustic attenuation of such DSF configurations. There is a clear need for more acoustic research in the other areas of DSF classification including configuration, type, ventilation type, mode of operation, geometry, climate and region.

The scope of such research could possibly take a number of years to complete but It would be prudent for an industry that recognises natural ventilation and acoustics as an integral part of sustainable design to plan for a systemised approach to completing the research task.

1.3 CONTEXT OF THE PERCEIVED ACOUSTIC ISSUES WITH NATURALLY VENTILATED DOUBLE SKIN FAÇADES

There are contradicting opinions within the façade industry regarding the acoustic performance of DSFs and in particular those that are naturally ventilated.

The common perception is that a DSF will provide a degree of acoustic attenuation and will improve the acoustic performance of a façade.

However, there is a conflict between the principles of natural ventilation and those of sound insulation.

Dr Chris Fields, Arup Acoustics, asserts that ‘the lack of accurate prediction of the acoustic performance of naturally ventilated façades is hindering their widespread adoption in sustainable building design’, (Fields 2011).

This conflict and the perception that natural ventilation brings an acoustic penalty, supports the need for more research and empirical validation of existing simulation tools to allow a more holistic modelling approach.

1.4 DELIVERABLES, LIMITATIONS AND BOUNDARIES

1.4.1 DELIVERABLES

The purpose of this research is to evaluate data from field testing, undertake parametric analysis and empirical study of selected NV DSFs. The aims of this research and the benefits to the wider industry will deliver:-

1. A sound experimental procedure/methodology that can accurately measure the acoustic attenuation of a NV DSF. This has, to-date, not been done before and would benefit acoustic consultants.
2. Field data to help validate the modelling capability of existing software to more accurately predict the acoustic attenuation of NV DSFs, would benefit both acoustic consultants and their clients.
3. A greater understanding of the propagation of sound through the DSF cavity to interested parties such as manufacturers, fabricators, designers, acousticians, consultants, clients and NGBs.

4. Clear indications as to whether the use of acoustic predictive software is suitable for natural ventilation in DSFs, in particular when modelling individual elements in the overall propagation of sound through a DSF.
5. Empirical calculation methods validated by real monitored data.

Table 1.1 below identifies the key challenges associated with each element of the sound path from the source through the DSF and finally to the interior rooms of the building.

The DSF classification model shown in Figure 1.2, outlines a potentially large set of permutations within the DSF range and as such would be subject to a significant research timeframe.

Sound Path Element	Key Challenges associated with the research of this element
Element 1 **Sound power level from source to NV DSF**	➢ **Establishing clear knowledge base in relation to sound field and Q.** $L_p = L_w + 10\, Log_{10} \frac{Q}{4\pi r^2}\, dB$ **(1.1)** ➢ **Appropriate use of ISO 140-5 on site** ➢ **Establishing the correct method of predictive modelling e.g., ray tracing, noise mapping**
Element 2 **Ingress and propagation of sound at the natural ventilation entry to the DSF and through the cavity.**	➢ **Identifying the appropriate procedure for testing and in particular the layout and positioning of receivers with the DSF cavity** ➢ **Establishing the correct method of predictive modelling e.g., ray tracing, noise mapping** ➢ **Identifying and verifying theoretical methods of SPL calculation within the cavity.**
Element 3 **Ingress and propagation of sound through an opening in the inner skin of DSF**	➢ **Investigating if a predictive model can calculate this scenario.** ➢ **Applying the correct procedures from ISO 140-5.** ➢ **Evaluating current research on this element.**

Table 1.1 Key Challenges associated with the research of Sound Path Elements

1.4.2 LIMITATIONS AND BOUNDARIES

1. The spectrum of DSF classification is particularly broad so the boundaries of this work are shown in Figure 1.1.
2. This study will focus on NV DSFs in particular using openable windows as a mode of ventilation. Despite being the most common mode to naturally ventilate a DSF there is uncertainty within the industry regarding the level of acoustic insulation lost due to an open window (Waters-Fuller 2009).
3. This study will only consider direct sound transmission and will not consider indirect flanking sound transmission (sound transfer from one open window to another)
4. The study will be limited to NV DSFs on one side of a building DSFs that are closed at the top and sides. Larger more complex façade configurations lie beyond the scope of this research.

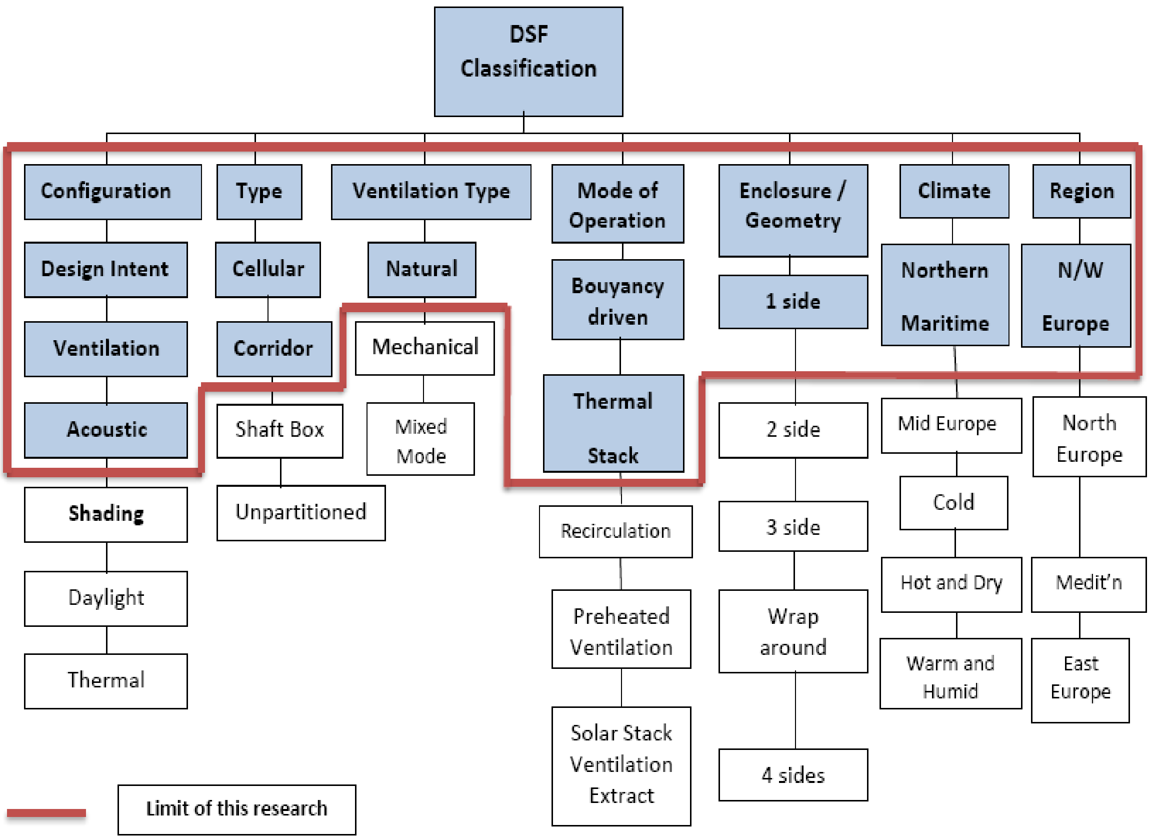


FIGURE 1.1 Double Skin Façade Clasification

1.5 OBJECTIVES AND RESEARCH METHODOLOGIES

Table 1.2 below outlines the research objectives. Each objective is described and the Research Methodology outlined for the objective.

Objectives	Detailed Description	Research Methodology
Characterise the DSF configuration	A detailed review of all the potential DSF configurations.	Desk based literature review of DSFs.
Review regulations and DSF parameters (Chapter 2).	A review of specific research related to regulations, standards for testing, and individual element of the path for SPL.	Desk based study.
Identify selected NV DSF projects	Selection of suitable DSF Projects that meet research criteria.	Industry contacts and personal interviews with building owners, building managers and facility managers.
Review parametric modelling procedures (Chapter 4)	A review of the most appropriate modelling techniques to model each element of the sound path shown in Figure 1.2.	Desk based review
Devise acoustic monitoring strategy (Chapter 5)	Selection of the most appropriate sensors to monitor each element of the DSF. Identification of suitable sensor locations and determination of optimum sample and record rates.	Laboratory based with field testing.
Parametric analysis (Chapter 6)	Collation of the resultant data by DSF element, mapped to relevant empirical equations and determination of appropriate methods of modelling.	Desk based analysis
Select most effective and useful analysed data to present to the Industry.	Analysis of resultant data and determination of it's benefit to selected industry domains.	Desk based study with on-site verification and industry feedback.

Table 1.2 Objectives and Research Methodology

1.6 CONTRIBUTION TO KNOWLEDGE

1. There is widespread anecdotal belief within the Façade Industry that glazed DSFs enhance the acoustic performance of the building envelope. This study will confirm whether such anecdotal beliefs can be supported empirically when DSFs are naturally ventilated.

2. Most manufacturer based industry research findings relate to closed cavity systems. A closed system is one which is completely sealed and the cavity environment is regulated by mechanical methods. There appears to be very little research for NV DSF systems that require the façade to open either on the inner or outer skins.

3. Academic research suggests that the acoustic challenge of NV DSF has yet to be resolved. This research seeks to offer clear direction towards validating viable naturally ventilated design solutions.

4. The contradictory nature of the existing research warrants more in-depth empirically supported research. As shown in Figure 1.2, each element of the sound path will be examined using different methods of analysis and a comparison made of the results. A comparison to current predictive models will represent a significant contribution to the industry knowledge capital in this field.

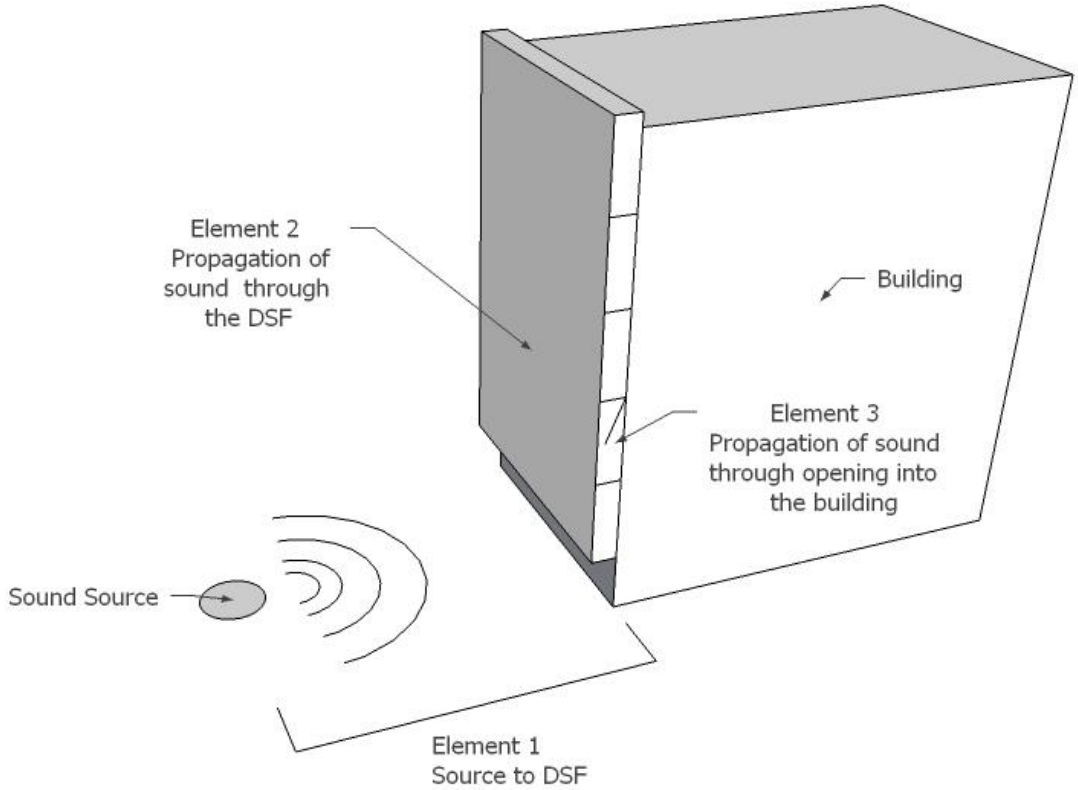


Figure 1.2 Generic Sound Propagation Elemental Layout

1.7 DISSERTATION STRUCTURE

This dissertation will examine the sound pressure level of three key elements along the sound path from sound source to building interior (Figure 1.2). This is necessary because each element of the sound path requires a separate analytical approach as summarised in Table 1.3.

Element	Analysis Method		
	Theoretical	**Parametric**	**Experimental**
1. Source to DSF	Select open field theoretical calculation	Examination of Cadna Model and CATT model	Using standard ISO 140 -5 procedure.
2. Propagation through DSF cavity	Propagation of sound theory through ducts, long flat rooms including image sourcing.	Ray tracing and image sourcing model - CATT acoustics	Measurements in the cavity in accordance with the best fit method within ISO 140 -5
3. Open windows in the inner skin of DSF	Empirically derived equation from existing studies.	CATT acoustic model	Testing using the methodology stated in ISO 140-5.

Table 1.3 Summary of analysis method for each sound element.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This study is configured so that the investigation of sound pressure levels along the path of sound is divided into three elements (see figure 1.2) from exterior sound source to building interior. This literature review will examine some of the more influential research into the field of acoustics and natural ventilation and, where relevant, map research to each element of the sound path.

The review of research papers in relation to acoustics, natural ventilation and DSFs shows that there is very little conclusive evidence of accurate acoustic predictive methods for NV DSFs. Most sources concluded that further research is required in predictive methodologies. This suggests that the DSF is technologically advanced in terms of product development (the building physics of heat, light, shading and ventilation) but is still in it's infancy in relation to the acoustic attenuation of DSF in the NV mode.

This may be due to greater focus on natural ventilation as a driver in sustainable project design. Dr Chris Field noted that selected sustainable design rating systems recognised worldwide do require acoustic credits in their respective systems. The acoustic criteria adopted normally relates to mechanically ventilated buildings, thus making naturally ventilation design options almost unachievable (Field, 2010). This will be explored further in Section 2.2.

Table 2.1 maps the body of research to the acoustic element that it will support.

Research Author	Research	Acoustic Component
Dr Chris Field	Acoustics in a sustainable design, predictive acoustic modelling	Predictive modelling and general commentary of acoustics in natural ventilation design
Dr Marcello Blasco	Research into predictive modelling of DSF.	Components 1,2 & 3
Napier University	Research into acoustic insulation of open/closed windows	Acoustic insulation of windows in the open position – component 3
Fuller and Lurcock	Further research of open/closed windows	Empirical calculation derived from research
Ze Nunes	Acoustic research on open windows	Open windows as a mode of ventilation with derived calculations
Bees and Hanson	Theoretical concepts of room acoustics	Hypothesis that component 2 should be examined by interpretation of 'flat room' acoustic calculation methods

Table 2.1 Summary Research Table Mapping Research To Acoustic Elements

2.2 RESEARCH OF DR. CHRIS FIELD

The research of Dr Chris Field was a determining factor in starting this study. His 2011 paper noted that, 'the lack of accurate prediction of the acoustic performance of naturally ventilated façades is hindering their widespread adoption in sustainable building design'.

Dr Field questioned the meaning of sustainability with respect to the acoustic environment (Field, 2010) by challenging the industry to re-evaluate the criteria for acceptable indoor noise levels for office buildings when natural ventilation is used.

2.2.1 CHALLENGING INTERNATIONAL STANDARDS

In his paper 'acoustic design criteria for naturally ventilated buildings' in 2008 with J. Digerness, Fields described how international standards provide recommended guidelines for internal background noise limits for building use. He contended that these limits assumed sealed buildings with air-conditioning, so the use of natural ventilation was considered unfeasible in particular projects. This presented a challenge for designers to overcome boundaries with innovative design. However, Field pointed out that there were no internationally recognised standards for internal background noise limits with the use of natural ventilation.

There is research to suggest that allowable indoor noise limits could be higher than for a sealed, air-conditioned building. Fields quoted three different sources of research.

- Wakernagel et al, 1999, indicate 'that internal noise levels of up to 65 db L_{Aeq} could be acceptable in naturally ventilated offices'.
- Ghiaus and Allard, 2005, contended that 55 – 60 dB L_{Aeq} is acceptable in open plan offices and that current International standards are too stringent to be applicable to naturally ventilated buildings.
- McCartney and Nicol, 2002, showed that European office noise levels would be tolerable at 60 dB L_{Aeq}

2.2.2 REVISING INTERNATIONAL STANDARDS FOR NV BUILDINGS

In his 2010 paper, Dr Fields again challenged the International Regulators by outlining the current recommended background noise limits for unoccupied mechanically ventilated spaces. This table is reproduced in Table 2.2

Occupancy Type	BS8233 (L_{Aeq} dB)		AS2107 (L_{Aeq} dB)		ASHRAE (NC)[1]	
	Satisfactory	Maximum	Satisfactory	Maximum	Satisfactory	Maximum
Private Office	35	40	40	50	25	35
Meeting Room	30	40	35	40	25	35
Open Plan Office	40	45	45	50	30	40

Table 2.2 Recommended background noise limits for unoccupied mechanically ventilated spaces (Field 2010, p3)

[1] For comparison purposes, the NC rating is typically 5 dB lower than the L_{Aeq}

He went on to cross reference the acoustic criteria with the green building rating standards and a summary is given in table 2.3.

Green Building Rating Scheme	Standard to which the Scheme refers
Greenstar (Australia)	AS2107 (L_{Aeq} dB)
LEED (US)	None
BREEAM (UK)	BS8233 (L_{Aeq} dB)

Table 2.3 Green building Rating Schemes and their associated acoustic standard.

Field proposes the way forward utilising revised criteria:-

- Subjective testing using auralisation in a controlled environment:
  Controlled experimental laboratory testing indicated that L_{Aeq} levels could be 10dB higher than currently recommended.
- Revised Noise Criterion curves for NV Buildings:
  He proposed that a study be carried out to modify NC curves to ‘NC-NV curves’ suitable for applying to the design of naturally ventilated office spaces.

- Subjective Testing in an existing NV Building:
  In the same manner as the laboratory testing above, subjective testing should be carried out on existing naturally ventilated buildings. This is the challenge of this current research except that this research will focus more on NV DSFs.

2.2.3 PREDICTION OF INTERNAL NOISE BREAK IN THROUGH QUANTITATIVE METHODS

In 2011, Dr. Fields developed a quantitative method of predicting noise break in through 'dual vented windows' used in naturally vented buildings. The study used the results of Kerry and Ford, 1973, to calibrate the new predictive model, Volume Acoustic Cavity Solver (VACS). According to Dr Fields, the acoustician could investigate and numerically predict the acoustic performance of various double glazed unit (DGU) configurations and cavity widths in conjunction with openings to allow natural ventilation. Parameters such as receiving room volume and reverberation time (RT) could be specified for each octave band to allow both D_n and sound reduction index (SRI) to be calculated.

The predictive model theory and methodology is complex and begins by taking the theoretical equation for the natural frequency of a rectangular volume of air. By using Strand 7 and a set of theoretical assumptions, the VACS system produced a set of frequency response curves using finite element analysis (FEA), level differences, D_n, and SRI by using RT based on Sabine's (equation 3.3) and room volume.

Dr Field verified his VACS solver with the results of Kerry and Ford. He stated that this predictive model reduced uncertainty in the prediction of sound insulation of naturally ventilated façade designs.

The VACS solver has yet to be validated against further window configurations.

2.3 RESEARCH OF DR. MARCELLO BLASCO

2.3.1 ACTIVE FAÇADES

The research of Dr. Marcello Blasco made an important contribution to the field of acoustics within DSF. In 2004, Blasco et al, published ‘Acoustical Performances of Double Ventilated Glass Façades’ and characterised DSFs in the following manner:-

- Active
- Passive
- Interactive
- Hybrid

He differentiates the categories through their modes of ventilation:-

a) An active DSF is an internal mechanical system,
b) A passive DSF is a naturally ventilated cavity,
c) An Interactive DSF uses natural ventilation supplemented by mechanical means.
d) A Hybrid DSF is described as the combination of ‘several types’.

The testing campaign for this 2004 study was in the active category and examined various combinations of DSF typology. They concluded that ‘one obtains performances that meet the very highest requirements of the Belgian standard’. The results pointed to an acoustical performance of 43dB from outside to inside which he equated to 14cm of brick (180kg/m^3). The best performance in test 3 produced a result of 54dB corresponding to 14cm of poured concrete (350kg/ m^3) or 19cm of concrete blocks (285kg/ m^3). The report stated that ‘a typical façade from an office block gave 6dB less acoustical façade insulation than the poorest performing Double Vented Glazed Façade (DVGF)’.

2.3.2 EVALUATION OF STANDARDS AND REQUIREMENTS

In 2008, Loncour, Blasco et al published ‘Ventilated Double Façades – Evaluation of the existing standards/requirements applying on buildings equipped with ventilated double façades. Overview of the existing documents and potential problems.’

The paper was large in scope and attempted to identify and examine all of the performance criteria across a general framework. Part 5 of the document related to ‘protection against noise – acoustical aspects’.

The document summarises European standards in relation to the acoustic performance of the façade.

The interesting section of this report, section 5.3.3, challenged BS EN 12354-3 Building Acoustics – Estimation of acoustic performance of buildings from the performance of products – Part 3: Airborne Sound Insulation against Outdoor Sound.

Blasco challenged the standard by pointing out the lack of method in assessing:

- ‘Morphology’ of a ventilated double façade from the open to closed state.
- The standard only ‘gives a good fit for single pane constructions’. He asked ‘what should be done for double constructions?’

These were very appropriate questions and not easily answered and hence the need for acoustic research in all classifications of DSF.

2.3.3 PREDICTION MODEL

Blasco published his Doctoral Thesis in 2012, ‘an acoustic approach to double façades – a general overview and sound insulation prediction model’. This was a complex document that examined several different analytical and predictive methods to eventually develop a semi-empiric hybrid model (SEHM).

The predictive models were designed for what he describes as ‘closed and empty cavity’, implying a DSF that has a mechanical ventilation mode. The goal that Blasco set was to create a new model with minimum prediction error in all frequency bands, depending on the type of DSF.

The final SEHM consisted of using different models depending on the frequency band investigated and on the type of DSF to be simulated. In other words, a laboratory test was required to determine which category the DSF was in, before the SEHM was run.

The laboratory test rig used a standard opening of 1.25m x 1.5m. Blasco asserted that there was ‘a 1.81db average prediction error with the SEHM and an average prediction error for SRI of 0.5dB’.

This research was promoted by a leading global building envelope contractor and this may be the reason for the specific concentration on ‘closed cavity’ construction. Nevertheless, this research work made a significant contribution to the body of research into the acoustic performance of the DSF.

2.4 RESEARCH OF NAPIER UNIVERSITY

Research by Napier University resulted from a sponsored research project funded by the Department for Environment, Food and Rural Affairs (DEFRA), to *'undertake a thorough review of current knowledge/literature of acoustic losses through windows (open and closed), and produce a detailed summary of the findings'.* This is equivalent to element 3 in the sound path as outlined in Figure 1.2.

2.4.1 BACKGROUND TO NAPIER RESEARCH

The need for research stemmed from 'UK policy outlined in 2000 by the Office of the Deputy Prime Minister's Planning Policy Guidance Document 3, Housing' (PPG 3) which 'commits to sustainable patterns of development through the concentrated use of previously developed land whilst ensuring that homes are decent and are capable of improving quality of life'.

The development of brown field sites for residential purpose presents particular challenges. In terms of acoustics, brown field sites are generally exposed to high levels of noise from a combination of retained industrial neighbours, concentrated transport infrastructure, adjacent entertainment venues or utility plant.

This provided an opportunity to produce detailed advice on acoustic prediction methodologies suitable for the planning process however key research needed to be undertaken. NAN116: 'Open/Closed Window Research was awarded to the Napier University on this basis.

2.4.2 HISTORICAL PERFORMANCE OF OPEN WINDOWS

Napier compiled a list of the available research for the insulation performance of open windows. This is compiled in Table 2.4 which outlines the research and the resulting performance. The table gives a range of 5 – 15dBA, however the standard range cited in literature is 10-15dBA.

Information Source	**Summary of Findings**
PPG 24 (1994)	A reduction of 13 dB(A) from the façade level is assumed for an open window
WHO (1999)	A reduction of 15 dB from the façade level is assumed for a partially open window. (no reference)
BS 8233 (1999)	Windows providing rapid ventilation and summer cooling are assumed to provide 10 - 15 dB attenuation (no specific reference)
BRE Digest 338 (1988)	A partly open window has an averaged level difference, D1m,av100-3150 of 15 dB
DoE Design Bulleting 26	A reduction of 5 dB(A) with a window wide open
Nelson – Transportation Noise (1987)	Sound insulation of an open single window is 5 – 15 dB (theoretical).
Mackenzie & Williamson DoE Report (1972–73)	A vertical sliding sash window open 0.027 m2 (summer night-time ventilation) and 0.36 m2 (daytime summer ventilation) provided a sound level reduction of 16 and 11 dB(A) respectively. (Lab Study)
Kerry and Ford (1973 – 74)	A horizontal sliding sash window open 25 mm and 200 mm provided averaged sound reduction indices, R_{av} of 14 and 9 dB respectively.(Field Study)
Lawrence and Burgess (1982 – 83)	A vertical sliding sash open 9% of the total façade provided a sound reduction index Rw 10 dB. (Field study)
Hopkins (2004) [15]	Road traffic noise reductions through window openings resulted in reductions of between D2m,n,T 8 and 14 dB. (Field Study)

Table 2.4 Summary of open-window acoustic transmission literature (Napier, 2007)

Napier conducted an intensive literature review, concluding that the factors for accurate assessment of internal noise levels from external sources was complex and affected by a host of parameters.

A summary of the factors commonly affecting the transmission of noise through a façade is shown in table 2.5, divided into effects related to the source, propagation and receiver environment.

2.4.3 TEST METHODOLOGY

NAPIER selected 7 windows for testing and a combination of 14 configurations. The laboratory tests were conducted using the following standards as guidelines:

- BS ISO EN 140 Part 3 ‘Laboratory measurements of airborne sound insulation of building elements’.
- BS ISO EN 140 Part 5 ‘Field measurements of airborne sound insulation of façade elements and façades’.

The laboratory was set up in accordance with BS ISO EN 140-1:1998 as far as was practicable.

Source	Propagation	Receiver Environment
constancy	separation	façade build-up
size	line of sight	workmanship of build
directionality	reflective surfaces	internal volume
spectral characteristic	relative geometries	surface finishes
meteorology	meteorology	location

Table 2.5 Factors commonly affecting the transmission of noise through a façade (Napier, 2007)

2.4.4 RESULTS

This research produced a large amount of data comprising nine individual sets of one-third octave sound pressure spectra across a frequency of 50 to 5000Hz. The single figure results were an integer calculated weighted level difference, $D_{w,}$ determined by the reference curve as described in BS EN ISO 717-1.

NAPIER concluded that:-

a) For the dataset considered, the doubling of window area (with the windows closed) caused a reduction in the D_w of approximately 5dB.

b) The influence of the glazed area was negligible once the window is open.

c) It was noticeable that once the window was opened the influence of the glazing specification was nullified.

d) The influence of the window frame material became insignificant when the window was opened.

e) The influence of upgrading to acoustic seals became negligible once the window was opened.

Napier conducted a best fit empirical solution to assess the effect of the window opening on the façade insulation. Empirical estimates were performed and deductions were reached in terms of the small element parameter; the element normalised level difference $D_{n,e}$. The data used for the assessment was taken from BS EN ISO 140-5. The calculation method was summarised by Equation 2.1.

$$D_{n,e,i} = -10Log_{10}\left[\frac{1}{10}S10^{\left(-\frac{R\,facade}{10}\right)} - S_{wall}\ 10^{\left(-\frac{Rwall}{10}\right)}\right] \qquad (2.1)$$

Where, S_{wall} is the wall area appropriate to the measurement (i.e. S-$S_{Element}$)

2.4.5 NAPIER RESEARCH CONCLUSION

The NAPIER study involved 720 individual measurements across 7 window types, 14 configurations using six receivers on each test.

The results derived single figure insulation ratings for the window types and the study addressed the goals of their report by replacing the broad historical statement of 5-15dB insulation loss for an open window, with the fully researched data supplied.

2.4 RESEARCH OF FULLER AND LURCOCK

In 2009 the authors of the 2007 NAPIER University report published, ‘research into the transmission loss of open and closed windows’. They summarised the findings of the 2007 report and then expanded with new material.

A data-fit for previous open window results was undertaken and an empirically derived relationship is proffered.

$$D_{2m,nT} = Log_{10}\,(f)x\,\lfloor 2.2 - 0.8\;x\;Log_{10}(S_{op})\rfloor - 3.2\;x\;Log_{10}\left(S_{op}\right) + 8.1\;dB \qquad (2.2)$$

Where,

f is the octave band centre frequency between 125 Hz to 4000 Hz

S_{op} is the open window area (m²)

Fuller and Lurcock, stated that the preferred façade insulation parameter used in predictive schemes is the Sound Reduction Index (SRI), given in equation 2.3.

$$R' = D_{2m,nT} - 10xLog_{10}\left(\frac{V}{6T_oS}\right)\;dB \qquad (2.3)$$

Where,

R’ is the apparent sound reduction index of the façade (dB)

V is the receiving room volume

S is the façade area (m²)

Fuller and Lorcock produced an equation for the best fit line within their graph of the apparent façade SRI, $R'_{w,}$ of $X = -5.8\,Log_{10}\,(x) + 13.2$. (2.4)
The conclusion to this paper was that the trend for the resultant dataset from the Napier Paper indicated that there would be an average sound reduction at a rate of 1.8 dBA per doubling of opening window area.

2.6 RESEARCH OF NUNES, WILSON AND RICKARD.

This research carried out by Nunes, Wilson and Rickard in 2009 was entitled, 'An assessment of the acoustic performance of open windows, in line with ventilation requirements for natural ventilation'.

It summarises the Napier Research and introduces the research of Anderson and Hopkins, 'Sound Measurement and Natural Ventilation in Schools'.

This paper presented the results of the Hopkins paper in the form of octave band element normalised level differences. These results are then compared with the Nunes results from a series of tests on a Velfac 200 window at a range of openings.

Nunes et al contended that after reviewing the available literature on the topic of open window sound insulation, it was clear that there were many issues with using the available data. The inconsistency in calculation meant that values were expressed in SRI, dBA or a simple dB level.

The aim of the Nunes paper was to extend the available information on the subject and to provide further evidence that the conventional recommendations of 10-15 dBA reduction is not appropriate for accurate acoustic design.

The Nunes research indicated that the insulation results in the field were characteristically better than the equivalent performances as measured in diffuse laboratory conditions. It was noted that as the open window distance decreased, 'the insulation improved in a manner best described as logarithmic'.

Nunes plots the difference in the D_{ne} performance for incremental increases in the window opening area compared to a base case, taken as the smallest window opening area. In addition, the theoretical difference based solely on the increase in the window opening area was included as 3 dB per doubling of area.

The plots indicated that there were significant differences in the actual insulation performance compared to the theoretical performance. They contended that the theoretical approach was not appropriate for accurate predictions.

2.6.1 VARIATION IN D_{NEW} FOR DOUBLING OF OPEN AREA.

Nunes contended that as a general rule, it is accepted that the sound reduction of a window decreased to 10 log (N) or $10\ Log_{10}\left(\frac{area1}{area2}\right)$ (2.5)

Where, $\left(\frac{area1}{area2}\right)$ is the difference between the open area for different windows.

Nunes plotted the results of field testing against laboratory results that 'further suggest that the 10-15 dB typically quoted in documentation may not be appropriate for use in all cases'. The graphs show that the 10 log (N) equation tends to significantly over predict the sound reduction as the open area increases. The paper suggested that a more accurate representation was:-

- Free Field Condition 5 log (N)
- Diffused field condition 8.5 log (N)

2.7 RESEARCH OF BEES AND HANSON

The hypothesis that is used to examine the propagation of sound in a DSF (element 2 of the sound path in Figure 1.2) is described in Chapter 5. Bees and Hanson outlined their theory of 'flat rooms' in their text, Engineering Noise Control, 1988.

A long and flat room with specularly reflecting floor and ceilings was considered and they deemed this to be a convenient starting point for the analysis of room acoustics. They described the flat room as 'an empty space between two relatively smooth and reflecting surfaces'.

The principle of a flat room with highly reflective surfaces as the boundary condition is precisely the condition for the DSF and therefore the resulting Bees and Hanson principles are adopted to examine DSFs.

The theoretical model is examined in two cases:

1. When the distance between the source and the receiver is small (the bottom of the DSF where the sound enters)
2. The condition where the distance between the receiver and the source is large so that $r \gg a$.

Bees and Hanson introduced the concept of image sourcing in a similar way as the parametric models in Chapter 7.
A more detailed review of this hypothesis will be outlined further in Chapter 5, Empirical Study.

2.8 LITERATURE REVIEW SUMMARY.

This literature review focuses on the main influences on this body of acoustic research mostly all carried out in the last decade. Research in this topic needs to be current such is the advancement of DSF technology and the other building physics elements that comprise the DSF.

The concept of an elemental approach to the attenuation analysis of the DSF is not dissimilar to the 5 chamber model of Dr Blasco in his FEA research.

The research of Bees and Hanson has been used in Chapter 5 as the predictive hypotheses for the acoustic attenuation of element 2.

The conclusions of Napier, Lurcock and Fuller and Nunes et al have all been utilised in Chapter 5 to examine element 3.

Most of the research that has been reviewed challenges current views of acoustic insulation calculation and prediction methods. All the researched literature makes attempts to either derive solutions or make suggested alterations to existing standards. They are not simply desk based studies and reviews.

However, it is abundantly clear that the quantity of acoustic research source material is significantly less than the other elements of building physics. This is particularly so in relation to NV DSF.

DSF construction worldwide is a multi-million pound micro-industry within the broader façade industry and yet acoustic research is either not being released or not completed.

The suggestion would be that it is the latter and this research is an attempt to initiate a strategic approach to NV DSF acoustic research and a wider body of DSF acoustic research.

CHAPTER 3

CHARACTERISING THE GEOMETRY AND TYPOLOGY OF DOUBLE SKIN FACADES

3.1 INTRODUCTION

Characterising DSF's is difficult insofar as the terminology used to describe aspects of a DSF differs by region, country, market and supply chain. This characterisation of a DSF will endeavour to explain components and terminology in a consistent manner to allow a uniform use of description and terms.

3.1 BRIEF HISTORY OF THE DSF

History shows that one of the earliest DSF's was designed and built in 1903 at the Steiff factory in Geingen, Germany (see Figure 3.1). It is still in use today which is a testament to the excellent engineering employed. The energy crisis in the 1970's resulted in a drive to enhance the thermal properties of glass walls and one of the strategies developed was adding a second sheet of glass outside the plane of the double glazed unit (DGU) of the thermal envelope. The 'Klimmafassade' or 'Abluftfassade' was developed in the seventies, commonly known now in the UK as the climate façade. It came to prominence in the UK in 1978 when Richard Rogers used it in his design of the Lloyds HQ in London (Dickson, UOSG).

Figure 3.1, The Steiff Factory (Blasco, 2012)

One of the earlier NV DSF's as we know it today, is the RWE Headquarters in Essen, Germany completed in 1997 (See figures 3.2 and 3.3). This building provided natural ventilation to the internal rooms of the building and differs from previous systems that would have ventilated the cavity between the inner and outer skins.

Since 1997 and the completion of the RWE building, there have been many examples of DSF in Europe and it would appear to be a symbol of architectural and technological innovation. Indeed, many of the iconic buildings in major cities across Europe utilise DSF technology, one of the more prominent being The Shard in London by architect Renzo Piano (Figure 3.4)

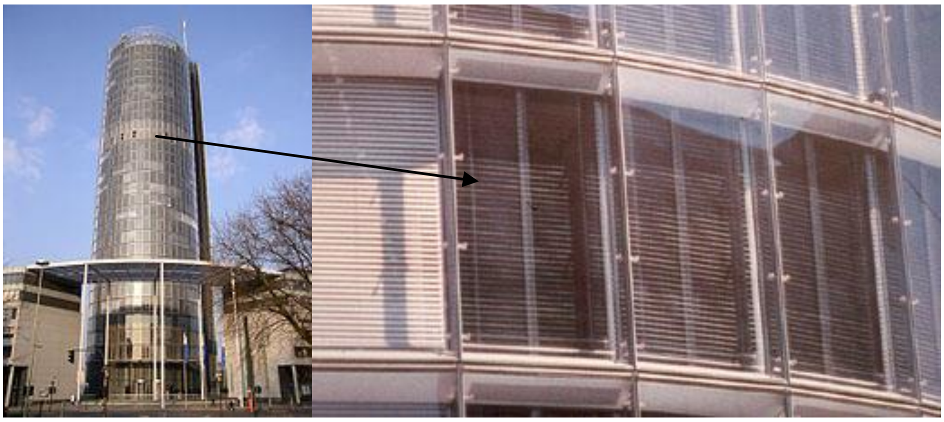


Figure 3.2, RWE Building (BESTFACADE, 2008)   Figure 3.3, RWE, closer detail (BESTFACADE, 2008)

It is fair to say that the DSF developed rapidly in the 1990's because of design constraints placed on designers to fulfil their environmental responsibilities. It can be argued whether these drivers were cost attributed to whole life performance of a building, a sustainability responsibility to the wider environment or both.

Figure 3.4,The Shard

Regardless of the drivers for the development of advanced façade solutions, the DSF has evolved into the highly engineered product it is today. So, why has the acoustic research and development of NV DSF's not kept abreast with advances in the other building physics elements and disciplines applicable to DSFs?

The project BESTFACADE, sponsored by the Energy Intelligent Europe Program of the European Union, and led by MCE-Anlagenbau, Austria, accumulated data on 28 double skin façades in seven European countries between 2005 and 2007. It published 'Best Practice for Double Skin Façades EIE/04/135/S07.38652' in 2008 with a view to providing all interested parties with the confidence to continue using DSFs. The report cited acoustic attenuation as a benefit with the warning of 'flanking' as a disadvantage. However, the document predominantly examined thermal, solar control and comfort issues with very little commentary on acoustic research. This was the most comprehensive review of DSF's in it's short existence yet the acoustic review was minimal compared to the other elements within DSF technology.

3.2 COMPONENTS OF A DSF

There are many varied descriptions and names for a DSF. In Chapter 2, many important authors have described and named the DSF using their own terminology.

In terms of the components of a DSF, all authors appear to agree on the general principle that the DSF is comprised of two skins (an inner skin and an outer skin) with a cavity inbetween both skins. The inner skin is connected to the 'primary' structure and the outer skin becoming the envelope to the building. The term 'thermal envelope' is not being used for the outer skin because there are a great number of situations where the outer skin is not the thermal envelope.

If we consider a hierarchy of building structure to be:-

1. Primary Structure – all loadbearing and core elements of a structure to carry the imposed horizontal and vertical loads

2. Secondary Structure – construction that is not primary structure such as roof, façade, partitions, floors that are not primary.

3. Tertiary Structure – construction elements that are secondary structure but are not necessary to the structural stability of the secondary structure.

The DSF will fit into elements 2 and 3 in the hierarchy of building structure. In most cases the inner skin will form part of the secondary structure with the outer skin most likely being categorised as being tertiary structure.

The material composition of a DSF is not limited to just glass and aluminium. There can be limitless combinations of glass, aluminium, steel, stainless steel, composite panel, shading devices, louvre devices, decking, and many more, in the total construction and make up of a DSF.

3.2.1 DSF CONSTRUCTION

The inner skin of a DSF would normally be a curtain wall system. There are no set design rules that state the inner skin must be stick CW, unitised CW or a definitive construction - it could simply be punch-hole windows in a brick façade. The configuration of the inner skin design is set by the architectural intent and performance criteria required.

The cavity can vary from 100mm to in excess of 2m and is a function of performance, specification, design intent and user control. Figure 3.5 shows a cavity of approximately 1000mm that can house a solar shading system and a maintenance deck.

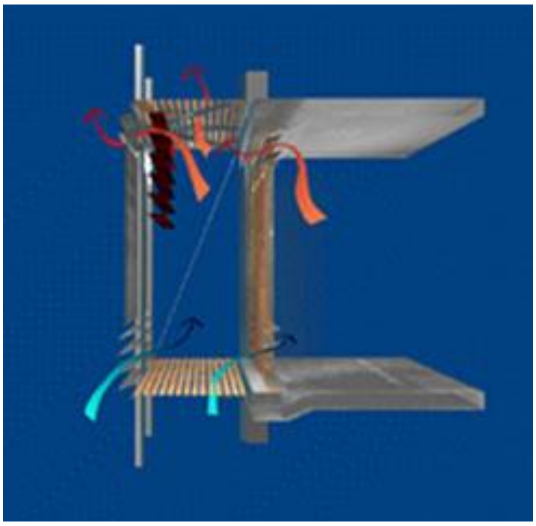


Figure 3.5 Cavity in a DSF

The outer skin construction can vary and be comprised of anything from a curtain wall system to a point fixed glazed to a louvered system. The outer skin can be supported by an external structural support system, on cantilevered brackets from the inner leaf or be part on the inner leaf CW system.

There does appear to be norms for DSF construction in certain regions according to Uuttu, 2001. Uuttu mentions that both cantilevered bracket structures and suspended structures are used in Finland and attributes this to the function of the

DSF. In Finland, there is a tendency for the DSF cavity to be the full height of the building which dictates the construction. In Germany, Uuttu concludes that the DSF cavity is partitioned horizontally at the intermediate floors and then vertically at window breaks. This allows for window natural ventilation design in Germany, whilst in Finland the main purpose of the DSF '*is to act as a raincoat for the inner façade.'*

These are very general statements but it is interesting to note that the construction type that is selected and defined by the mode of use is inherently popular within a country or region.

The design choices are endless when deciding on the type of DSF system. This is the fascination with this type of façade construction – there are countless construction options with the ability to creative cutting edge design for the façade. These possibilities in option and design are enhanced by the advanced environmental and technological advantages that DSF's can offer. The DSF construction options make it very attractive to designer and end-user alike.

3.2.2 DSF CONFIGURATION

In Chapter 1, Figure 1.1, DSF Classification, the double skin façade is examined across a number of headings. Figure 1.1 is shown again for clarity. This research is focused on naturally ventilated double skin facades and acoustics so the boundary conditions were also indicated in Figure 1.1.

The DSF commentary on classification and configuration will remain within the limitation boundaries set.

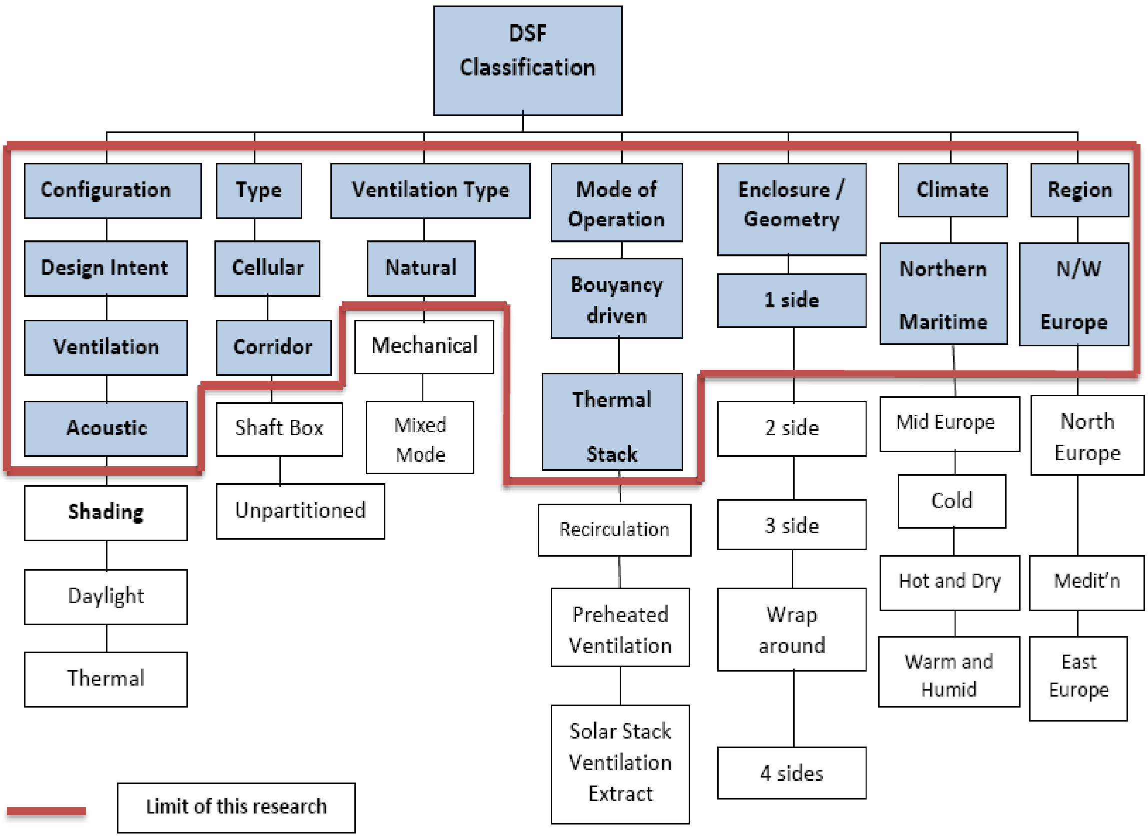


Figure 1.1 Double Skin Façade Classifications

3.2.3 NATURAL VENTILATION

Natural ventilation is only one of the ventilation modes that can operate within a DSF. According to Poirazis, 2004, the air velocity and the type of flow inside the cavity depends on:

1. The depth of cavity
2. The type on openings used on the inner skin.
3. The type of openings used on the exterior skin.

These openings can be either 'active' or 'passive'. A passive system whereby the openings are left open all of the time and an active system which will allow the openings to be opened and closed by hand or machine, manually or automatically. This description for active systems relates to openings on both the outer and inner skins. Figure 3.6 shows glass louvres opening to ventilate the cavity in this DSF in Dublin. The passive description relates to the either the outer or inner skin

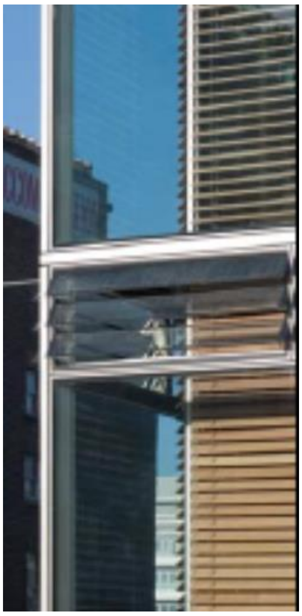


Figure 3.6 Active DSF Glass Louvre Opening

depending on the design, but cannot be both for obvious reasons. Figure 3.7 shows the open bottom of the tested project (Chapter 6). It is a project in London that naturally ventilates the cavity from the bottom. In this instance the bottom is just open however there can also be openings where there is an opening element, such as louvres or dampers. In a similar way the opening on the inside may be a simple window, damper or louvre, operated manually, automatically or left open. Figure 3.7 shows a diagram of a DSF system with both external and internal passive louvres.

Figure 3.7 Building A, London, Open Bottom for natural ventilation

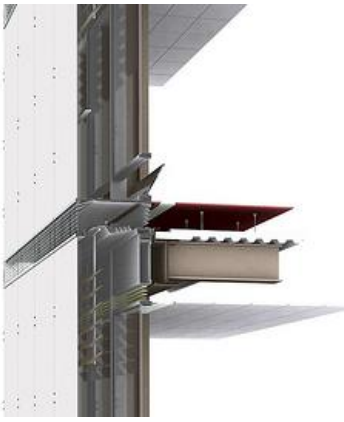


Figure 3.8 External and Internal grilles ventilating the raised floor space

Figure 3.8 shows a DSF system that is using natural ventilation via a damper system that is ventilating the internal ceiling void through ceiling grilles.

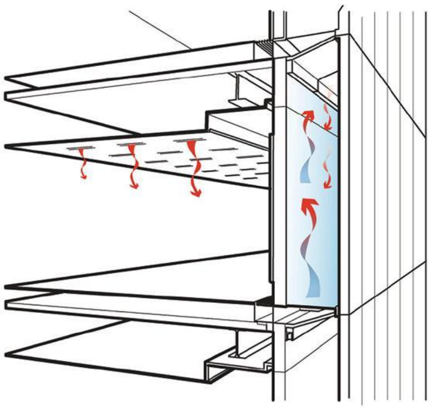


Figure 3.9 Damper on the inner skin ventilating the internal ceiling void.

The openings in the inner skin have been extensively studied by many including Oesterle 2001 and Jager 2003, however, these studies purely focused on ventilation efficiency. Oesterle's study examines the ventilation efficiency of various casement windows in relation to elevational area of the opening light. Jager's research focuses on the air inlet and outlet and the relative air change efficiency relating to the visible area of the opening sash.

These are important pieces of work however the focus on the inner skin transmission loss and ventilation comes from the Fuller and Lurcock, 2009, and Napier University research in 2007. The importance of the inner skin ventilation type, configuration and associated transmission loss is outlined in detail within Chapter 2 and will also be incorporated in theoretical calculation within Chapter 5.

3.2.4 GLASS

The selection of glass for DSF's is an interesting topic when the sole purpose is to examine the acoustic function of the DSF.

Poirazis contends that the most common panes types used for DSF's are:-

- Internal Skin – double or triple glazed, thermal insulating units with the unit cavity filled with air, argon or krypton. The glass panes can be toughened, laminated or annealed depending on structural, safety and code constraints.
- External Skin – usually it is toughened, laminated or a combination of both in a single pane.

The description by Poirazis is very much a condensed summary of the DSF condition where the outer skin is single glazed. Of course, there is the DSF construction where the outer skin is double glazed and so the above description would need to be reversed (Poirazis, 2004)

Many authors have their own description of the glass construction comprising a DSF, however, such is the flexibility of the DSF design, that it appears that each description is just a variation of the same theme.

The acoustic treatment of glass in the DSF is a complex decision making process. The inner skin, if in the double glazed condition, can be acoustically treated in the same manner as any external façade. Glass and frames with enhanced acoustic properties can be utilised and relatively good sound insulation can be achieved.

The general principles to achieve better acoustic insulation with insulating units are as follows: -

- The thicker the glass the better
- Vary the glass thicknesses to eliminate resonance
- Use an acoustic laminate glass if possible

Figure 3.10 shows a comparison of double glazed units from the SAINT-GOBAIN range using their published acoustical data for each type.

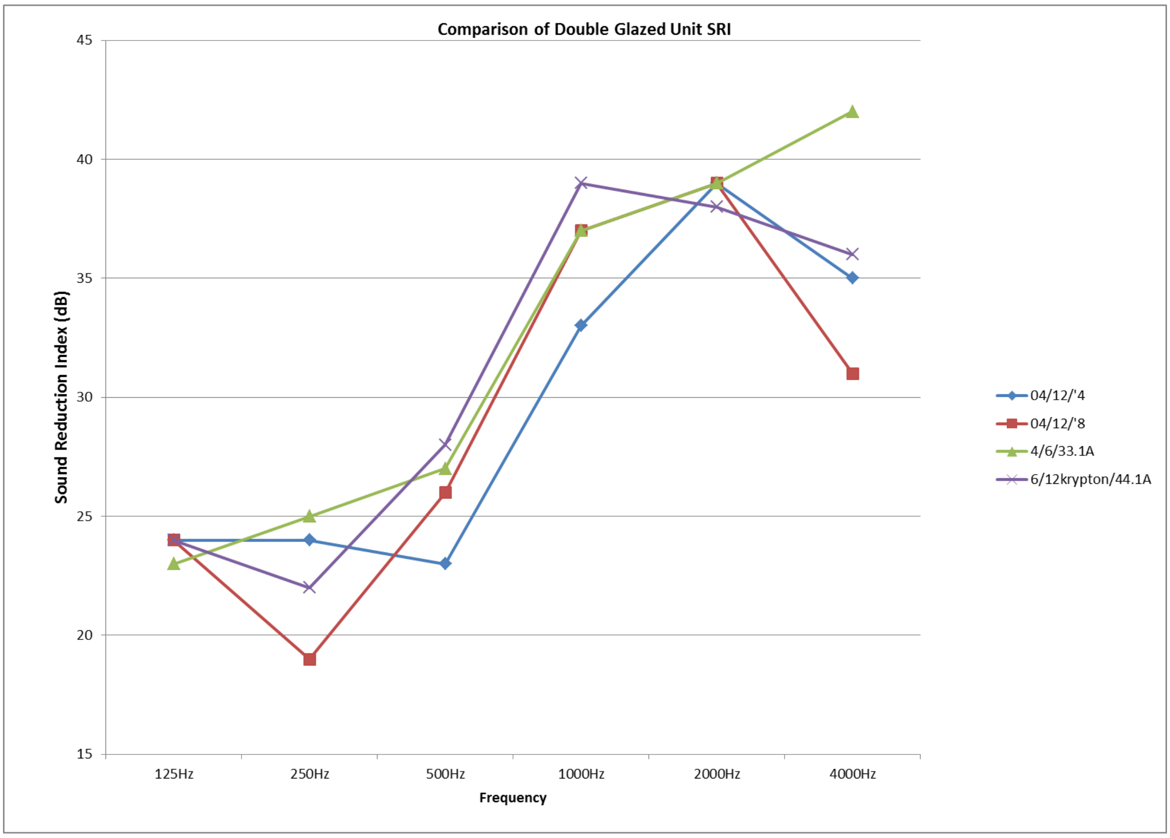


Figure 3.10 Comparison of Double Glazed Unit SRI

The four DGU types have varying acoustic characteristics and Table 3.1 shows the glazing make up, the DGU thickness and the $R_{w.}$

Glass	Thickness (mm)	R_w (dB)
4 (12) 4	20	30
4 (12) 8	24	34
4 (6) 33.1A	16	34
6 (12kryp) 44.1A	27	43

Table 3.1 Double Glazed Unit R_w

It is interesting to note that 4/12/8, with no acoustic treatment per se, can have the equivalent R_w as 4/6/33.1A. It is probably an unfair comparison because the 6mm cavity is not normally used however it does highlight the importance of all aspects of glass specification and selection. The cost difference between these two glass specifications could be in the order of 1.5 - 2 making the incorrect glass specification an expensive mistake.

The outer skin glass can be compared in the same manner and Figure 3.11 shows 4 different glass types from the SAINT-GOBAIN range and again used their published acoustical data for each type.

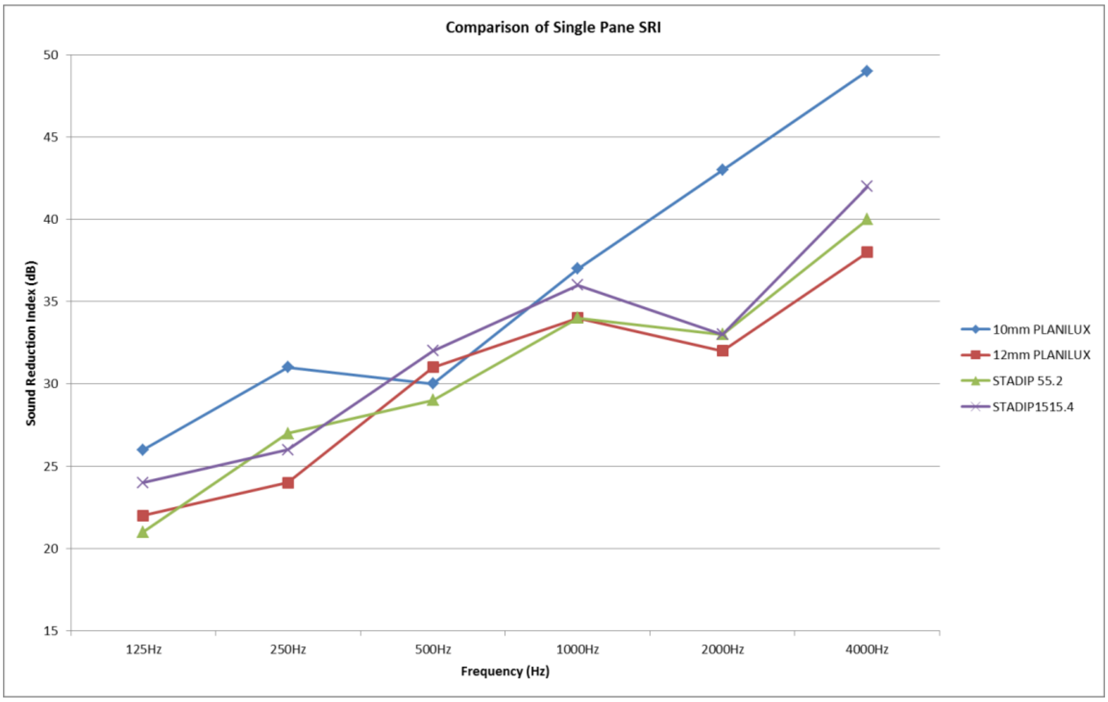


Figure 3.11 Double Glazed Unit R_w

The importance of knowing the specific acoustic problem to be managed is highlighted very well in this comparison of four different single panes. If the acoustic issue is high frequency sound then 10mm PLANILUX is the obvious product. It is curious to note that the published R_w for 10mm PLANILUX is the lowest of the selected panes as shown in Table 3.2.

Glass	Thickness (mm)	R_w (dB)
10mm PLANILUX	10	33
12mm PLANILUX	12	34
STADIP 55.2	10.8	35
STADIP1515.4	31.5	44

Table 3.2 Single pane R_w

If the mode of ventilation is natural ventilation and the method of ventilation utilised is opening windows, then how important is the inner skin glass selection and outer skin selection? Is the inner skin glass selection critical when the window is open? According to the comprehensive report issued by Napier University in 2007 it is not critical. In fact, their report states that '*for open windows the level of sound insulation was not affected by the glass specification*'. This may be an obvious and important conclusion; however it has not been cited in any other research during the preparation of this study.

Moving on to the outer skin – is there a need for the acoustic performance of the outer skin glass to be acoustically enhanced when natural ventilation is being utilised? The automatic answer is yes. However, is there logical reasoning behind this answer. If the sound enters the cavity through natural ventilation, then what is the reason for having the outer glass enhanced for acoustic performance? Chapter 4 will allude to a hypothesis that the cavity can be examined as a duct and appropriate acoustic equations applied to the physics of the duct. The contention is that the propagation of sound through the duct is conditional to the reflection coefficients of the boundary surfaces conditions – see equation 4.6. This concept is examined further in Chapter 5.

3.3 TYPES OF CAVITY WITHIN THE DSF

The partitioning of the air cavity in a DSF refers to the physical division within the cavity.

Partitioning of the cavity can be made in many ways, some of which are listed below, some of which are shown in figure 3.12:-

- Corridor cavity
- Multi Storey cavity
- Shaft-box cavity
- Box window
- Cell

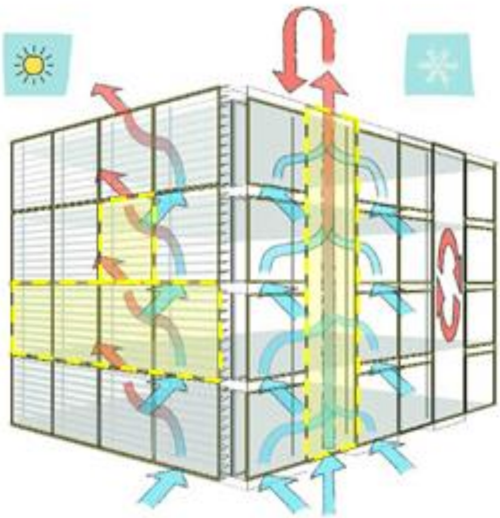


Figure 3.12 Cavity Types (Bath, 2013)

The corridor cavity will have partitioning on each floor at the head, floor and both ends. This form of cavity construction is sometimes used when the inner skin is set back from the façade front in an existing building. Figure 3.13 shows this type of cavity construction.

Figure 3.13 Corridor Cavity (BESTFACADE 2008)

Figure 3.14 Multi storey cavity

The multi storey cavity is a cavity that spans over multiple floors with no partitioning. The tested building in Chapter 6 has a multi storey cavity as seen in Figure 3.14. It is possible to see in Figure 3.14 that the cavity spans uninterrupted from bottom to top and side to side.

The shaft box cavity is a partitioned cavity that forms a vertical shaft designed as part of the ventilation strategy and in some cases as part of the fire strategy. Figure 3.15 shows corridor cavities feeding into the vertical shaft cavity. The stale and hot air moves upwards either naturally by the buoyancy effect or mechanical means or a combination of both buoyancy and mechanical sometimes called hybrid or mixed mode method.

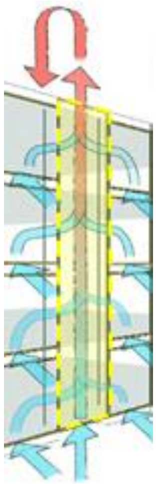


Figure 3.15 Shaft Box Cavity (Bath 2013)

Figure 3.16 Box window construction (Façade Blogspot 2013)

The box window is a double skin concept whereby the double skin is in isolation for one particular window. Figure 3.16 shows a diagram of a box window construction. It would be likely that the outer skin would be single glazed and the inner skin forming the thermal envelope of the structure. In continental Europe it would be common for the external skin to incorporate sliding elements and become a 'winter garden'.

The cell type cavity can be either a horizontal or vertical portion of the DSF that is partitioned from the remainder of the DSF. Figure 3.17 denotes the partitioned cell areas in dotted yellow line. There can be any number of reasons for constructing in this manner. It may be part of the ventilation strategy to compartmentalise this area. It could also be for commercial reasons – a commercial lease to one tenant may require that specific areas are separated from other tenants. Another reason may be as part of the fire strategy for the building.

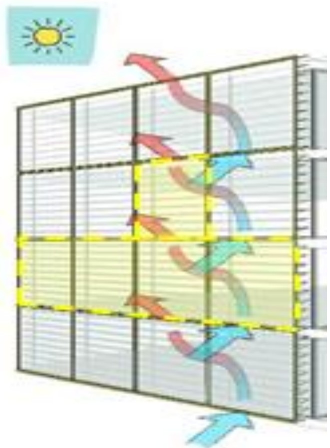


Figure 3.17 Cell type DSF Cavity (Bath 2013)

3.4 CONCLUSION

Characterising Double Skin Facades in one chapter is a near impossible task. There are complete books published on the subject and to a certain extent this chapter only summarises the headings that directly affect natural ventilation and acoustics.

The historical development of the DSF is a diverse subject and even though the technology can be traced to the early 1900's, it is not until the mid to late 1990's that building physics research started to take place.

The BESTFACADE project, as outlined earlier in this chapter, set out a DSF typology overview in Figure 3.18. This reflects an overview based firstly on type of ventilation and then on the partitioning type.

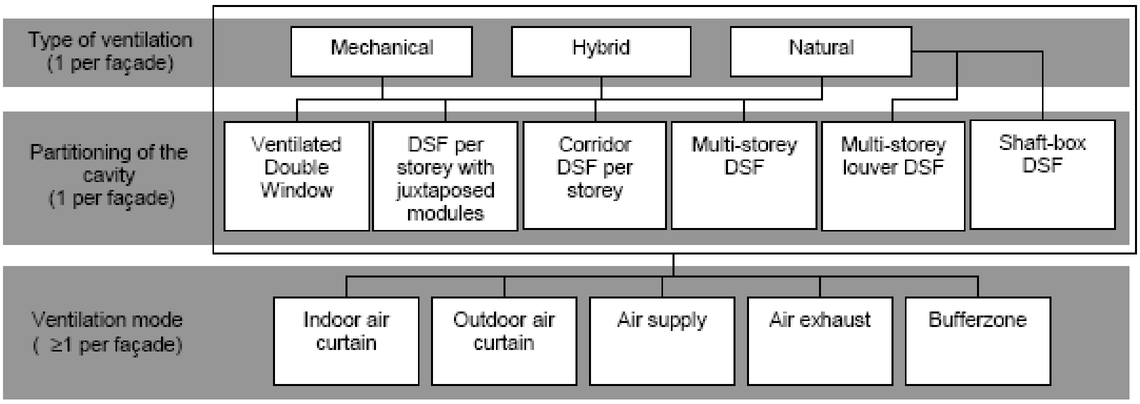


Figure 3.18 DSF Typology overview (BESTFACADE, 2008)

It is very apparent that the research and development of acoustics has not kept abreast with the other elements of building physics within DSF technology. This is reinforced with the BESTFACADE research that produced excellent review and recommendations in relation to DSF construction but produced very little information in relation to acoustics.

The anecdotal premise that an acoustic advantage is gained by constructing a naturally ventilated DSF has not been researched enough and the validity of this premise is examined and challenged in the following chapters.

CHAPTER 4

RESEARCH METHODOLOGY

4.1 INTRODUCTION

The research for this study will comprise three methodologies:-

- Field testing
- Predictive acoustic modelling
- Empirical calculation

These methodologies will be applied to each element of the sound path as outlined in Figure 1.2 and as described previously in Chapters 1 and 2.

This work aims to use field measurements to validate the fundamental equations governing the calculation methods used by proprietary acoustic modelling software.

Field testing will be predominantly carried out in accordance with ISO 140-5, “Acoustic testing of façade elements and façades”.

Predictive modelling techniques will be evaluated and mapped to the selected elements of sound propagation through a DSF cavity and the façade’s inner skin. A comparison will be made against the actual field test results to establish key correlations between measured data and theoretical calculation methods.

A theoretical study will be made of the propagation of sound through the DSF cavity and the building’s inner skin by identifying particular theoretical calculation methods. These calculation methods will be investigated and assessed to determine whether the results support both the tested and simulated scenarios.

4.2 OUTLINE PROCEDURES OF ISO 140-5, FIELD MEASUREMENTS OF FAÇADES AND FAÇADE ELEMENTS.

4.2.1 INTRODUCTION TO ISO 140-5.

ISO 140 – 5 specifies two series of methods for the measurement of airborne sound insulation of façades:-

1. Element Method
2. Global Method

The element method measures the Sound Reduction Index (SRI) of a façade element (e.g. a window). The most accurate method is to use a loudspeaker as an artificial sound source. There are alternative, less reliable methods, such as using available road traffic, railway traffic and air traffic. The element loudspeaker method yields an apparent SRI which can be compared to the measured SRI taken in a laboratory. This method is the preferred method if the aim is to compare the acoustic performance of a façade element, such as a window, against it's laboratory performance. If there are practical reasons why the loudspeaker method cannot be used then the road traffic method can be utilised, but the results will differ between each method, due to inconsistency in the road traffic sound source. The result must be labelled to reflect the source used.

The global method measures the sound level difference between outdoor and indoor under actual traffic conditions. The global method will use actual traffic as the sound source. Where this is not possible a loudspeaker will be used as an artificial outdoor sound source.

It is envisaged that this research will most likely use the loudspeaker method but the standard does offer alternatives as shown in table 4.1.

No	Method / Element	Reference	Result	Application
1	Element Loudspeaker	Clause **5**	$R'_{45°}$	Preferred method to estimate the apparent sound reduction index of façade elements.
2	Element road traffic	Clause **6**	$R'_{tr,s}$	Alternative to method no.1 when road traffic noise of sufficient level is available.
3	Element railway traffic	Annex D (informative)	$R'_{rt,s}$	Alternative to method no.1when railway traffic noise of sufficient level is available.
4	Element air traffic	Annex D (informative)	$R'_{at,s}$	Alternative to method no.1 when air traffic noise of sufficient level is available.
	Global			
5	Global loudspeaker	Clause **5**	$D_{ls,2m,nT}$ $D_{ls,2m,n}$	Alternative to methods 6,7 and 8
6	Global road traffic	Clause **6**	$D_{tr,2m,nT}$ $D_{tr,2m,n}$	Preferred method to estimate the global sound insulation of façade exposed to road traffic noise.
7	Global railway traffic	Annex D (informative)	$D_{rt,2m,nT}$ $D_{rt,2m,n}$	Preferred method to estimate the global sound insulation of façade exposed to railway traffic noise.
8	Global air traffic	Annex D (informative)	$D_{at,2m,nT}$ $D_{at,2m,n}$	Preferred method to estimate the global sound insulation of façade exposed to air traffic noise.

Table 4.1 – Overview of the different measurement methods (ISO 140-5:1998)

4.2.2 EQUIPMENT

The standard outlines the equipment to be used to test the acoustic performance of the DSF. The microphones must have a maximum diameter of 13mm. The appropriate standards that the monitoring equipment must meet are outlined in Table 4.2.

Equipment	Standards
SPL measurement equipment	Must meet the requirements of a class 0 or 1 instrument according to IEC 60651 or IEC 60804.
Acoustic calibration	Carried out to class 1 or better acoustical calibrator in accordance with IEC 60942.
Octave band and one-third-octave band filters, (where used)	Must meet the requirements of IEC 61260.
Reverberation time measurement equipment	Must meet the requirements of ISO 354.
Loudspeaker directivity in a free field.	This was required to have a local SPL difference of less than 5dB in each band of frequency when measured on an imaginary surface of the same size and orientation as the test specimen. If the test specimen had any dimension of more than 5m then a 10dB difference is acceptable.

Table 4.2 – monitoring Equipment Standards

All the equipment used during testing is described in Chapter 6 with the technical data sheets in the appendix.

4.2.3 MEASUREMENT WITH LOUDSPEAKER NOISE

Despite the many different methods of measurement as shown in Table 4.1, this research will focus on those directly related to the testing of large façade specimens using the loudspeaker method.

This method requires that the loudspeaker should be placed in one or more positions outside the building at distance *d* from the façade as shown in figure 4.1. The angle of incidence of the sound source must be 45° ± 5°. The average SPL is specified in the global method as 2m in front of the façade and 2m from the façade in the receiving room. In addition to the above ISO requirements, this research will also place receivers in the DSF cavity and the level difference $D_{ls,2m}$ is calculated on this basis.

The results from the façade face, DSF cavity and the internal room will be compared to assess their relative magnitude and contribution to the overall level of acoustic attenuation across the whole DSF configuration.

The sound generation is steady and has a continuous spectrum frequency range. ISO 140-5 specifies a minimum range of 100Hz to 3150Hz, however this research will test up to 8000Hz to gain more accuracy in the measured data. The loudspeaker for the global method will be located as close to the ground as is possible and the minimum distance to the centre of the test sample is 7m (d >5m).

There are minimum separation distances for the microphone positions as set out in ISO 140.5, section 6.5.2.

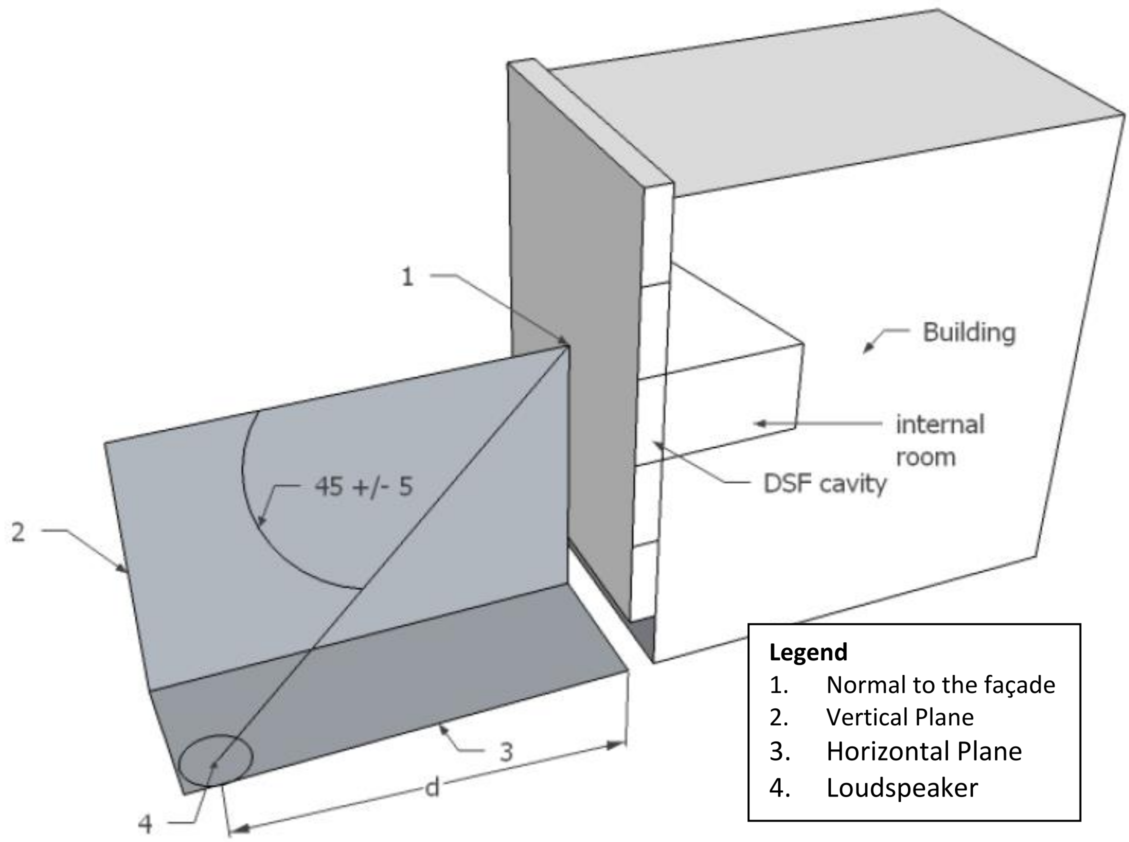


Figure 4.1 – Geometry of the loudspeaker method.

4.2.4 CORRECTION FOR BACKGROUND NOISE

The correction for background noise levels must be made so that observations of the DSF and receiving room are not affected by extraneous sound. The background level should be at least 6bB but preferably more than 10dB below the signal level and the background noise combined.

If the difference in levels is <10dB but >6dB, then the signal level is corrected to

$$L = 10\, log(\, 10^{Lsb/10} - \, 10^{Lb/10}\,)\, dB \quad (4.1)$$

where,

L is the adjusted signal level

L_{sb} is the level of signal and background noise combined in dB

L_b is the background noise level in dB

If the difference in level is ≤ 6dB then a correction of 1.3dB is used.

4.2.5 REVERBERATION TIME MEASUREMENT AND EVALUATION OF EQUIVALENT SOUND ABSORBTION AREA

The equation for the standardised level difference, $D_{ls,2m,nT}$ is calculated from the formula

$$D_{2,m,n,T} = D_{2m} + 10\, log_{10} \left(\frac{T}{T^0}\right) dB \quad (4.2)$$

Where, T_o is 0.5s

The correction term in this equation for the equivalent sound absorption area is evaluated from Sabine's formula:

$$A = \frac{0.16V}{T} \quad (4.3)$$

Where, A is the equivalent absorption area, in square metres (m²)

V is the receiving room volume, in cubic metres (m³)

T is the reverberation time in the receiving room, in second (s)

4.2.6 PRECISION

ISO 140-5 states that the measurement procedure must give satisfactory repeatability in accordance with ISO 140-2 and that it should be verified, in particular, when there is a change in procedure or instrumentation. The repeatability with the global method should be in the order of ± 2dB.

4.2.7 EXPRESSION OF RESULTS

The expression of results in accordance with ISO 140-5 for the airborne sound insulation of a façade is given at all frequencies in accordance with the forms in the annex of the standard. Graphs in the test report shall show the level in decibels plotted against frequency on a logarithmic scale. A sample of the standard test report is given in Figure 4.2.

Area S of test specimen: m^2
Receiving room volume: m^3

Frequency f Hz	$R'_{45°}$ (one-third octave) dB
50 63 80	
100 125 160	
200 250 315	
400 500 630	
800 1 000 1 250	
1 600 2 000 2 500	
3 150 4 000 5 000	

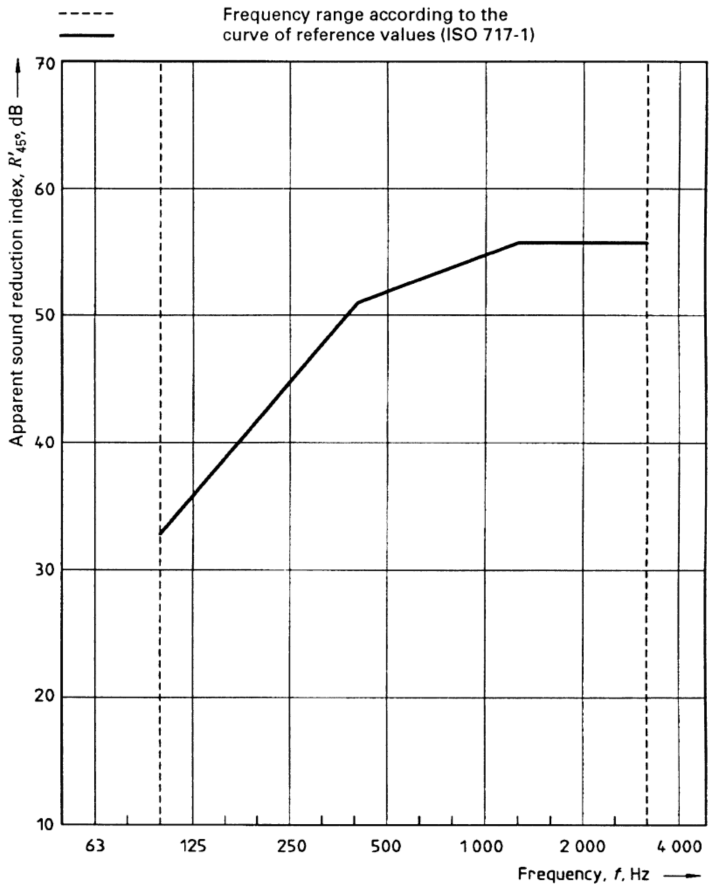


Figure 4.2 Results template in accordance with ISO 140- 5 and ISO 717-1

4.3 MODELLING TECHNIQUES

4.3.1 INTRODUCTION

Acoustic predictive modelling is the prediction of sound levels at a predefined receiver location or on a horizontal or vertical grid using a software based tool.

The calculation method is entirely dependent on the software chosen and the type of modelling utilised within the model such as:-

- Ray Tracing
- Noise Mapping
- Finite Element Analysis

Any predictive model will be based on data input which can be produced by keyboard, digitised from paper plan and digital data from an external source. It is normal to model the environment, as far as it is relevant for noise generation and propagation, on a computer.

The resultant model represents a virtual environment whereby elements can be examined, altered and manipulated, but more importantly, it is a starting point for a detailed calculation process.

The calculation within a modelling program depends on the type of modelling being utilised such as ray tracing or noise mapping.

The calculations are based on models which utilise algorithms for both calculation standards and technical parameter values (default standards or client input). The issue with predictive modelling is that the algorithm models are:-

1) In most cases hidden
2) Extremely complex and cannot be altered when they are accessible.

According to Bengt-Inge Dalenbäck, the field of Geometrical Acoustics 10-15 years ago comprised very classical prediction of direct sound based on a Sabine

RT, (see equation 4.3), to estimate some intelligibility measures (Dalenbäck 2010). Current prediction models allow complex geometries to be considered as well as options to input accurate material absorption coefficient and frequency dependent scattering coefficients. However, Dalenbäck reminds users that there are limitations to software that are not emphasised by software developers and that predictive software must be treated as a ’qualified discussion partner’ and not a complete acoustic solution.

4.3.2 RAY TRACING

Ray tracing allows the examination of the propagation of sound ‘rays’ in a room from a sound source. Figure 4.2 illustrates the build-up of a sound field in a room by showing both direct and reflected sound rays. The sound source and receiver are denoted by S and R respectively. The sound energy at any point within the room is the sum of a complex series of single and multiple reflections. The SPL within the room is affected by the reflection of sound from the room boundaries, leading to the engineering concept of two sound fields, these being:

1. Direct sound, the sound ‘ray’ transmits directly from the source sound, S, in Figure 4.2 to the receiver, L.
2. Reflected Sound is the remaining sound ‘rays’, reflected from the room boundaries.

Figure 4.2 is only a figurative example of schematic sound rays whereas in practice there are an infinite number that contribute to the sound level at the receiver, L.

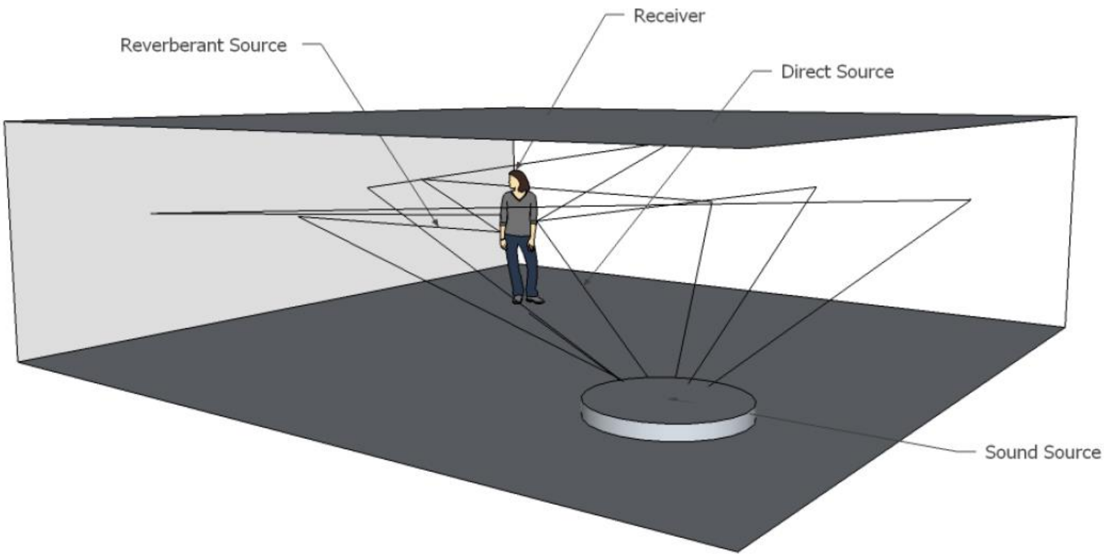


Figure 4.2 Sound Rays in a Room.

As the sound ‘ray’ reflects it will lose part of it’s energy travelling over a distance. The overall decay in SPL of L_p (direct) is a direct consequence of the inverse square law and r^2 in equation (1.1), $L_p = L_w + 10\log_{10}\frac{Q}{4\pi r^2}\ dB$.

Surface directivity, Q, and the total sound field, combining direct and reverberant sound will be explained further in Chapter 5, as it is a key element in the explanation of sound propagation from source and through the DSF.

Current ray tracing models can examine early and late reflections and determine the possible reflection sequences within a room. These models can normally produce a reflectogram which will give details of many image reflections. In addition to ray tracing, current predictive models will also examine image sources for early reflections and secondary sources for late reflections.

These conventional ray tracing models also have hybrid models which, during calculation, use ray tracing and then vector based scattering and particle tracing. This has been the evolution of software from basic ray tracing onwards.

Vector based scattering is a more realistic reflection model. Vectors representing the specular and diffuse reflections are weighted according to the scattering co-efficient of the surface and are added to the direction of the reflected ray. A small scattering co-efficient of for example, 0.2, will only have minor deviations from the direction of the specular reflection.

Particle tracing has been another significant additional application to the prediction models categorised under the ‘ray tracing’ umbrella. Each ray is assumed to carry a small amount of acoustic energy and a portion of this energy is dissipated after each reflection. The prediction model will calculate this decay in accordance with the absorption co-efficient assigned to the reflecting surface.

The energy decays as a function of time and the method of calculating the global decay curve is to add the contributions together. Reverberation time is found from this global decay method. This is a quick and reliable method of calculating the reverberation time taking into account the absorption co-efficient of the boundary walls for the room.

Predictive modelling using ray tracing, vector based scattering and particle tracing would appear to be a suitable method to model the DSF as a room or tube. All the current software models give a flexibility in design configuration insofar as it is possible to sketch and model in ‘Google SketchUp’ and import into the software package. All materials are given coefficient ratings by the user from whatever credible source is available.

It may even be possible to create a model of the DSF cavity with an internal room within the building and an opening between them both.

There are a substantial number of proprietary ray tracing software packages on the market in Europe. However, a study of the top four brands reveals that they all have the same features and in general they all support the same ISO standards – see table 4.3.

CATT, SoundPlan, Odeon, Akustikon would all appear to be similar, however, the difference is in the hidden algorithmic models that the software has adopted for calculation. This means that in practice there is a slight difference in results for all models. The only way of making a comparison is to run comparative models of all software systems and analyse the results. Therefore, for the purposes of this research the CATT Acoustics software will be used. This decision is based on access to software and not on any commercial or feature based decision.

The most recent development within these predictive modelling packages is the introduction of Auralisation, which means means making calculated acoustics audible. The software calculates the binaural room impulse response (BRIR) by the using head related transfer function (HRTF) for the left and right ear.

Feature	CATT	Soundplan	Akustikon	Odeon	Comments
Supported ISO Standards					
ISO 3382-1	x	x	x	x	For performance places
ISO 3382-2	x	x	x	x	For ordinary rooms
ISO 3382-3	x	x	x	x	For open plan offices
ISO 14257	x	x	x	x	Workplaces
IEC 60288-10	x	x	x	x	Speech transmission index
Room Acoustic Parameters					
Sound Pressure Level (SPL)	x	x	x	x	
SPL (A)	x	x	x	x	
Spatial Decay DL_2	x	x	x	x	
Reverberation Time T_{30}	x	x	x	x	
Early Decay Time EDT	x	x	x	x	
Speech Transmission Index STI	x	x	x	x	
Sound Strength G	x	x	x	x	Calculated for source with 0dB SPL on axis at 10m
IACC	x	x	x	x	Degree of Spatial Impression
Global Parameters					
Global Reverberation Time T_{30}	x	x	x	x	An average of the whole room
Global Reverberation Time T_{20}	x	x	x	x	
Sound Sources					
Point Sources	x	x	x	x	
Line Sources	o	o	x	x	Used mainly in Industrial applications
Surface Sources	x	x	x	x	
Array Sources	o	o	x	x	PA Systems

Table 4.3 Ray tracing software comparison

O not a feature

X featured option

4.3.3 NOISE MAPPING

A Noise Map is a map of an area which may be coloured according to the noise levels in the area. Sometimes the noise levels may be shown as contour lines which show the boundaries between different noise levels in an area.

The noise levels over an area will be varying all the time. For example, noise levels may rise as a vehicle approaches, and reduce again after it has passed. This would cause a short-term variation in the noise level. Over a slightly longer term, noise levels may be higher in peak periods when the roads are busy and congested, and lower in off-peak periods.

This means that it is not possible to say with confidence what the noise level will be at any particular point at any instant in time, but where noise sources are well-defined, such as road and rail traffic, or aircraft, then it is possible to say with some confidence what the long-term average noise level will be.

It may be thought that the best way of doing this is by measurement, but experience shows that this is not the case. Firstly, a long-term average is be measured over a long period of time. Secondly, to obtain complete coverage of an area, measurements often have to be made on private property, where access might be difficult. Thirdly, measurements cannot distinguish the different sources of noise, so they would not be able to give information on how much noise was being made by each of the sources in an area.

For these and other reasons, noise mapping is usually done by calculation based on a computerised noise model of an area, although measurements may be appropriate in some cases.

A further benefit of having a noise model is that it can be used to assess the effects of transportation and other future development plans. Thus the effect of a proposed new road can be assessed and suitable noise mitigation can be designed to minimise its impact. This is particularly important in noise action planning, where a cost-benefit analysis of various options can be tested before a decision is made.

A noise model, at its simplest level, can be regarded as a special form of digital map. The noise model must describe:

- Noise source, such as roads, vehicles, plant, railway tracks
- Transmission path, particularly noise barriers, ground topography and hard or soft ground cover
- Receiver locations

The noise model resembles the three-dimensional physical situation, but only includes the features which affect the spread of noise. These only need to be shown to a level of detail and accuracy which will give acceptable noise calculations.

There are numerous commercial noise mapping software suppliers on the market. CadnA, IMMI, Bruel & Kjaer, Lim A, Predictor and SoundPlan are only are selected few brand names and in the norm, they would generally all produce noise maps with the same input data. The resultant noise map may differ slightly due to their different algorithmic calculation methods, but to differentiate the brands apart is almost an impossible task. The background calculation methods are almost always hidden with the only manual input being the environmental source data.

According to Manvell and Hartog (2010), the major factors affecting good practice in the use of noise mapping software include:

- the user’s knowledge of the standard,
- the user’s knowledge of the software,
- documentation of software functions and its implementation of the standard,
- quality assurance of software implementation,
- documentation of software settings in calculation results,
- the user’s analysis of the quality and impact of the input data.

These factors would appear obvious; however, the industry had to respond to concern following European Directive 2002/49/EC relating to the assessment and management of environmental noise. A two day workshop organised by the European Commission and the European Environment Agency on target quality and input values requirements for noise mapping was held in 2009. EU Member States' noise representatives, public authorities, private noise consultants and software developers discussed the development of requirements on the input values and their associated quality in view of the next round of European noise mapping. One of the recommendations from the workshop was to maximise the reliability and comparability of results through setting up guidance on the competent use of noise assessment methods accompanied by a quality system covering:

- The relevant quality and quantity of input data.
- Guidance on how to use, extract, extrapolate and manage input data.
- Software calculation settings.
- Software use and modelling.
- The mandatory use of the European Commission's reporting mechanism.

CadnA will be used as the noise mapping software for this research. There is no specific reason other than the licence was made available for research purposes. CadnA has the same functions and data input as any of the other noise mapping predictive models mentioned in this section.

The main uses of CadnA will be to predict noise levels for element 1 of the sound path. In other words, predicting the noise levels at the face and bottom of the DSF. The limitations to the software would appear to be that it cannot examine noise at a finite level such as within the DSF.

4.3.4 ACOUSTIC ELEMENT ANALYSIS.

Boundary Element Analysis (BEA) and Finite Elemental Analysis (FEA) do not form part of this research but should be included in the types of research methodology that can be utilised.

FEA will examine the numerical solution of partial differential equations (PDEs). The mathematical problem is analysed by choosing the following variables within the software (White, 2012):-

- ✓ PDE representing the physics.
- ✓ Geometry on which to solve the problem.
- ✓ Boundary conditions (for static or steady state problems) and initial conditions (for transient problems).

White, states that the sequence for solving any FEA problem is the following:-

1. Decide on the representative physics (choose the PDE).

2. Define the geometry on which to solve the problem.

3. Set the "material properties", that is, all the constants that appear in the PDE.

4. Set the boundary conditions (for static or steady state problems) and initial conditions (for transient problems).

5. Choose an element type and mesh the geometry.

6. Choose a solver and solve for the unknowns.

7. Post-process the results to find the information wanted.

There are many FEA commercial software programs available such as Strand 7, Comsol, Ansys, Abaqus, Pzflex and, in general, they will be flexible in terms of import, export and integration with other software programs such as Matlab and Autocad.

There will usually be a focus on coupling different elements of physics together such as acoustics and solid mechanics. The more current modelling programs allow an element of programming individual equations if not already implemented in the software. Models can be built in 1, 2 or 3D. The computational time increases with the use of 3D models.
Dr. Marcello Blasco's research in 2012, used statistical energy analysis (SEA) in which he partitions the DSF into 'subsytems' and considers the frequency range of 100Hz to 5000Hz. He considers three finite parallel planes separating two finite volumes with assumed diffuse (reverberant) field conditions.

Even though this research does not model in FEA or SEA, it will be seen in later chapters that there is some correlation between Dr Blasco's experimental results and the field tested data acquired in this research.

4.4 EMPIRICAL STUDY

The concepts identified in this section will be clarified further in Chapter 5. The theoretical hypotheses are being introduced here to explain the research methodology.

4.4.1 ELEMENT 1 (Source to DSF)

The propagation of sound over distance in the open field condition will be discussed in this section. The difference between each DSF can be examined when considering the distance from the façade face to the dominant sound source.

Using equation $$L_p = L_w - 20log10 * r - 11dB \quad (4.4)$$

Where
- L_p = sound pressure at receiver;
- L_w = sound power level of source
- r = distance between source and receiver
- 11dB = correction assuming spherical radiation*

* The distance from the source to the receiver and the type of source sound (point, line or plane) will determine the correction.

4.4.2 ELEMENT 2 (Propagation of sound through the DSF)

The research methodology within this section is examined at the entry to the DSF and then throughout the DSF.

The hypothesis is that the DSF is to be examined using conventional long flat room attenuation methods. The theory is explained in more detail in Chapter 5.

Element 2, Condition A examines (where the appropriate constraint conditions apply) the very small DSF, for example a shadow box.

Element 2, Condition B is the condition at the DSF ventilation entry.

Element 2, Condition C examines the balance of the DSF after condition B.

4.4.2.1 ELEMENENT 2 (Hypothesis for Condition A)

According to SRL,1988, the smaller the duct passageway, the greater the attenuation per metre run and so the DSF 'shadow box' type construction (Condition A) must fall within the following constraints:-

1. The width (a) or the depth (b) are ≤ 900mm
2. 0.5 ≤ $^{a}/_{b}$

If these two conditions are satisfied, then we can assume that in accordance with conventional acoustic theory the DSF attenuation is considered to be:

$$1.07\left(\frac{P}{S}\right)\propto^{1.4}\ dB/metre \qquad (4.5)$$

Where, P = the perimeter inside lining, m

S = cross sectional area of the duct, m^2

∝ = absorption coefficient

4.4.2.2 ELEMENT 2 (Hypothesis for Condition B)

In condition B, if the distance between the source and receiver is small and the reflection coefficients approach unity, then according to Kuttruff, 1985:

$$p^2 = \frac{W\rho c}{4\pi}\left[\frac{1}{r^2} + \frac{2\pi^2}{3a^2}\right] dB \qquad (4.6)$$

Where, W = radiated sound power

ρ = mean density of air

c = speed of sound

r = distance from source to receiver

a = distance between the reflecting planes (i.e. outer and inner skins of the DSF)

4.4.2.3 ELEMENT 2 (Hypothesis for Condition C)

Condition C sets out the parameters for a long flat room where the distance from source to receiver is greater than condition B. The reverberant field sound pressure may be greater than or less than the direct field depending upon the values of the reflection coefficients (Bies and Hanson, 2003)

$$p^2\,(r) = \frac{W\rho c}{4\pi r^2}\left[1 + \frac{\beta_1 + \beta_2 + 2\beta_1\beta_2}{1 - \beta_1\beta_2}\right] \qquad (4.7)$$

Where, W = radiated sound power

ρ = mean density of air

c = speed of sound

r = distance from source to receiver

β_1 = reflection coefficient of surface 1

4.4.3 ELEMENT 3, PROPAGATION OF SOUND THROUGH AN OPEN WINDOW.

Up until 2009, there was a deficit of published research into the acoustic transmission of open and closed windows in naturally ventilated façades (Fuller 2009).

The approximation of 5-15dBA was still being used as a reference for the transmission loss across naturally ventilated façades.

The Department of the Environment in the UK has acted as sponsors for a research study by Napier University through Research Contract (NANR 116). The research is an extensive experimental study of transmission loss across multiple window types and fenestration.

This portion of the research will examine the findings of the Napier report, and in particular, the attempt to equate the results from experiments undertaken with a single parameter empirical model.

4.5 SUMMARY

The research in this study is approached by element in accordance with the sound path shown in Figure 1.2. As simplistic as it does seem, this approach taken is not entirely dissimilar to the ‘5 coupled subsystems model’ approach of Dr. Marcello Blasco in his research of closed DSF systems. (Blasco, 2012, p98)

By using this element approach a method of cross referencing and mapping between the separate research tools has been established, whether it is theoretical (Chapter 5), experimental (Chapter 6) or parametric (Chapter 7).

CHAPTER 5

ACOUSTICS APPLIED TO DOUBLE SKIN FACADES

5.1 INTRODUCTION

The method of identifying acoustic attenuation in a DSF is continued in this chapter, insofar as the elements, set out in Figure 1.2, will continue to be the areas of analysis. Each element will be labelled and the applicable research method is mapped to it. As a reference, Figure 1.2 is shown again below.

The intention of this study is to provide empirical validation to the field testing and parametric analysis that has been undertaken.

The elements identified below in Figure 1.2 are as follows:-

1. Source to DSF (section 5.2)
2. Propagation of sound through the DSF (section 5.3)
3. Sound entry through an opening into the buildings internal rooms (section 5.4)

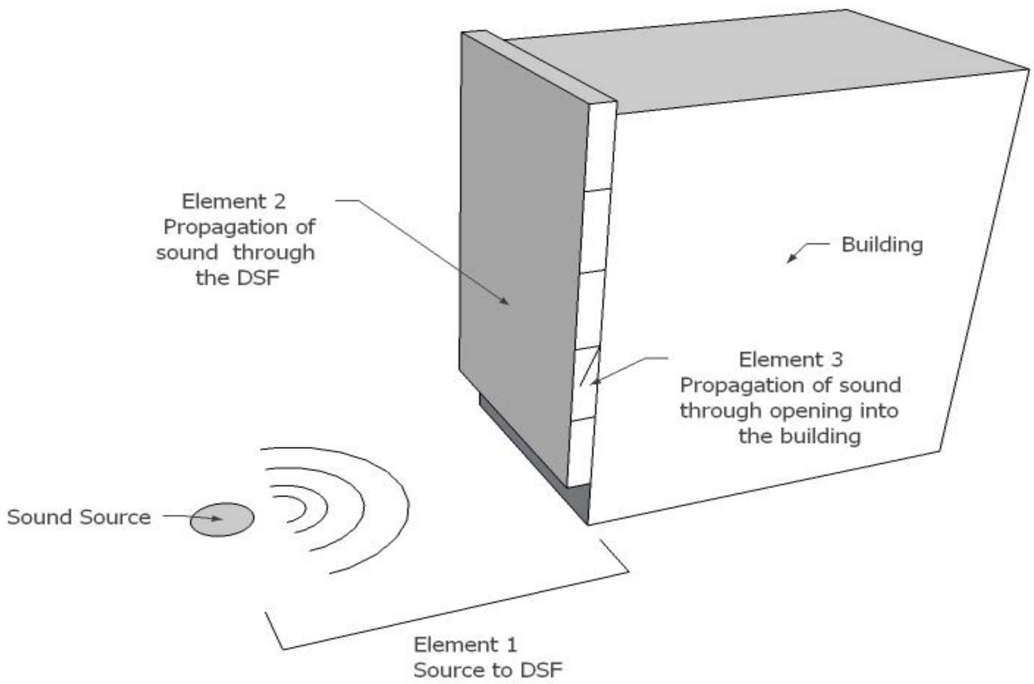


Figure 1.2 Generic Sound Propagation Element Layout

5.2 ELEMENT 1 – SOURCE TO DSF

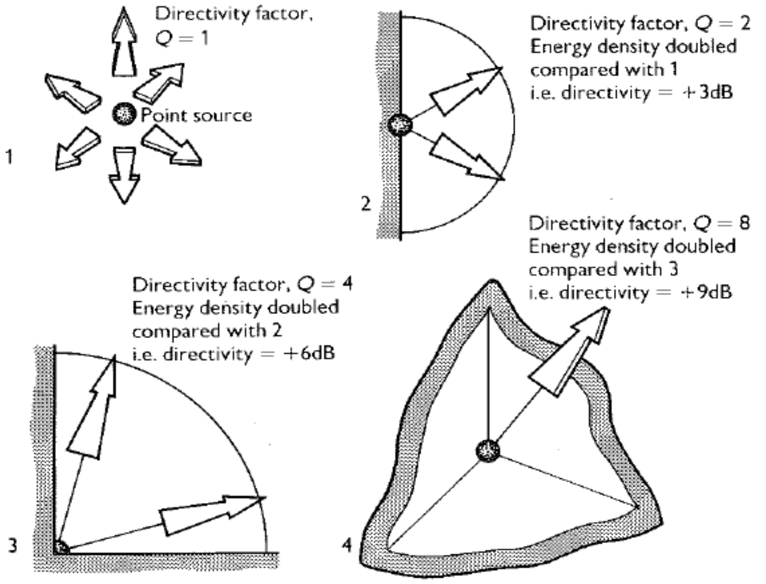
5.2.1 INTRODUCTION

Acoustic 'Rays' are schematically shown in Figure 3.2 as, sound rays, that illustrate the build-up of a sound field in a room. The sound source and receiver are denoted by S and R respectively. The sound energy at any point within the room is the sum of a complex series of single and multiple reflections. The SPL within the room is affected by the reflection of sound from the room boundaries, leading to the engineering concept of two sound fields, these being:

3. Direct sound, the sound 'ray' which transmits directly from the source sound, S, in Figure 3.2 to the receiver, L.
4. Reflected Sound which is the remaining sound 'rays', which are reflected from the room boundaries.

Figure 3.2 is only a schematic example of a few sound rays whereas in practice there are an infinite number that contribute in some way to the sound level at the receiver, L. As the sound 'ray' reflects it will lose part of it's energy traveling over a distance. The overall decay in SPL of L_p (direct) is a direct consequence of the inverse square law and r^2 in equation 1.1, $Lp = Lw + 10\log_{10}\frac{Q}{4\pi r^2}\ dB.$

Q is the 'surface directivity' factor and is dependent upon the position of the sound source in relation to the room boundaries (SRL, 1988). Figure 5.1 outlines the different permutations of directivity and boundary walls.



For an omnidirectional source positioned in mid-air, the sound radiates spherically and decays as a function of $4\pi r^2$ and in the open field case Q is likely to be 1.

Figure 5.1 Q Factor (SRL, 1988)

However, in the case of a DSF, it is more likely that the sound source will have three boundaries and as such Q=8.

When the sound strikes a boundary it becomes a reflected sound. The reverberant field depends on the effect of the boundary material and as such the expression of the reverberant sound field will take the boundaries into account:

Sound Pressure Level, $Lp\ (reflected) = Lw + 10\log_{10}\left(\frac{4}{R}\right) dB$ (5.1)

Where R is the room constant, $R = \frac{S-\bar{\propto}}{1-\bar{\propto}}$

$\bar{\propto}$ is the mean absorption co-efficient of the room boundaries.

$\propto$ is the absorption coefficient of a material. It is defined as the proportion of incident sound energy arriving from all directions that is not reflected back into a room. Therefore $\propto$ = 1.0 is total absorption and 0.0 is total reflection.

S is the total surface are of the receiving room.

Therefore the total sound field is the logarithmic addition of the direct and reverberant fields:

L_p (total) = $L_w + 10\log_{10}\left(\frac{Q}{4\pi r^2} + \frac{4}{R}\right)$ dB (5.2)

5.2.2 FREE FIELD ATTENUATION OVER DISTANCE

The propagation of sound over distance in the open field condition can be considered using equation 3.4 when the following conditions are known:-

A. Distance from the source to the receiver
B. Whether screening exists between the source and the receiver
C. The existence of any reflections at the receiving point

$L_p = L_w - 20log10 * r - c\ dB$ (3.4)

Where, L_p = sound pressure at receiver;

L_w = sound power level of source

r = distance between source and receiver c dB = correction assuming spherical radiation*

*the correction factor for distance is dependent on the source type. A generic diagram is shown in figure 5.2 showing the attenuation with distance for various sources.

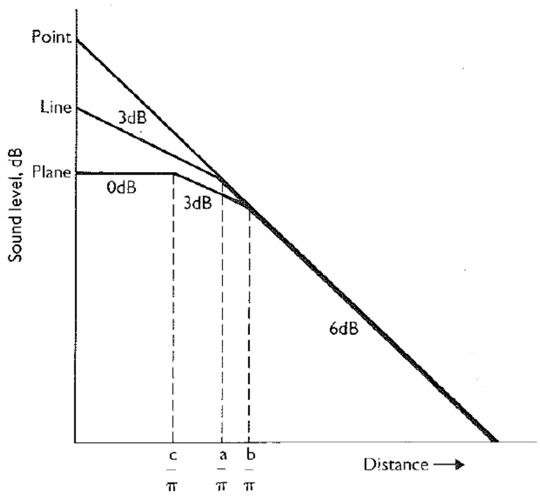


Figure 5.2 Attenuation with distance (SRL 1988, p326)

A more simple approach is the deduction of the correction factor when it is taken from a dedicated chart. The correction factor for a point source is given in Figure 5.3 and the correction factor for a line and plane source is shown in Figure 5.4.

This method of deduction is the conventional method of acoustic attenuation calculation. If equation 3.4 is applied to the data from Test 1, Building A, London using DSF E1 as a test case, an calculated, L_p can be calculated and compared to measured data. This is shown in Figure 5.5. A measured L_w is used and r is measured from the motorway to the receiver point. In this instance r is calculated to be 29m. The correction factor is taken from the table in Figure 5.4 at 40dB.

Attenuation over distance using S1 data from Building A, London (Test 1 dataset)									
	Octave Band Frequency								
	63 Hz	**125 Hz**	**250 Hz**	**500 Hz**	**1.0 kHz**	**2.0 kHz**	**4.0 kHz**	**Dw**	**dBA**
Lw	80.4	71.8	72.1	70.2	70.9	64.8	58.6	-	-
r(m) from Fig 5.4	5	5	5	5	5	5	5	-	-
20*log10*r	-13.98	-13.98	-13.98	-13.98	-13.98	-13.98	-13.98	-	-
correction factor	-33	-33	-33	-33	-33	-33	-33	-	-
Lp	66.50	57.90	58.20	56.30	57.00	50.90	44.70	58.00	60.10
Measured Lp	73.3	68.3	65.4	61.8	62.7	55.1	48.5	60	62.1

Figure 5.5 attenuation calculations over distance

The calculated and measured L_p are very close and the conclusion is that this calculation is both simple and accurate to an error of 2dB.

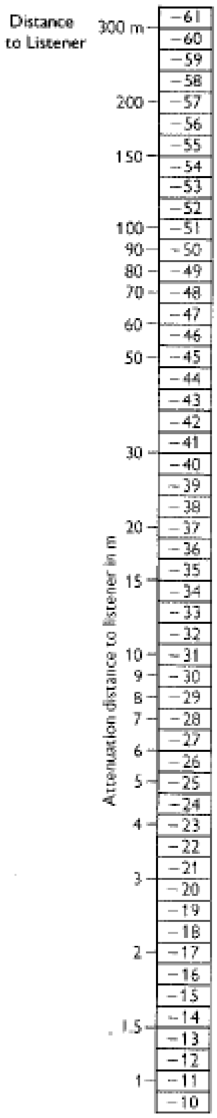


Figure 5.3 correction factor for a point source (SRL 1988,p325)

Distance in metres	LINE SOURCE m				RECTANGULAR PLANE SOURCE m × m							
	3	10	30	100	1 × 3	1 × 10	3 × 3	3 × 10	3 × 30	10 × 10	10 × 30	30 × 30
50	45	45	45	45	45	45	45	45	45	45	45	45
	44	44	44	44	44	44	44	44	44	44	44	44
	43	43	43	43	43	43	43	43	43	43	43	43
	42	42	42	42	42	42	42	42	42	42	42	42
	41	41	41	41	41	41	41	41	41	41	41	41
30	40	40	40	40	40	40	40	40	40	40	40	40
	39	39	39		39	39	39	39	39	39	39	39
	38	38	38	39	38	38	38	38	38	38	38	38
20	37	37	37		37	37	37	37	37	37	37	37
	36	36	36	38	36	36	36	36	36	36	36	36
	35	35	35		35	35	35	35	35	35	35	35
	34	34	34	37	34	34	34	34	34	34	34	34
	33	33	33		33	33	33	33	33	33	33	33
	32	32	32	36	32	32	32	32	32	32	32	32
10	31	31	31		31	31	31	31	31	31	31	31
	30	30	30	35	30	30	30	30	30	30	30	30
	29	29			29	29	29	29		29		
	28	28	29	34	28	28	28	28	29	28	29	30
	27	27			27	27	27	27		27		
	26	26	28	33	26	26	26	26	28	26	28	30
5	25	25			25	25	25	25		25		
	24	24	27	32	24	24	24	24	27	24	27	30
	23	23			23	23	23	23		23		
	22	22	26	31	22	22	22	22	26	22	26	30
	21	21			21	21	21	21		21		
3	20	20	25	30	20	20	20	20	25	20	25	30
	19				19		19					
	18	19	24	29	18	19	18	19	24	20	25	30
2	17				17		17					
	16	18	23	28	16	18	16	18	23	20	25	30
	15				15		15					
	14	17	22	27	14	17	14	17	22	20	25	30
	13				13		13					
	12	16	21	26	12	16	12	16	21	20	25	30
1	11				11		11					
	10	15	20	25	10	15	10	15	20	20	25	30

Figure 5.4 correction factor for a line source (SRL 1988,p325)

5.2.3 SCREENING

If the source and receiver are not in direct line of sight then there are additional attenuation correction factors to be applied. The screening effect varies with frequency because the acoustic diffraction is dependent on the sound wavelength size in relation to the size of screen. Figure 5.6 illustrates the principle of screening in a very simple diagram.

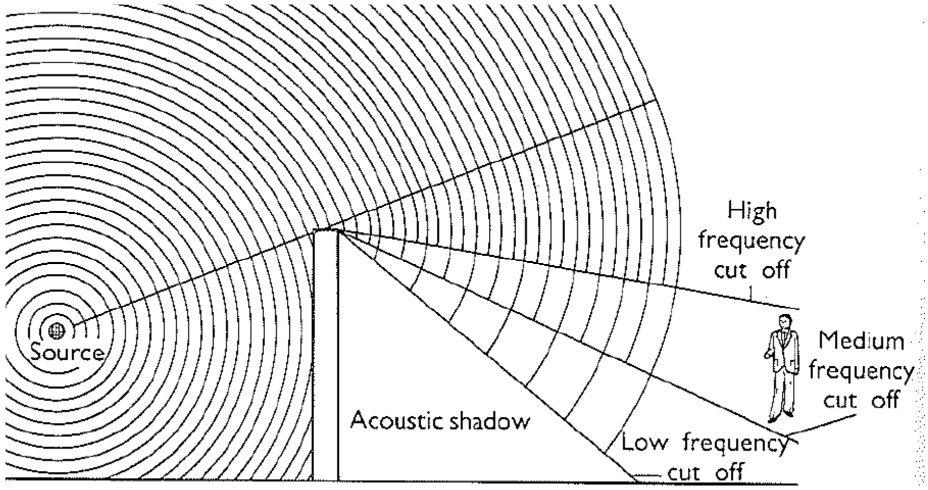


Figure 5.6 Acoustic attenuation by screening

According to the Sound Research Laboratory (SRL 1998), ‘screening is less effective at low frequency than high’. This is because the wavelength of low frequency sound is equal to or greater than the screen dimensions. This means that the incident wavelength is not greatly affected by the presence of a screen.

However, high frequency sound is greatly reduced by the introduction of screening and a more pronounced cut off will occur on the receiver side of a screen. The effective screening attenuation is given in figure 5.7. The value for δ in the table gives the appropriate spectral attenuation across the 63 Hz – 4k Hz frequency band width.

δ is calculated using the addition of the length of the screening sound path (A, length to the screen from the source, and, B, length after the screen to the receiver) and deducting the actual length (d).

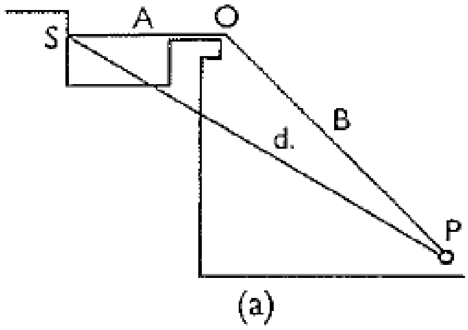
$$\delta = A + B - d \quad (5.3)$$

It will most likely be the case that there may be 3 or 4 sound paths and so a calculation is made for each path distance and the standard acoustic addition is made in dB of the individual attenuation effects. This presents the effective attenuation as shown in an example in figure 5.8.

Additional Attenuation due to Screens

$\delta = A + B - d$

δ(m)	63	125	250	500	1k	2k	4k	Hz
−0.3	1	0	0	0	0	0	0	dB
−0.2	2	1	0	0	0	0	0	
−0.1	3	2	1	0	0	0	0	
−0.05	3	3	2	1	0	0	0	
−0.01	4	4	4	3	3	2	1	
0	5	5	5	5	5	5	5	
0.01	5	6	6	6	7	8	8	
0.05	7	7	8	9	10	12	13	
0.1	7	8	9	10	11	14	16	
0.2	8	9	10	11	14	16	19	
0.3	8	9	10	13	16	18	20	
0.4	9	10	12	14	17	20	22	
0.5	9	10	12	15	18	20	23	
1.0	11	12	14	18	20	23	25	
1.5	13	14	16	19	22	25	27	
2.0	14	15	18	20	24	27	29	
3.0	15	17	20	22	25	28	30	
4.0	16	18	20	24	26	30	31	
5.0	16	18	21	25	27	30	32	



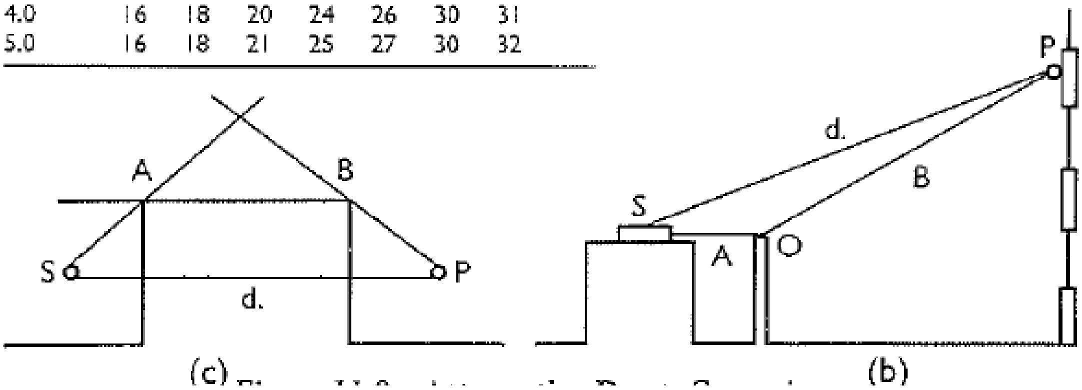


Figure 5.7 attenuation correction factor due to screening (SRL, 1998)

The attenuation of a screen is widely used in design to attenuate sound. The examples in Figure 5.7 would be:-

a) δ is positive – there is no direct line of sight between the source and the receiver. An example is where there is a rooftop louvre and there is a parapet providing shielding at the edge of the building

b) δ is negative – there is a line of sight between the source and the receiver but there is an effect from a barrier adjacent to the source.

c) δ is positive but takes into account the effect of a thick barrier such as an earth mound or a building.

		Octave Band Frequency (dB)						
	δ (m)	63	125	250	500	1	2	4
Path 1	2	-14	-15	-18	-20	-24	-27	-29
Path 2	0.4	-9	-10	-12	-14	-17	-20	-22
Path 3	4	-16	-18	-20	-24	-26	-30	-31
Effective attenuation		-7.2	-8.3	-10.5	-12.7	-15.8	-18.9	-20.8

Figure 5.8 Effective Screen Attenuation Calculation

It is important to note that construction of a screen needs only to be lightweight in most cases. The average screening limit is about 15 dB and so the structure needs to only achieve a SRI of 20-25dB. It would mean having a superficial weight of approximately 6kg/m². Acoustic louvres are suitable for this type of screening material.

5.2.4 ATMOSPHERIC ATTENUATION

Sound propagation over distance can be affected by the weather conditions but the effects are only of significance at distances of over 0.5km.

a. Temperature and humidity becomes significant when the temperature is $> 15°C$ and the humidity is $< 60\%$ RH

b. Wind gradients – the increase in wind velocity with height above ground. This is not the same condition as the wind blowing noise away. Figure 5.9 shows a diagrammatic view of how the normally straight line sound rays will bend upwards on the upwind side of the source creating an acoustic shadow.

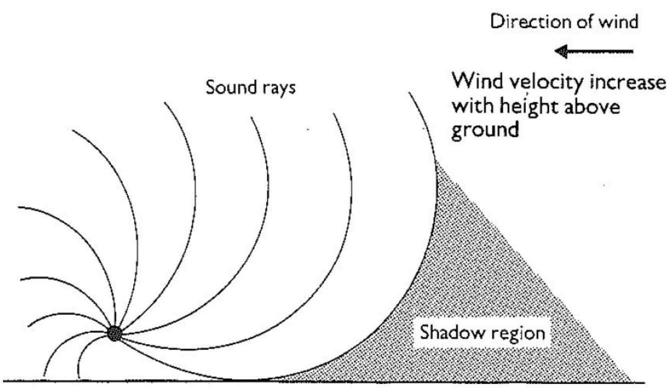


Figure 5.9 Wind Gradient (Bies and Hanson, 2003)

5.2.5 ATTENUATION DUE TO GROUND ABSORPTION

Ground covered with dense vegetation will give a greater attenuation of 6dB per doubling of distance. Figures 5.10 and 5.11 give a correction for traffic noise in dBA over hard ground and grassland.

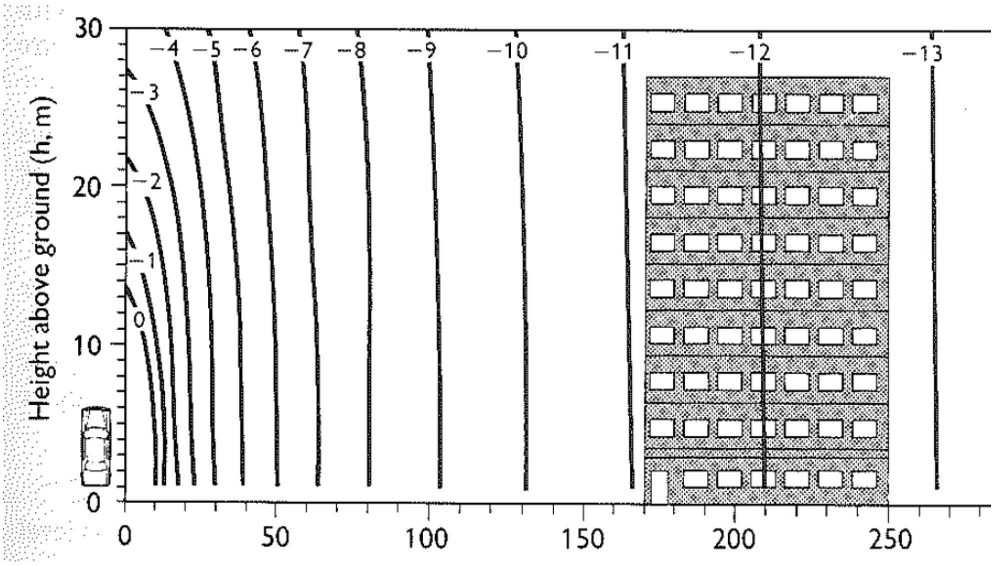


Figure 5.10 Acoustic correction due to road traffic noise for Hard Ground and height adjacent a road

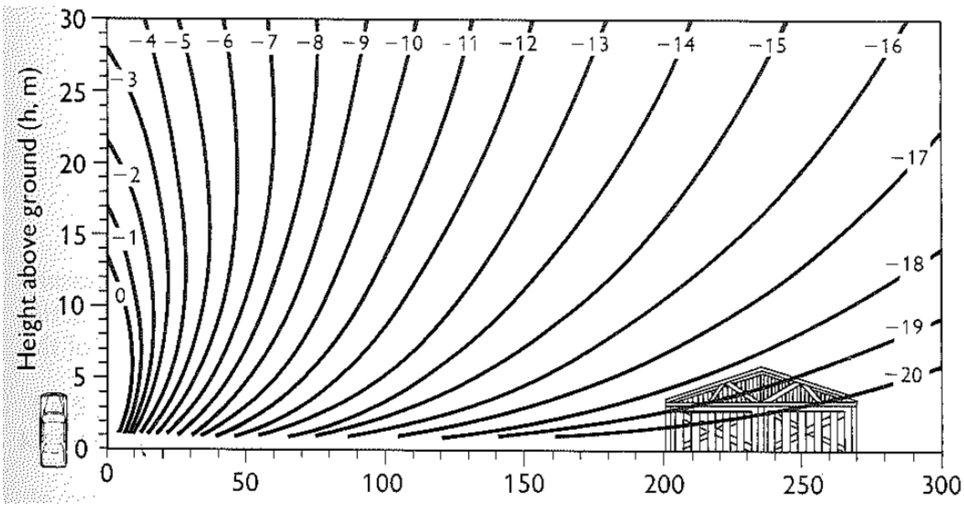


Figure 5.11 Acoustic correction due to road traffic noise for grassland and height adjacent a road

5.2.6 ELEMENT 1 – CONCLUSION

Each of the appropriate calculations and corrections from this section, Element 1, will be added to an overall calculation sheet to form a proposed calculation model for DSF acoustic attenuation. This section will be labelled as step 2 and the conclusion of step 2 will be a total effective attenuation after calculation and correction factors have been applied (see Figure 5.15)

5.3 ELEMENT 2 – PROPAGATION OF SOUND THROUGH THE DSF

The hypothesis that is used to examine the propagation of sound through a DSF (element 2 of the sound path in Figure 1.2) is comprised of some conditions that will be examined.

The long and flat room with specularly reflecting floor and ceilings is considered and an introduction to this was set out in Chapter 2.

The methodology for the research of propagation of sound through a DSF is considered in the following manner:-

- Element 2, Condition A examines the very small DSF, for example a shadow box.
- Element 2, Condition B is the condition at the DSF ventilation entry.
- Element 2, Condition C examines the balance of the DSF after condition B.

5.3.1 ELEMENT 2 (Hypothesis for Condition A)

As set out in Chapter 2, the smaller the duct passageway, the greater the attenuation per metre run of ductwork. This hypothesis originates from the study of the acoustical treatment of ductwork and in particular rectangular ductwork.

The following constraints apply and so this condition applies only to a very limited amount of DSFs such as the DSF 'shadow box' type construction:-

3. The width (a) or the depth (b) are ≤ 900mm
4. $0.5 \leq a/b \leq 2$

This gives the maximum height of the DSF to be 0.9m with a maximum cavity of 0.45m and unrestricted length. This size could be viewed as either an individual shadow box type DSF or as a DSF with a corridor type cavity.

This type of construction would not be deemed unusual for DSFs constructed in mainland Europe and maybe less so in the UK.

If the two conditions are satisfied, then we can assume that in accordance with conventional acoustic theory the DSF attenuation is considered to be:

$$1.07\left(\frac{P}{S}\right) \propto^{1.4}\ dB/metre \qquad (3.5)$$

Where, P = the perimeter inside lining, m

S = cross sectional area of the duct, m^2

$\propto$ = absorption coefficient

If an example is considered with the following criteria:

DSF dimension of 900mm high x 450mm wide x 10m long with heavy plate glass, then the attenuation is calculated using equation 3.5. The calculation process is illustrated in Figure 5.12 and then plotted in Figure 5.13.

	Octave Band Frequency (dB)					
	125	**250**	**500**	**1**	**2**	**4**
$\propto$ **heavy plate glass**	0.10	0.06	0.04	0.03	0.02	0.02
P	2.70	2.70	2.70	2.70	2.70	2.70
S	0.41	0.41	0.41	0.41	0.41	0.41
$1.07\left(\frac{P}{S}\right) \propto^{1.4}$	0.28	0.14	0.08	0.05	0.03	0.03
attenuation of DSF (x 10m long)	2.84	1.39	0.79	0.53	0.30	0.30

Figure 5.12 Attenuation of a duct/DSF using the criteria for Element 2, Condition A.

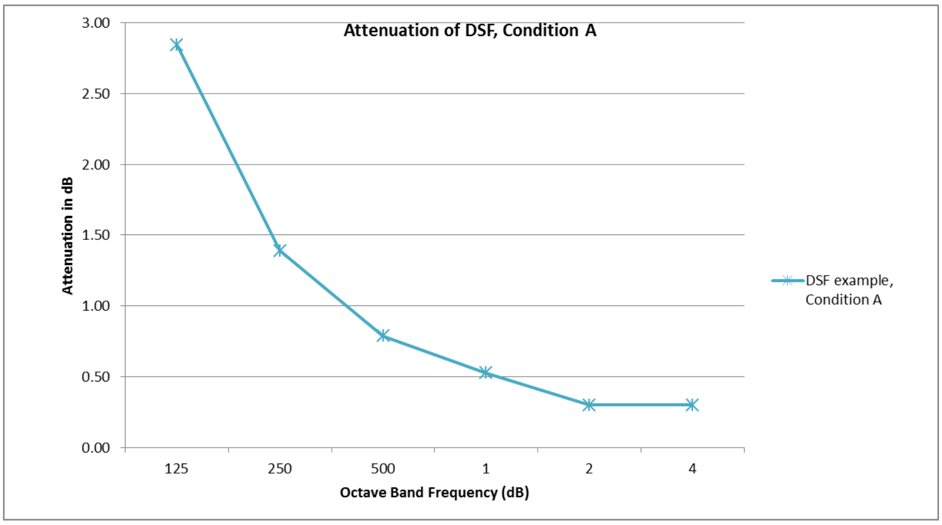


Figure 5.13 Example of attenuation of a DSF, Element 2, Condition A.

5.3.2 ELEMENT 2 (Hypothesis for Condition B)

The principle of considering the DSF as a long flat room or a duct has been introduced in Chapters 2 & 3.

The concept of a flat room with highly reflective surfaces as the boundary condition is precisely the condition for the DSF and therefore the resulting Bees and Hanson principles are proposed to examine the DSF.

The theoretical model is examined in two cases:

3. When the distance between the source and the receiver is small (the bottom of the DSF where the sound will enter (condition B).
4. The condition where the distance between the receiver and the source is large so that r>>a (condition C).

In condition B, if the distance between the source and receiver is small and the reflection coefficients approach unity, then according to Kuttruff, 1985:

$$p^2 = \frac{W\rho c}{4\pi}\left[\frac{1}{r^2} + \frac{2\pi^2}{3a^2}\right] db \tag{3.6}$$

Where, W = radiated sound power

ρ = mean density of air

c = speed of sound

r = distance from source to receiver

a = distance between the reflecting planes (i.e. outer and inner skins of the DSF)

In equation 3.6, the first term on the right-hand side is the direct field and the second term is the reverberant field. Bees and Hanson assert that in equation 3.6 the direct field is dominant to a distance of

$$r = \left(2\sqrt{3/\pi}\right) a \simeq 1.95a. \qquad (5.4)$$

Where,

a is the distance from floor to ceiling or, in the case of the DSF, the cavity width.

On this basis, this equates to approximately twice the cavity width. As an example, if the DSF cavity width is 900mm then equation 3.6 applies to a receiver up to 1.8m from the bottom of the DSF.

If the assumption was made that:

1. the cavity width (a) is 0.9m
2. r is the maximum receiver dimension, 1.8m

then, taking the log of both sides of the expression, the equation becomes:

$$Lp = Lw + 10\log(5.6/4\pi) \qquad (5.5)$$

This equation will form an integral part of an overall calculation sheet and will be shown as step 3a in the proposed calculation method.

5.3.3 ELEMENT 2 (Hypothesis for Condition C)

Condition C sets out the parameters for a long flat room (or DSF), where the distance from source to receiver is greater than condition B ($r \gg a$). The reverberant field sound pressure may be greater than or less than the direct field depending upon the values of the reflection coefficients (Bies and Hanson, 1988).

Bies and Hanson consider a sound source placed between two infinite parallel reflecting surfaces. They contend that an infinite series of image sources will be created along a line through the source and located normal to the two surfaces.

If the source is located at the origin and the receiver is located at $r = r_o$, and they are both located midway in the DSF, then the line of image sources will take the form of figure 5.14.

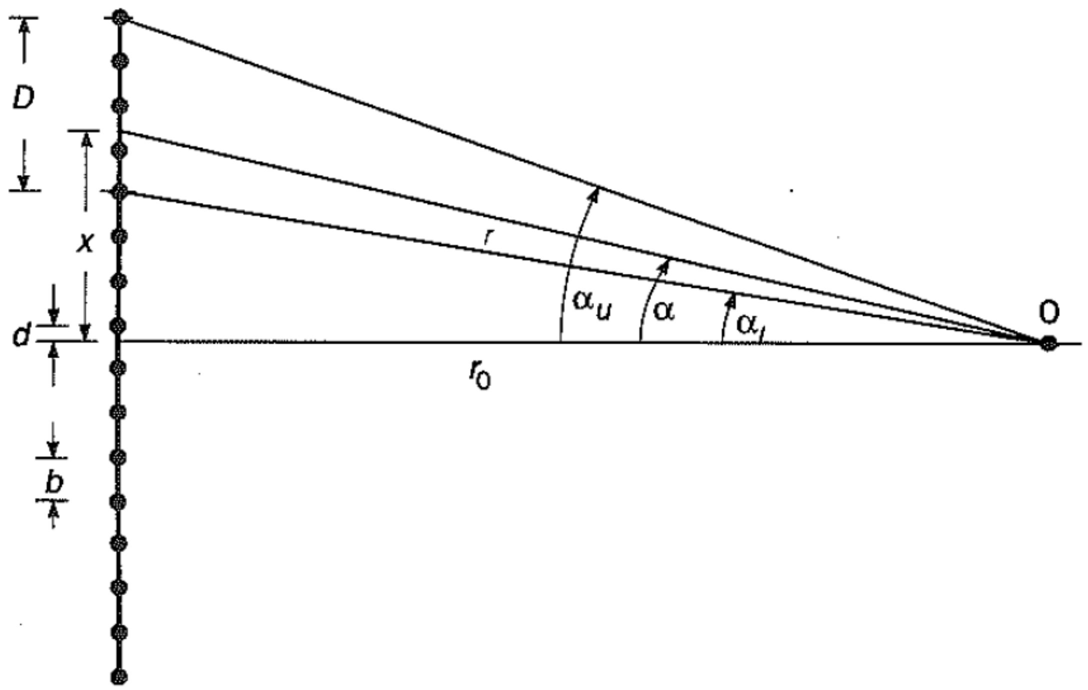


Figure 5.14 Image source

In figure 5.14, b will become the distance, (a), between the two reflecting surfaces or the width of the DSF cavity. The effective distance from the nth image to the receiver point will be $r_{n,}$ where the index n represents the number of reflections required to produce the image.

It is assumed that the surfaces have uniform reflection coefficients, $\beta_1, \beta_2,$ and are independent of incidence angle. W is the sound power of the source.

Bies and Hanson show this condition in the following expression:

$$p^2(r) = W\frac{\rho c}{4\pi}\left[\frac{1}{r^2} + \sum_{k=1}^{\infty}\left(\frac{1/\beta_1 + 1/\beta_2}{r_{2k-1}^2} + \frac{2}{r_{2k}^2}\right)(\beta_1\beta_2)^k\right] \qquad (5.6)$$

For $n = 2_k \ or \ 2_k - 1$ and k is the image order.

Bies and Hanson derive equation 3.7 from equation 5.4 where $r \gg a$.

$$p^2\,(r) = \frac{W\rho c}{4\pi r^2}\left[1 + \frac{\beta_1 + \beta_2 + 2\beta_1\beta_2}{1 - \beta_1\beta_2}\right] \qquad (3.7)$$

Where, W = radiated sound power

ρ = mean density of air

c = speed of sound

r = distance from source to receiver

β_1 = reflection coefficient of surface 1

It is apparent that the sound field, which includes both direct and reverberant fields, decays with the inverse square of the distance from the source. Bees and Hanson contend that 'the reverberant sound field may be greater than or less than the direct field at large distances from the source depending upon the values of the reflection co-efficients $\beta_1 \ and \ \beta_2$. In the case of the fully glazed DSF, $\beta_1 \ and \ \beta_2$ may be as high as 0.9.

If β_1 and β_2 are considered hard and reflecting (0.9) and the log is taken on both sides of the equation, then, the equation becomes:

$$L_p = L_w + 10\ Log\ \left(\frac{19}{4\pi r^2}\right) \tag{5.7}$$

This expression allows the user to calculate the sound pressure in the DSF cavity at any distance from the bottom of the DSF..

This equation can be used to evaluate the data from field testing in Chapter 7.

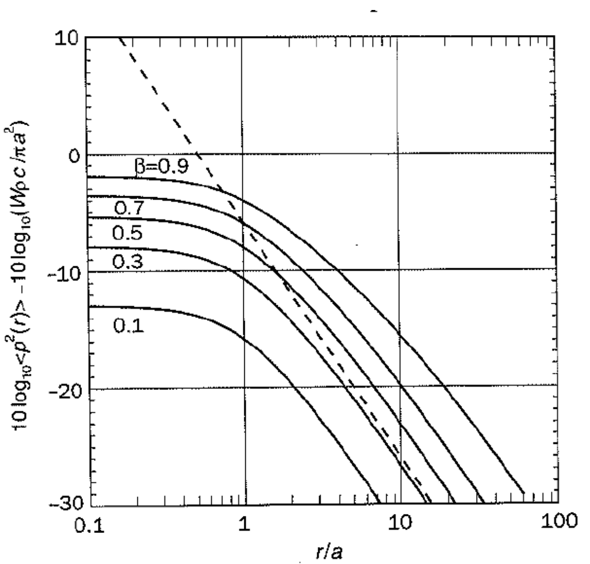


Figure 5.15 Direct and reverberant field (SRL, 1998)

This can be shown clearly in figure 5.15 where the direct and reverberant fields in a flat room (DSF) of height, a, and with specularly reflecting boundaries are plotted as a function of the normalised distance from source to receiver. The reverberant field condition is shown as a function of β. The direct field is shown by a dashed straight line.

The derivation of equation 5.6 (equation 5.7) will be another correction factor (step 3a) that can be calculated in an overall calculation sheet.

It is possible to continue this line of calculation for diffusely reflecting boundary surfaces but this is beyond the boundaries and limits of this research.

5.3.4 ELEMENT 2 – CONCLUSION

Each of the appropriate calculations and corrections from this section, Element 2, will be added to an overall calculation sheet to form a proposed calculation model for DSF acoustic attenuation. This section will be labelled as step 3 and the conclusion of step 3 will be a total effective attenuation after calculation and correction factors have been applied (see Figure 5.16).

5.4 ELEMENT 3 - PROPAGATION OF SOUND FROM THE DSF THROUGH AN OPEN WINDOW

5.4.1 NAPIER UNIVERSITY

The research of Napier University was introduced in Chapter 2. The goal of the Napier project was to *'undertake a thorough review of current knowledge/literature of acoustic losses through windows (open and closed), and produce a detailed summary of the findings'.* (Napier 2007)

Napier compiled a list of the available research for the insulation performance of open windows and this research is set out in table 2.4. The table gives a range of 5 – 15dBA however the standard range cited in literature is 10-15dBA.

Napier chose a selection of 7 windows to use during testing and a combination of 14 configurations.

Napier concluded that:-

f) For the dataset considered, the doubling of window area (with the windows closed) caused a reduction in the D_w of approximately 5dB.
g) The influence of the glazed area is negligible once the window is open.
h) It is noticeable that once the window is opened the influence of the glazing specification is nullified.
i) The influence of the window frame material becomes insignificant when the window is opened.
j) The influence of upgrading to acoustic seals becomes negligible once the window is opened.

Napier conducted a best fit empirical solution to assess the effect of the window opening on the façade insulation. Empirical estimates and deductions were performed in terms of the small element parameter and the element normalised level difference $D_{n,e}$. The data used for the assessment was taken from BS EN ISO 140-5. The calculation method is summarised by Equation 2.1.

$$D_{n,e,i} = -10Log_{10}\left[\frac{1}{10}S10^{\left(-\frac{R\,facade}{10}\right)} - S_{wall}\ 10^{\left(-\frac{Rwall}{10}\right)}\right] \quad (2.1)$$

Where, S_{wall} is the wall area appropriate to the measurement (i.e. S-$S_{Element}$)

The empirically derived conclusion to this research is summarised in the Fuller and Lurcock paper published in 2009.

5.4.2 RESEARCH OF FULLER AND LURCOCK

The authors of the 2007 Napier University report published a paper in 2009 entitled – 'research into the transmission loss of open and closed windows'. The authors summarize the findings of the 2007 report and then set out some new material.

A data-fit for previous open window results was undertaken and an empirically derived relationship is proffered.

$$D_{2m,nT} = Log_{10}\,(f)x\left\lfloor 2.2 - 0.8\ x\ Log_{10}(S_{op})\right\rfloor - 3.2\ x\ Log_{10}\left(S_{op}\right) + 8.1\ dB \quad (2.2)$$

Where,

f is the octave band centre frequency between 125 Hz to 4000 Hz

S_{op} is the open window area (m^2)

Fuller and Lurcock, state that the preferred façade insulation parameter used in predictive schemes is the Sound Reduction Index (SRI), given in equation 2.3.

$$R' = D_{2m,nT} - 10Log_{10}\left(\frac{V}{6T_oS}\right)\ dB \quad (2.3)$$

Where,

R' is the apparent sound reduction index of the façade (dB)

V is the receiving room volume

S is the façade area (m^2)

Fuller and Lurcock produce an equation for the best fit line within their graph of the apparent façade SRI, $R'_{w,}$ of $X = -5.8\ Log_{10}\,(x) + 13.2$.

The conclusion to this paper is that the trend for the resultant dataset from the Napier Paper indicates that there will be an average sound reduction at a rate of 1.8 dBA per doubling of opening window area.

5.4.3 ELEMENT 3 – CONCLUSION

As with Chapter 2 & 3, each of the appropriate calculations and corrections from this section, Element 3, will be added to an overall calculation sheet to form a proposed calculation model for DSF acoustic attenuation. This section will be labelled as step 4 and the conclusion of step 4 will be a total effective attenuation after calculation and correction factors have been applied (see Figure 5.16)

5.5 CONCLUSION

The conventional calculation for the acoustic attenuation is by use of a deduction calculation sheet. Elements 1,2 & 3 offer a solution within each element and the opportunity to propose a calculation sheet specifically for DSF calculation from sound source to DSF, through the DSF and through an open window.

Figure 5.16 outlines such a calculation sheet with a step by step calculation for each element and the ability to apply correction factors where appropriate. The data from DSF S1 on the tested building, Building A, London is used to assess the calculation method.

Step	Calculation	Corrections	63 Hz	125 Hz	250 Hz	500 Hz	1.0 kHz	2.0 kHz	4.0 kHz
1	Lw Source Sound Power		80.4	71.8	72.1	70.2	70.9	64.8	58.6
2	**Component 1 (Source to DSF)**								
	Lp = Lw + 20log10*r								
	r (calc or measure)	5							
	20*log10*r		-14.0	-14.0	-14.0	-14.0	-14.0	-14.0	-14.0
	distance correction from fig 5.4	-33	-33	-33	-33	-33	-33	-33	-33
	screening correction								
	$\delta = A + B - d$ from Fig 5.6								
	Effective attenuation from screening								
	Correction for wind or ground								
	Total Effective Attenuation Component 1		-13.9	-13.9	-13.9	-13.9	-13.9	-13.9	-13.9
3a	**Component 2, Condition B**								
	Lp = Lw + 10log10(5.6/4πr)								
	r (assume maximum of 1.8m)	1.8							
	a (cavity width, assume 0.9m)	0.9							
	10log(5.6/4πr)		-6.1	-6.1	-6.1	-6.1	-6.1	-6.1	-6.1
	Total Effective Attenuation Component 2B		-6.1	-6.1	-6.1	-6.1	-6.1	-6.1	-6.1
3b	**Component 2, Condition C**								
	Lp = Lw + 10log10(19/4πr^2)								
	r (assume a receiver dimension from ?)	5							
	β_1 reflective coeffecient, assume 0.9	0.9							
	β_2 reflective coeffecient, assume 0.9	0.9							
	10log(19/4πr^2)		-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2
	Total Effective Attenuation Component 2C		-5.2	-5.2	-5.2	-5.2	-5.2	-5.2	-5.2
4	**Component 3**	opening x							
	-5.8 Log10(x) + 13.2	0							
	Total Effective Attenuation Component 3		0	0	0	0	0	0	0
5	**Total Attenuation Components 1,2,3**		15.0	15.0	15.0	15.0	15.0	15.0	15.0
6	**Calculated Lp at r =5m**		65.4	56.8	57.1	55.2	55.9	49.8	43.6
	Measured Lp at Level 3 of E1		**70.5**	**65.5**	**63.4**	**61.1**	**62.5**	**55.8**	**49.1**

Figure 5.16 DSF Acoustic Attenuation Calculation sheet

The difference in calculated and measured L_p is attributable to open joints on the outer DSF skin which 'leak' sound into the DSF and reduce the attenuation of the DSF.

The calculation sheet in figure 5.16 is representative of the final hypotheses reached for each element type in the sound path diagram in figure 1.2. It is not a definitive calculation sheet as there may be many factors affecting attenuation in the field that are not included.

Fig 5.16 is seen as a template using suggested correction tables and others that the user sees fit.

Chapters 6, parametric analysis and chapter 7 testing may refer back to the hypotheses promoted within this chapter as a comparison to modelled or actual field results.

CHAPTER 6

FIELD TESTING

6.1 INTRODUCTION

This chapter outlines the procedures followed during field testing with the standards and procedures, the reporting procedures, equipment used and full analysis of results.

The parameters for field testing the acoustic performance of façade elements are outlined in BS EN ISO 140-5:1998, Acoustics - Measurement of sound insulation in buildings and of building elements - pt 5: field measurements of airborne sound insulation of façade elements and façades (ISO 140-5).

The standards in table 6.1 through reference in ISO 140-5 contain provisions for field testing of façades.

Standard	Name of Standard	Stage
ISO 140-2:1991	Acoustics — Measurement of sound insulation in buildings and of building elements — Part 2: Determination, verification and application of precision data.	90.92
ISO 15186-3:2003	Acoustics — Measurement of sound insulation in buildings and of building elements — Part 3: Laboratory measurements at low frequencies.	90.20
ISO 354:2003	Acoustics — Measurement of sound absorption in a reverberation room.	90.92
ISO 717-1:2013	Acoustics — Rating of sound insulation in buildings and of building elements — Part 1: Airborne sound insulation.	60.60
IEC 60651: 1994	Sound level meters.	
IEC 60804:1985	Integrating-averaging sound level meters.	
IEC 60942:1991	Sound calibrators.	
IEC 61260:1995	Electroacoustics — Octave band filters and fractional — Octave band filters.	
ISO 5725-1: 1994	Accuracy (trueness and precision) of measurement methods and results – part 1: general principles and definitions	60.60

Table 6.1 Additional standards to be read in conjunction with ISO 140-5.

The stage column refers to the current international status of the document and the full schedule of stage references is set out in Appendix 2. It shows that most of the acoustic standards in relation to façades are being revised (stage 90.92) and it is most likely that there will be provisions for DSF's in any revised documents.

As previously outlined, this research is broken into elements for the purposes of analysis. BS EN ISO 140-5, acoustic field testing of façades, does not specifically describe how testing of a DSF must be carried out. The testing was conducted mapped the resulting data to it's associated element in a manner that satisfies ISO 140-5, in as much as is practical. Deviations from any standard were duly noted.

For reference purposes, Figure 1.2 is shown again to outline the three key elements clearly.

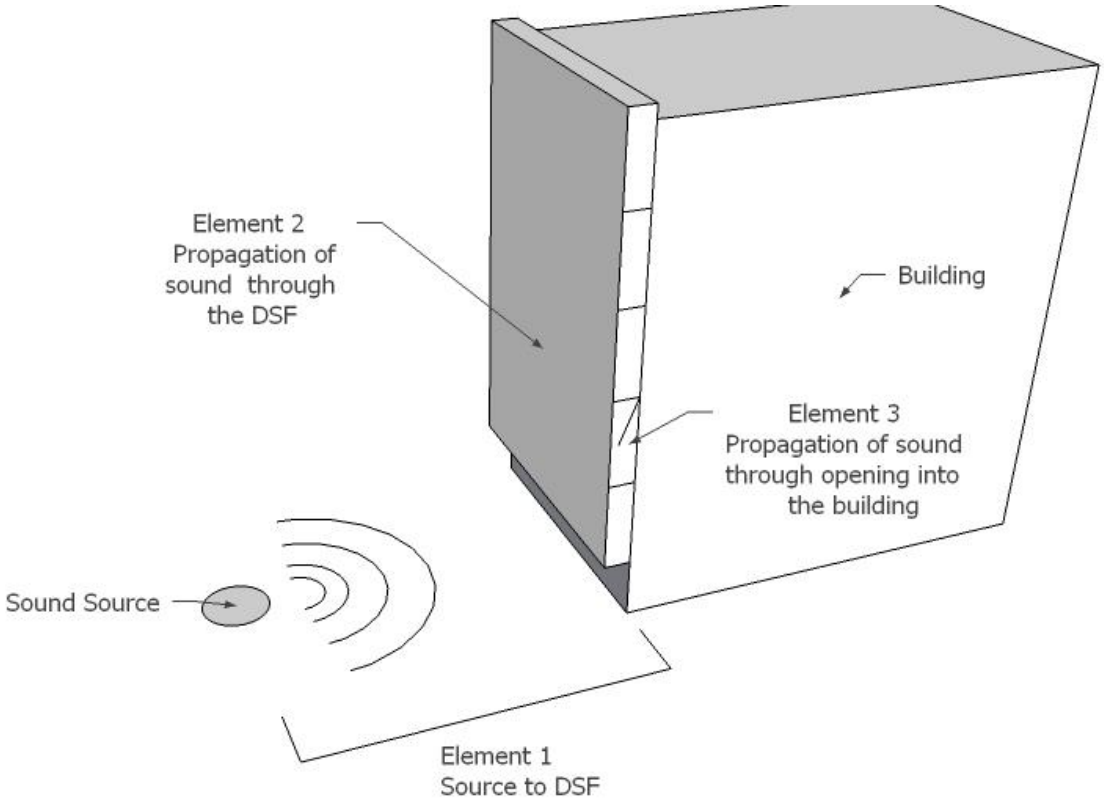


Figure 1.2 Generic Sound Propagation Element Layout

6.2 BUILDING A, FIELD TEST (LONDON)

6.2.1 INTRODUCTION

This field test was carried out on a 13 storey commercial office development on the outskirts of London. For reasons of confidentiality, the project cannot be named and as such it will be referred to herein as Building A, Field Test, London.

6.2.2 BUILDING SELECTION PROCESS

There are a limited number of double skin façades in the UK and the selection pool is small. Project identification was carried out by means of personal contact within the industry. A refined list of personal contacts was used that have experience of using DSFs. They were contacted with a view to deriving a list of possible test project locations. Compiling a list was relatively easy however getting building owner permission to test was more difficult. Client and project confidentiality was the biggest obstacle for building owners.

The project selection process needed to fulfil the following criteria:-

- ✓ The project needed to be in the UK.
- ✓ The project needed to be a NV DSF construction.
- ✓ The client needed to be aware of the implications of an acoustic test.
- ✓ The building needed to be unoccupied for a period of time in order that the test would be less invasive for the client.
- ✓ The building needed to be accessible from both outside and inside.
- ✓ The DSF needed to be in a fit state for testing and safe for easy access.
- ✓ The clients concerns and requests had to be considered and fulfilled at all times.
- ✓ A full risk assessment and method statement had to be completed and sent to the client, whether requested or not (MS01 and RA01 – Appendix 2 and 3 respectively)

- ✓ Any issues or concerns of confidentiality on the part of the client had to be fully addressed and adhered to.

6.2.3 PROJECT DESCRIPTION

Building A, London is the redevelopment of a four story municipal office site. The building is rectangular in shape and is bordered on all four sides by roads. On the South elevation, there is an arterial flyover within 6m of the façade. The East and West elevations are adjacent to city centre roads with moderate traffic. The North elevation is parallel to another city centre road within 6m and is considered to have normal road traffic noise. The site layout is shown in Figure 6.1.

The façade of Building A is multi-level and the DSFs that have been tested vary in height from 4 to 13 storeys high. Level 1 is the 1st floor and level 12 is the 12th floor and so hereafter the floor levels will be referred to as Level 1 or L1 etc. The façade is a naturally ventilated DSF comprising a unitised curtain wall system on the inner skin and point fixed single glazing on the outer skin.

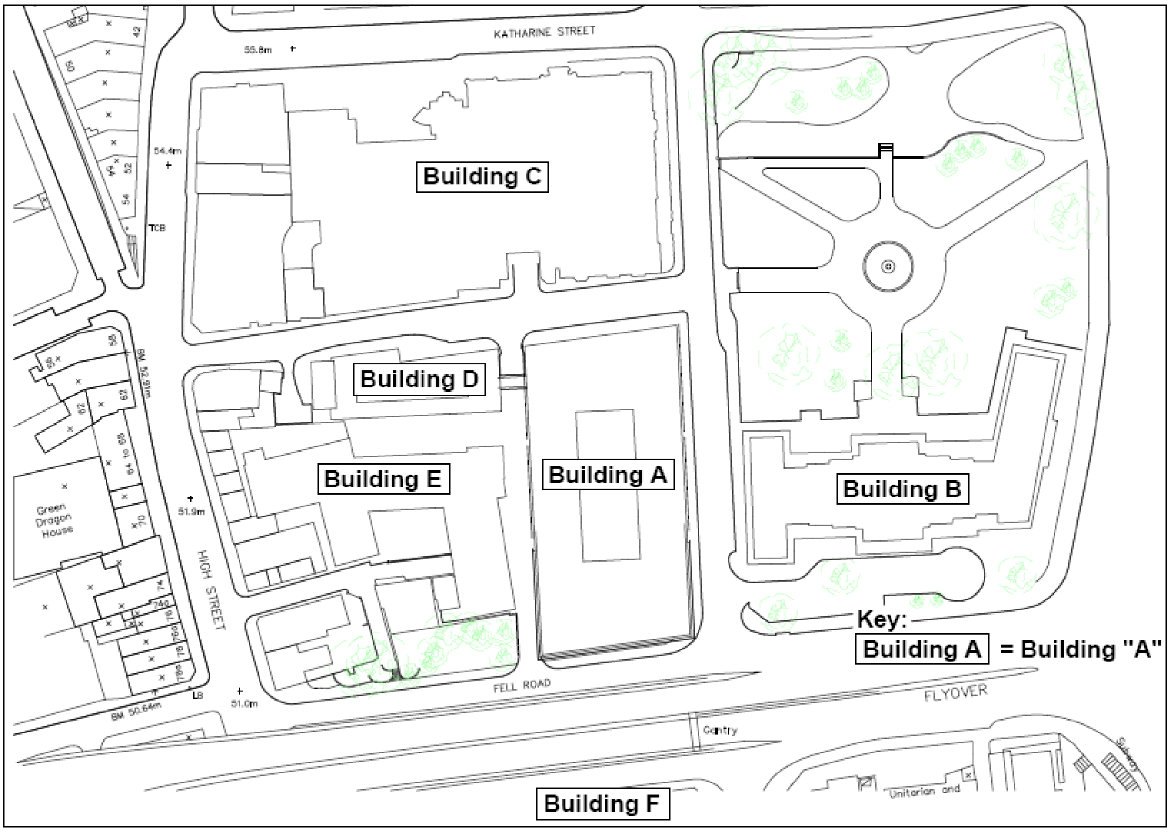


Figure 6.1 Site Layout

The link to a connecting building (Building D) on the West Elevation by means of a glazed link bridge and building D was not considered as part of the testing campaign.

The buildings surrounding Building A play an important role in the acoustic levels at the façade face of the test building. A list of the surrounding buildings are set out in Table 6.2 and referenced in Figure 6.1 – site layout.

The effects of the surrounding building topography on overall acoustic levels at the façade face will not be examined in this chapter but their importance must be noted. The influence of the sound reflection from adjacent buildings and the reflection co-efficient of materials (β) was illustrated through empirical calculation in Chapter 5. The significance of topography and surrounding building distribution is examined in Chapter 7, Parametric Analysis.

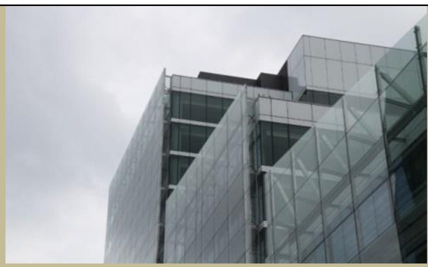
Building A Test Building	The test building may be affected by road traffic sound reflecting off surrounding buildings	
Building B The East elevation has a 20 storey office block with a stone clad façade	Building B will be moderately reflective and the close proximity of the lower 3 storeys will have a significance in reflecting sound.	
Building C The North Elevation has a 5 storey brick and stone building directly opposite with punch-hole windows.	This building will have least effect on the test building being further away (15m) and not having as hard and reflective surfaces as the other buildings.	
Building E The West Elevation has a very close 8 storey building (8m) directly opposite. It is a stone clad building with vertical strip windows	The façade of this building is not as reflective as the South and East however the close proximity causing a funnel effect will have a bearing on the test building.	
Building F The South Elevation has a modern office block directly opposite which is 9 storey and a 17 storey tower. The building façade is predominantly glass and metal composite cladding.	This building will reflect sound towards the test building because of the highly reflective nature of the façade.	

Table 6.2 Surrounding building demographic

6.2.4 PROJECT CONSTRUCTION

The façade is constructed from a bespoke unitised aluminium curtain wall system (200mm x 75mm profile, see figure 6.2) with structurally bonded double glazed units of varying specification. There are no opening windows in the curtain walling system and the natural ventilation into the DSF is just to ventilate the cavity only.

There are galvanised steel brackets protruding from the curtain walling from which the DSF façade is suspended. The galvanised DSF walkway deck is supported at 3m centres by the protruding brackets.

Figure 6.2 Unitised CW (viewed internally)

The outer skin of the DSF is a single glazed point fixed construction supported off 120 x 50mm vertical RHS steel profiles and s/s rotules.

The single glazed panels (3m wide x 1.875m high)have a 30mm gap both horizontally and vertically at every joint (figure 6.3).

The DSF cavity is 800mm deep internally with no vertical or horizontal divisions (Figure 6.3). The DSF is open at the bottom to provide ventilation to the cavity (Figure 6.4) and there are automated mechanical louvres at the top of the DSF that open to regulate the cavity environment (Figure 6.5).

Figure 6.3 30mm gap on external skin

Access into the DSF is by means of an access door at the end of each walkway on every level. Internally the access door is within a buffer / silence room to minimise sound propagation during access and maintenance periods.

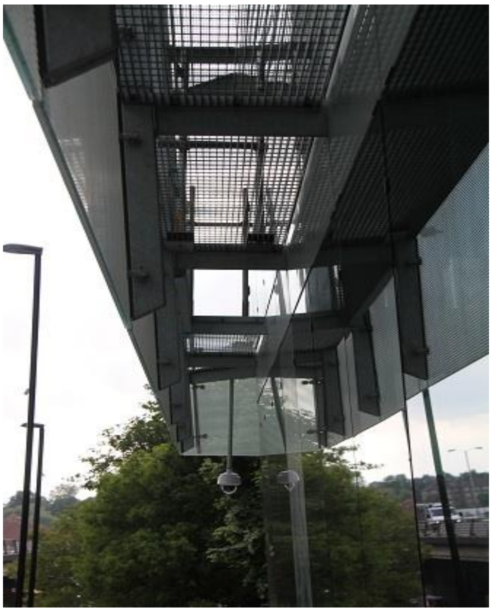


Figure 6.4 - NV at bottom of DSF

Figure 6.5 – Motorised Dampers

6.2.5 TEST EQUIPMENT

The equipment used for testing and their specification are listed in Table 6.3. In general terms, the Norsonic 118 precision sound analyser was designated to test outside and the Norsonic 131 precision sound analyser within the DSF cavity.

6.2.6 TEST METHODOLOGY

ISO 140-5 sets out the standard for acoustic testing of a façade. Field testing in urban environments can presents particular challenges and Building A, London is no different. The challenging aspects to testing Building A, London and the resulting decisions taken are set out in table 6.4.

NORSONIC 131			
Name	Serial No.	Calibration	Due
Norsonic Precision Sound Analyser Type 131 (Appendix 5)	1313109	May 2012	Mar 2014
Norsonic Type 1207 Pre-amplifier (Appendix 5)	12303	May 2012	Mar 2014
Norsonic Type 1228 Microphone (Appendix 5)	0812	May 2012	Mar 2014
Norsonic Sound Calibrator Type 1251 (Appendix 6)	32090	Feb 2013	Feb 2014
JBL Powered Loudspeakers (x2) PRX512M (Appendix 7)	-	-	-
NORSONIC 118			
Norsonic Precision Sound Analyser Type 118 (Appendix 8)	30562	Sept 2012	Sept 2014
Norsonic Type 1206 Pre-amplifier (Appendix 8)	30249	Sept 2012	Sept 2014
Norsonic Type 1225 Microphone (Appendix 8)	57530	Sept 2012	Sept 2014
Norsonic Sound Calibrator Type 1251 (Appendix 6)	32090	Feb 2013	Feb 2014
OLYMPIC 6			
Olympic 6, reverberation time test gun, 8 shot, 6mm calibre (.22 cal) (Appendix 9)	626E	Mar 2013	Mar 2014

Table 6.3 Equipment Schedule for testing Building A, London

Decision to be made	Decision Taken
What to test?	**The building has 4 sides and the DSFs are located on the S,E and W. The time frame was set by the client as 7pm onwards, therefore testing could continue as long as it was safe to do so.** **It was decided to test all DSFs starting with the South and East as it was the biggest façade and also faced the flyover.**
Decision on source type?	**The traffic noise was sufficient at 6pm (peak traffic) that a decision was made to use it as the sound source. There were a number of difficulties using loud speakers as the sound source at a 5-7m distance from the façade. There are no external power points on the building and there was very little distance between the façade face and the flyover (main arterial road) - ISO 140-5 requires 5-7m.**
$D_{tr,2m,nT}$ or $D_{ls,2m,nT}$	**It was envisaged before arriving at the test site that either $D_{tr,2m,nT}$ or $D_{ls,2m,nT}$ would be used. However the issue was that to achieve this, a measurement needed to be taken at 2m from the façade. The height above ground level to take this measurement was 6m and as such was unrealistic and unachievable with the resources available. The option was to take surface measurements at the façade, which could be taken internally. This method was adopted and therefore an in and corresponding out measurement was taken. This is explained in further detail within each test procedure.**
L_{Aeq} and L_{Amax}	**It was decided that L_{Aeq} and L_{Amax} measurements would be taken due to the fact that a 2m measurement could not be taken. The reason for this is repeatability insofar as when further project tests are undertaken, then an L_{Aeq} value can be examined. It is also possible to look at the resultant data in terms of dBA and D_w in accordance with ISO 717-1. These measurements were taken for a 30 second duration.**
Loudspeaker	**During the testing campaign, it was identified that traffic sound would at some point during testing become ineffective and insufficient; therefore a test procedure was adopted whereby a loudspeaker would be placed at the bottom of the DSF and then an L_{Aeq} reading would be taken at each floor level. This test was identified as one which could examine the decay of sound over distance within the DSF cavity and would also have repeatability.**
Determination of receiver	**A DSF cavity can vary in width from project to project and as such it was determined that readings would be taken at floor level and in the**

Table 6.4 Justification of Test Methodology for Building A, London Field Test.

The DSFs have been designated as per table 6.5, for reference purposes and as shown in isometric and plan in figures 6.6 – 6.8 inclusive.

Screen Elevation and Number	Façade Screen Designation	Figure Nos.
South Elevation	DSF S1	Fig 6.6
West Elevation	DSF W1	Fig 6.7
	DSF W2	Fig 6.7
	DSF W3	Fig 6.7
	DSF W4	Fig 6.7 & 6.8
East Elevation – Screens 1,2,3	DSF E1	Fig 6.6
	DSF E2	Fig 6.6
	DSF E3	Fig 6.6

Table 6.5 Building A, London, DSF Designation

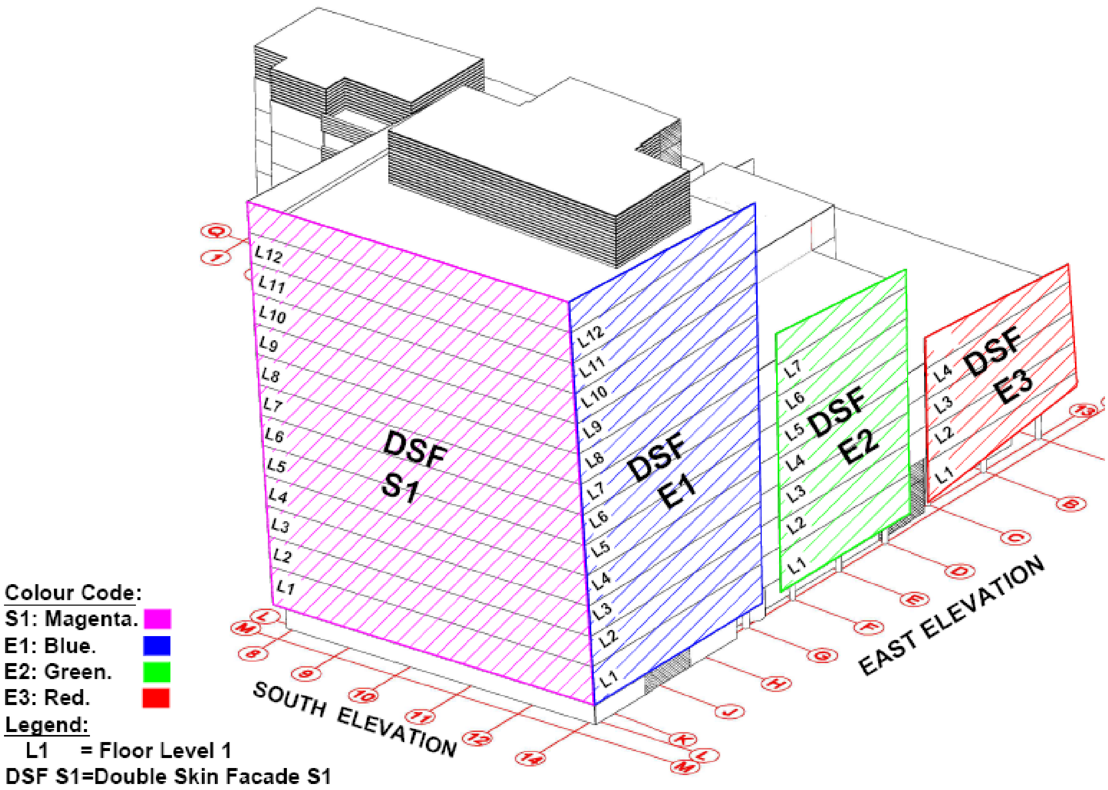


Figure 6.6 South East Corner DSF Designation

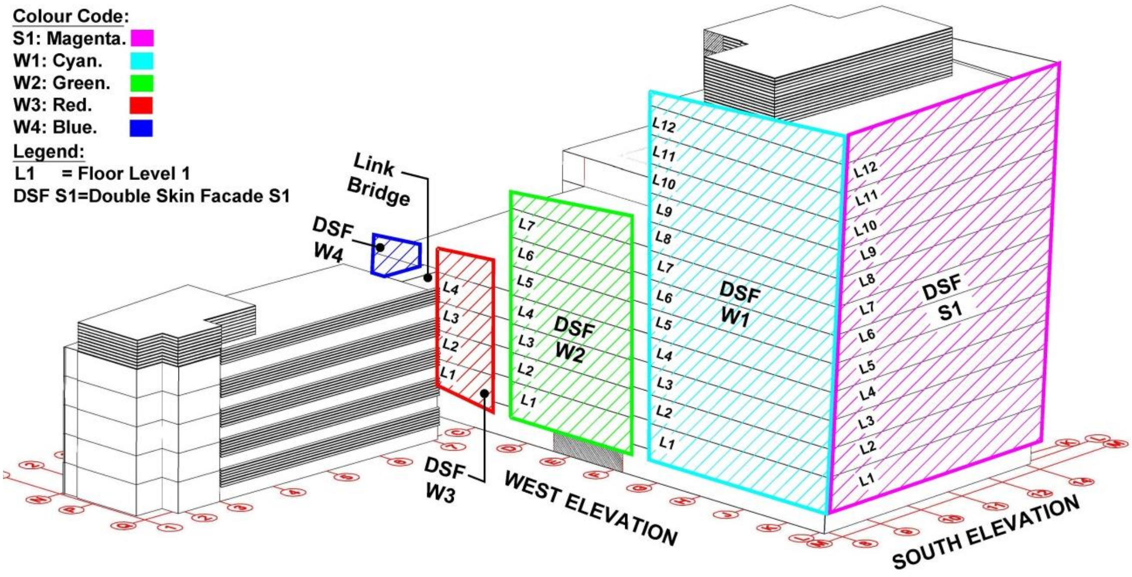


Figure 6.7 South West Corner, DSF Designation

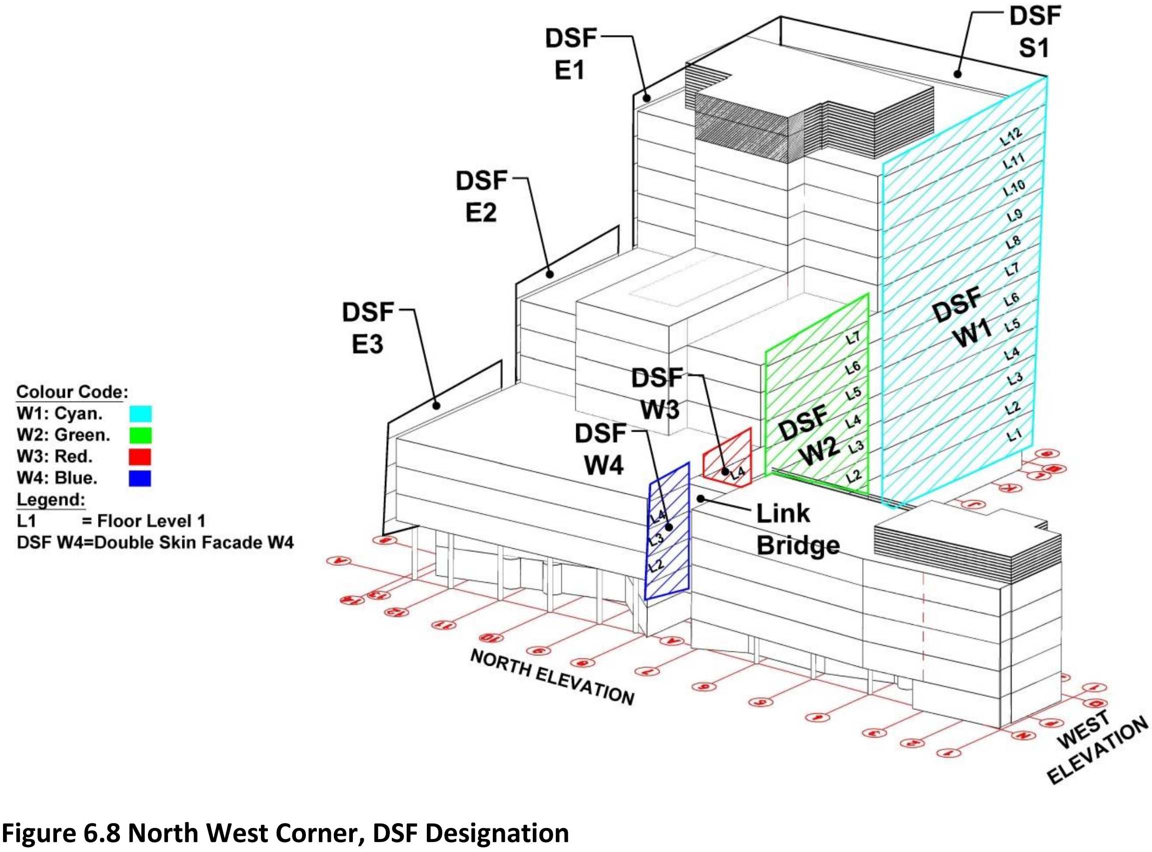


Figure 6.8 North West Corner, DSF Designation

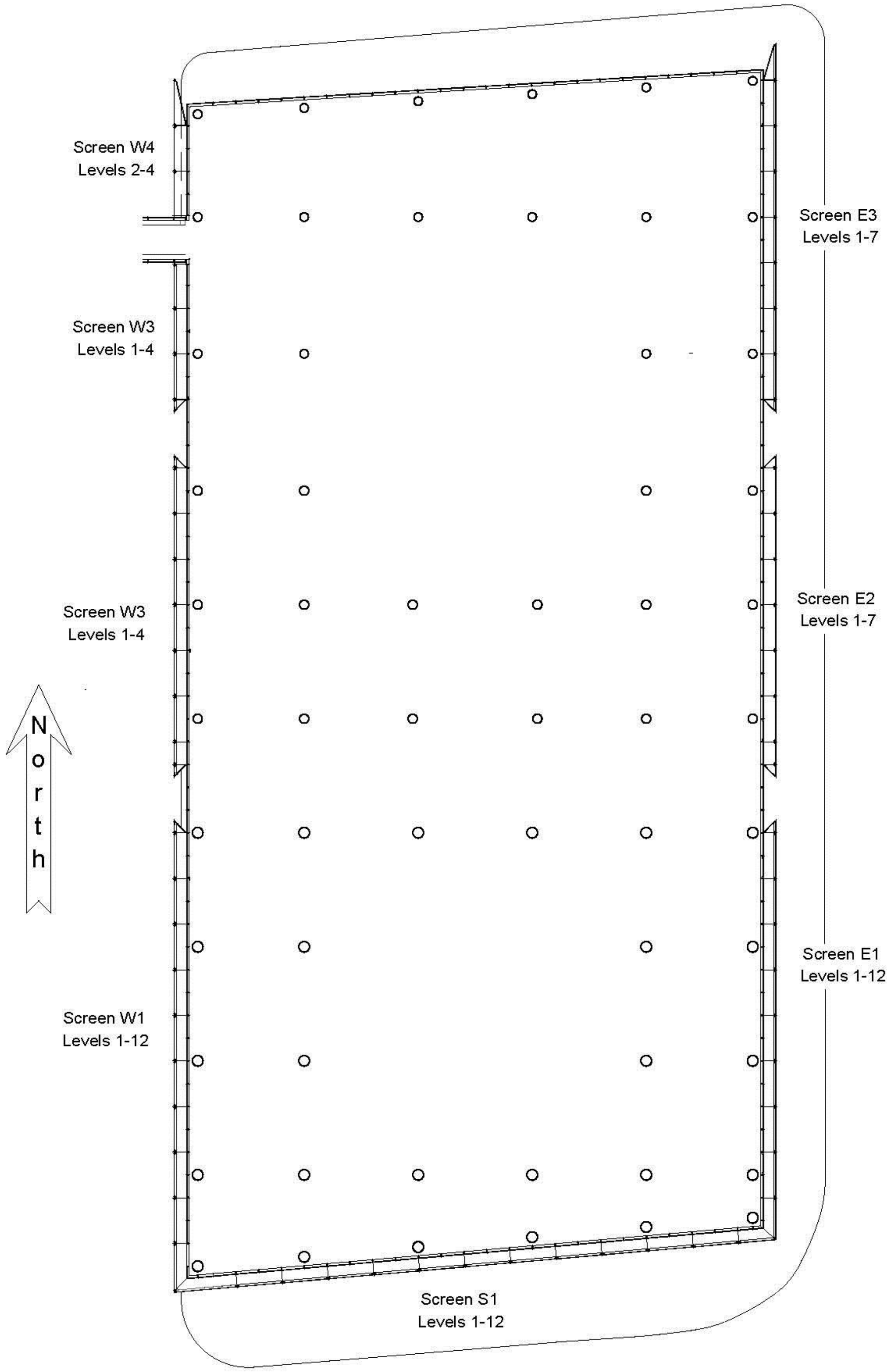


Figure 6.9 Plan Layout, DSF Designation

The number of tests undertaken was determined by the time frame on site. Light levels needed to be considered in terms of task lighting and safety. As such the final testing campaign was as per Table 6.6.

Test No	Screen No / Levels	Source Type	Figure No.	Results
Test 1	S1 / E1, Levels 1-12	Road Traffic	Figures 6.6, 6.11, 6.13,14	Appendix 12
Test 2	E3, E2, E1, S1, W3, W3, W2, W1, Level 4	Road Traffic	Figure 6.16-18	Appendix 13
Test 3	W4, Levels 2 – 4	Loudspeaker	Figure 6.23, 24	Appendix 14
Test 4	W3, Levels 1 – 4	Loudspeaker	Figure 6.26, 27	Appendix 14
Test 5	W2, Levels 1 – 7	Loudspeaker	Figure 6.30,31	Appendix 14
Test 6	S1, Levels 1 – 12	Loudspeaker	Figure 6.33,34	Appendix 14
Test 7	Reverberation, various levels	Gun	Figure 6.37-39	Appendix 15

Table 6.6 – Building A, London, Testing Campaign Summary

6.2.7 BUILDING A, LONDON, TEST 1

S1 and E1 are two connecting DSFs spanning over the full 13 storey height (figure 6.10). The test layout and location are as per Figure 6.11 and 6.12. The receiver locations were chosen for each DSF and this same location was used for every floor level (L1-L12) and so this testing campaign comprised 24 individual tests.

The test procedure for test 1 was to test the outdoor environment and the DSF cavity simultaneously using road traffic noise.

Figure 6.10 South East Corner (S1/E1 Levels 1-12)

The receivers were arranged as shown in Figure 6.12 and L_{Aeq} measurements taken, outside and inside, for 30 seconds simultaneously across the octave frequency spectrum of 63Hz to 8.0kHz. This process was repeated for each location and floor level as per the layout in Figures 6.11 and 6.13.

The resultant data is tabulated on the standard form for test report as per ISO 140-2 and in a global format which is collated in Appendix 10. Each separate test is labelled 1.1, 1.2, 1.3 and so on. Figure 6.14 shows the results for test 1.1 which is the DSF on E1 Level 1. Tests 1.2 to 1.24 are in Appendix 11.

The test format allows a standardised level difference calculated from the L_{Aeq} measurements taken and from this D_w and $D_{n,Tw}$ values were calculated. The results are plotted on a graph together with the standard reference curve in accordance with ISO 140-2. An abridged set of results is shown in Table 6.7 and can be identified by location in Figure 6.11 which identifies the screen numbers on the building.

Test No			LAeq	Dw	dBA
1.1	E1_Lev1_Out_181	L1	65.7	-	-
	E1_Lev1_In_131	L2	63.9	-	-
	Difference	L1-L2	1.8	2	2.6
Test No			LAeq	Dw	dBA
1.2	S1_Lev1_Out_181	L1	74	-	-
	S1_Lev 1_In_131	L2	71.5	-	-
	Difference	L1-L2	2.5	3	3.2
Test No			LAeq	Dw	dBA
1.3	E1_Lev2_Out_181	L1	65.3	-	-
	E1_Lev2_In_131	L2	63.4	-	-
	Difference	L1-L2	1.9	3	3.3
Test No			LAeq	Dw	dBA
1.4	S1_Lev_Out_181	L1	75.9	-	-
	S1_Lev2_In_131	L2	72.9	-	-
	Difference	L1-L2	3	4	3.6
Test No			LAeq	Dw	dBA
1.5	E1_Lev 3_Out_181	L1	68.2	-	-
	E1_Lev3_In_131	L2	64.7	-	-
	Difference	L1-L2	3.5	4	3.5
Test No			LAeq	Dw	dBA
1.6	S1_Lev3_Out_181	L1	77.7	-	-
	S1_Lev3_In_131	L2	73.9	-	-
	Difference	L1-L2	3.8	5	4.7
Test No			LAeq	Dw	dBA
1.7	E1_Lev4_out_181	L1	65.4	-	-
	E1_Lev4_In_131	L2	63.7	-	-
	Difference	L1-L2	1.7	2	2.7
Test No			LAeq	Dw	dBA
1.8	S1_Lev4_Out_181	L1	78.2	-	-
	S1_Lev4_In_131	L2	74.3	-	-
	Difference	L1-L2	3.9	5	4.7
Test No			LAeq	Dw	dBA
1.9	E1_Lev5_Out_181	L1	70	-	-
	E1_Lev5_In_131	L2	67.1	-	-
	Difference	L1-L2	2.9	3	3.1
Test No			LAeq	Dw	dBA
1.10	S1_Lev5_Out_181	L1	78.6	-	-
	S1_Lev5_In_131	L2	74.4	-	-
	Difference	L1-L2	4.2	5	4.4
Test No			LAeq	Dw	dBA
1.11	E1_Lev6_Out_181	L1	72.3	-	-
	E1_Lev6_In_131	L2	68.3	-	-
	Difference	L1-L2	4	4	4.5
Test No			LAeq	Dw	dBA
1.12	S1_Lev6_Out_181	L1	74.7	-	-
	S1_Lev6_In_131	L2	70.6	-	-
	Difference	L1-L2	4.1	5	4.6

Test No			LAeq	Dw	dBA
1.13	E1_Lev7_Out_181	L1	68.8	-	-
	E1_Lev7_In_131	L2	65.9	-	-
	Difference	L1-L2	2.9	3	3.7
Test No			LAeq	Dw	dBA
1.14	S1_Lev7_Out_181	L1	77.1	-	-
	S1_Lev7_In_131	L2	73	-	-
	Difference	L1-L2	4.1	5	4.4
Test No			LAeq	Dw	dBA
1.15	E1_Lev8_Out_181	L1	68.6	-	-
	E1_Lev8_In_131	L2	65.8	-	-
	Difference	L1-L2	2.8	3	3.1
Test No			LAeq	Dw	dBA
1.16	S1_Lev8_Out_181	L1	72.5	-	-
	S1_Lev8_In_131	L2	68.6	-	-
	Difference	L1-L2	3.9	5	4
Test No			LAeq	Dw	dBA
1.17	E1_Lev9_Out_181	L1	69.1	-	-
	E1_Lev9_In_131	L2	66.2	-	-
	Difference	L1-L2	2.8	3	3.1
Test No			LAeq	Dw	dBA
1.18	S1_Lev9_Out_181	L1	75	-	-
	S1_Lev9_In_131	L2	71.8	-	-
	Difference	L1-L2	3.2	4	3.9
Test No			LAeq	Dw	dBA
1.19	E1_Lev10_Out_181	L1	68.2	-	-
	E1_Lev10_In_131	L2	65.6	-	-
	Difference	L1-L2	2.6	3	3.2
Test No			LAeq	Dw	dBA
1.20	S1_Lev10_Out_181	L1	74.7	-	-
	E1_Lev10_In_131	L2	71.4	-	-
	Difference	L1-L2	3.3	4	3.9
Test No			LAeq	Dw	dBA
1.21	E1_Lev11_Out_181	L1	68.1	-	-
	E1_Lev11_In_131	L2	65.1	-	-
	Difference	L1-L2	3	3	3.1
Test No			LAeq	Dw	dBA
1.22	E1_Lev11_Out_181	L1	73.7	-	-
	S1_Lev11_In_131	L2	70.5	-	-
	Difference	L1-L2	3.2	4	3.6
Test No			LAeq	Dw	dBA
1.23	E1_Lev12_Out_181	L1	64.5	-	-
	E1_Lev12_In_131	L2	61.5	-	-
	Difference	L1-L2	3	3	3
Test No			LAeq	Dw	dBA
1.24	S1_Lev12_Out_181	L1	75	-	-
	S1_Lev12_In_131	L2	71.4	-	-
	Difference	L1-L2	3.6	4	3.5

Table 6.7 Test 1 Abridged Summary Results (Full Results Appendix 10)

The abridged results are given in a format that shows the single integer L_{Aeq} value with the calculated D_w and dBA values. The full set of results are attached in appendix 10 and show the full spectral range of results from 63Hz to 8kHz.

6.2.7.1 SUMMARY OF TEST 1 RESULTS

The results from test 1 give a D_w, dBA, $D_{n,Tw}$ and L_{Aeq} relationship across S1 and E1 at each floor level. There is an obvious difference in SPL levels because S1 is closer to the motorway than E1 and the average level difference between S1 and E1 on the façade face is 6.7dB. The average level difference in the cavity between S1 and E1 is 6.9dB.

The L_{Aeq} levels in the cavity are high on the upper floors and it was expected that these would be lower due to the decay of sound over distance. It was concluded that this resulted from the contribution of sound propagated through the 30mm vertical and horizontal open joints.

The D_w results were considered to be quite weak and this must again be due to the propagation of sound through the open cavities in the outer skin of the DSF.

The D_w of S1 environment Level 1 and S1 cavity Level 12 was 3dB. The conclusion was that the propagation of sound through the open joints was more dominant than any sound decay over distance through the cavity from Level 1 to Level 12.

This result is very important in the design of a NV DSF. If the design of a NV DSF is to achieve any form of acoustic performance then the joints must be closed and sealed.

These measurements (S1 Level 1 environment – S1 Level 12 cavity) were taken at different times and as such the results are dependent on both measurements being taken at the same levels of road traffic.

However an analysis of the road traffic measurements show a range of 6.8dB from lowest to highest reading and 3.1dB from highest to the S1 Level 12 environment reading.

A conservative interpretation of this result for S1 environment Level 1 and S1 cavity Level 12 would be $D_{w\,=}$ 3dB + 3.1dB correction for road traffic.

It is still not an encouraging acoustic reduction performance and the premise of closing the joints would still hold based on the data recorded.

It may have been more accurate to set up a loudspeaker at the bottom of S1 and E1 and this was the test methodology for Test 6.

In hindsight, even though $D_{tr,2m,nT}$ or $D_{ls,2m,nT}$ could not be taken, a 2m reference could have been taken to which reference could have been made. Possibly an $L_{Aeq\,(60\,mins)}$ taken at ground level might have given more consistency to the result.

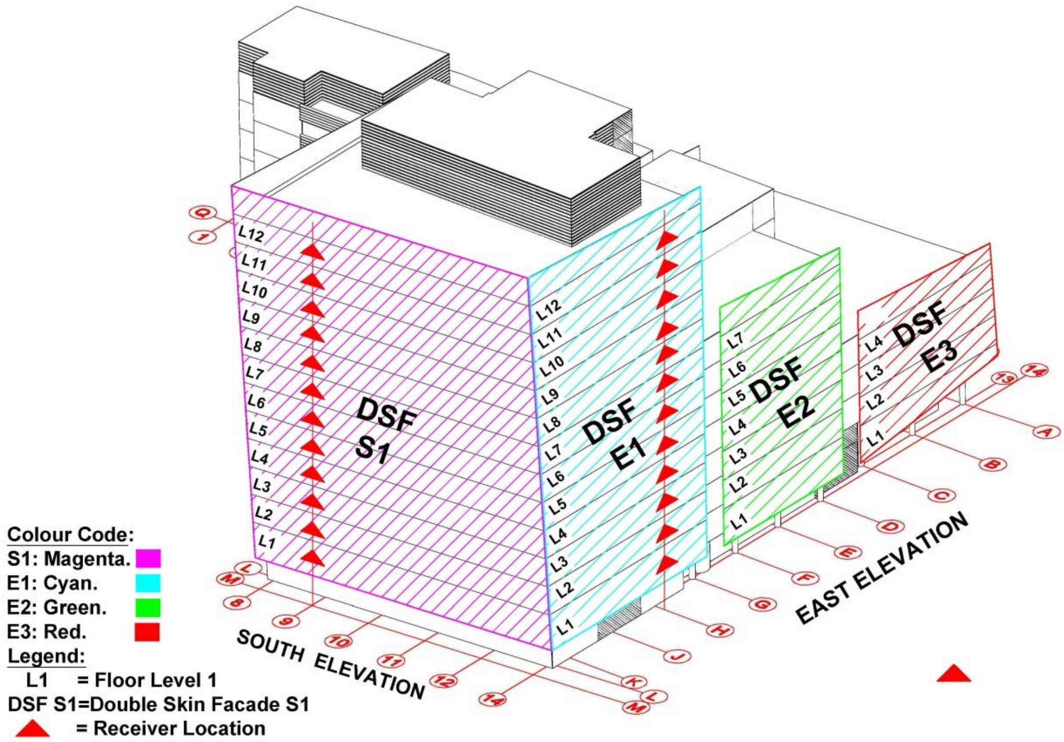


Figure 6.11 Receiver Set Out Test 1

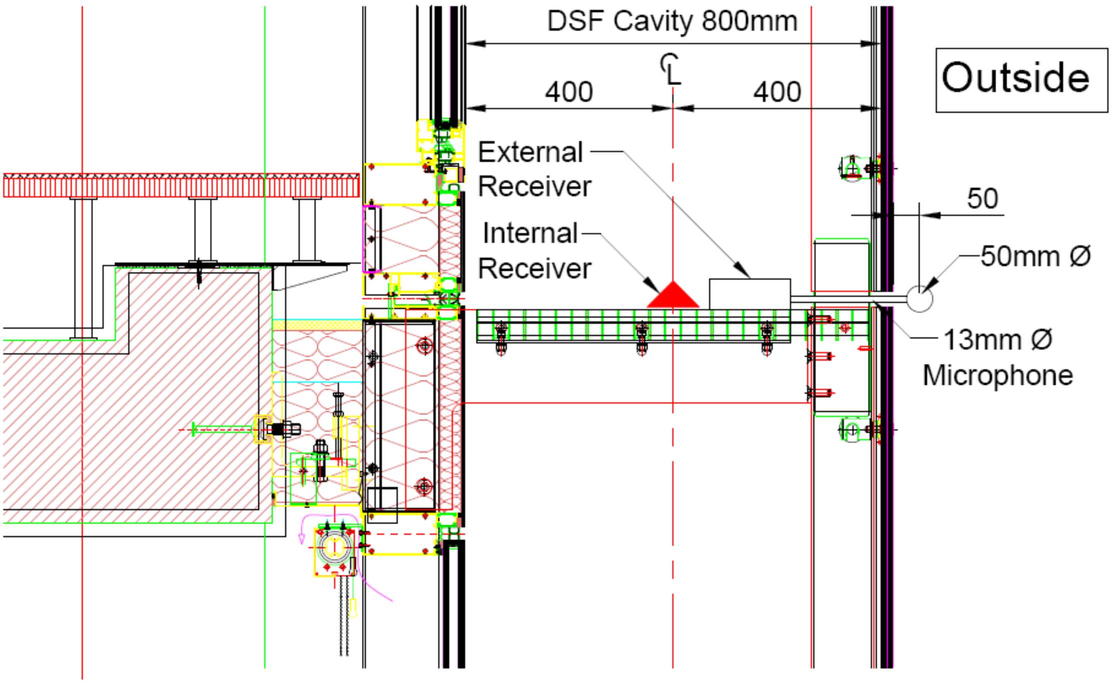


Figure 6.12 Receiver Set Out within the DSF cavity.

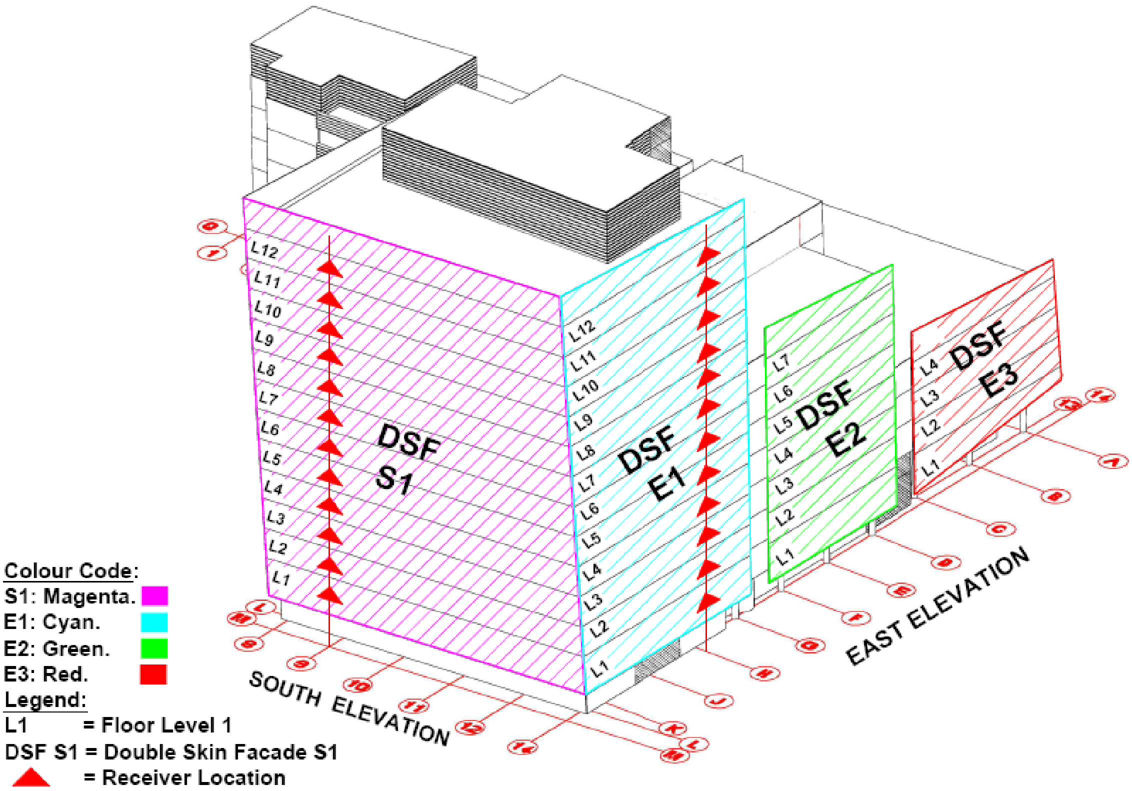


Figure 6.13 South East Corner Receiver Layout Test 1

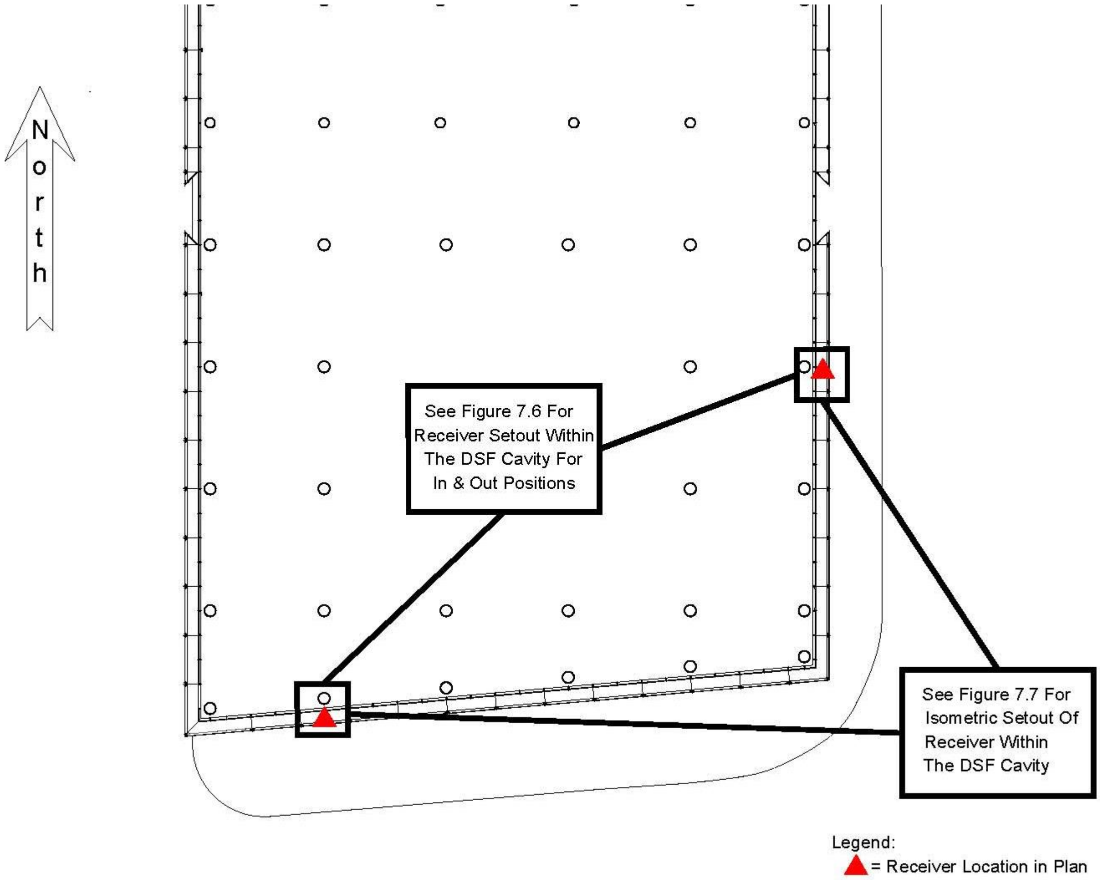


Figure 6.14 Plan Receiver Lay Out - Test 1

Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

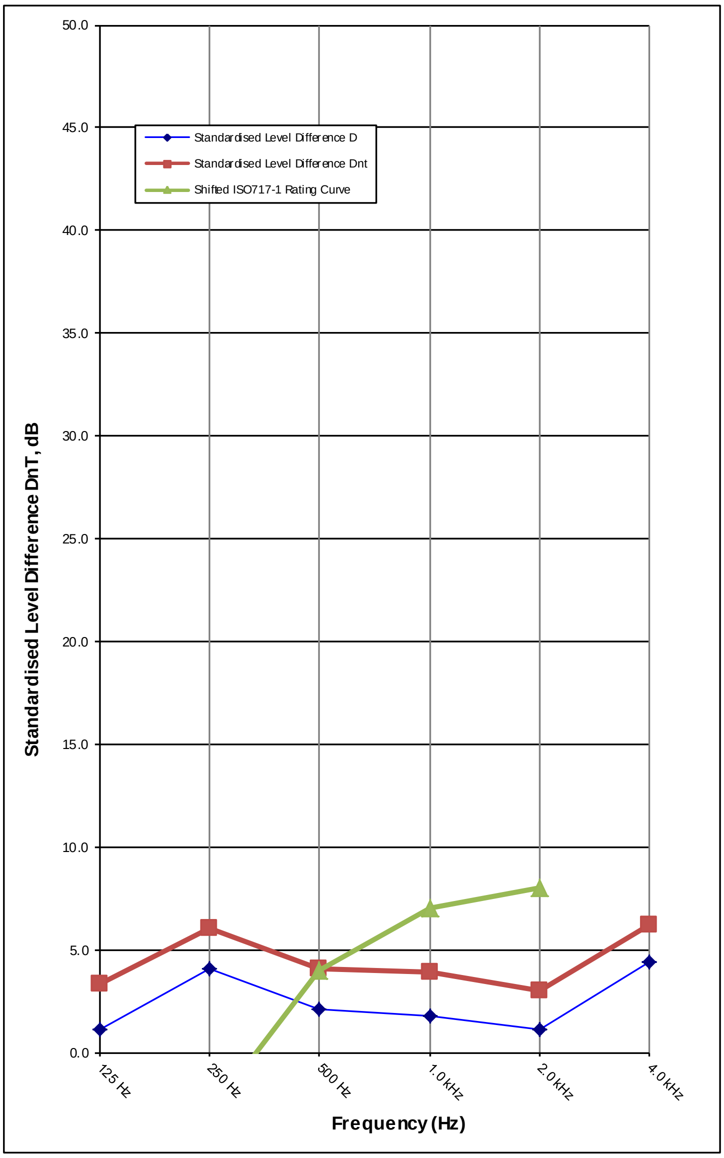
Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 1**

Site: Building A, London

Source room : E1_Level 1_Environment_181 Receiver room : E1_Level 1_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-5.0	-3.5
125	1.1	3.3
250	4.1	6.0
500	2.1	4.1
1k	1.8	3.9
2k	1.1	3.0
4k	4.4	6.2



Rating according to ISO 717-1

$D_{nT,w}$ = 4 dB **D_{w}=** **2 dB**

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

Figure 6.15 Standardised Level Difference Test 1.1 in accordance with ISO 140-2.

6.2.8 BUILDING A, LONDON, TEST 2

Test 2 comprised a series of L_{Aeq} measurements taken at Level 4 across all of the DSFs for a duration of 30 seconds with the receiver location within the DSF cavity as per figures 6.16-18.

L_{Aeq} values were taken to allow a comparison between each DSF. This test did not allow a standardised level difference calculation but instead gave an overall indication of the L_{Aeq} value for each DSF in relation to each other.

The abridged results are shown in Table 6.8 and the full data is reported in Appendix 12. The measurements were taken at the locations as set out in Figure 6.12 at floor level in the centre of the DSF (i.e. 400mm from the face of the curtain walling)

Reference	Level	Dw	LAeq	dBA
E3	L4	57	62.2	59
E3	L4	59	64.1	60.9
E2	L4	61	65.9	62.6
E1	L4	68	72.8	69.5
S1	L4	72	76.8	73.6
S1	L4	72	77.1	73.9
S1	L4	72	77.3	74.1
W4	L4	69	73.6	70.4
W4	L4	65	69.9	66.6
W3	L4	62	67.3	64
W2	L4	58	63.3	60.1
W1	L4	54	61.8	57.7

Table 6.8 Summary results of Test 2.

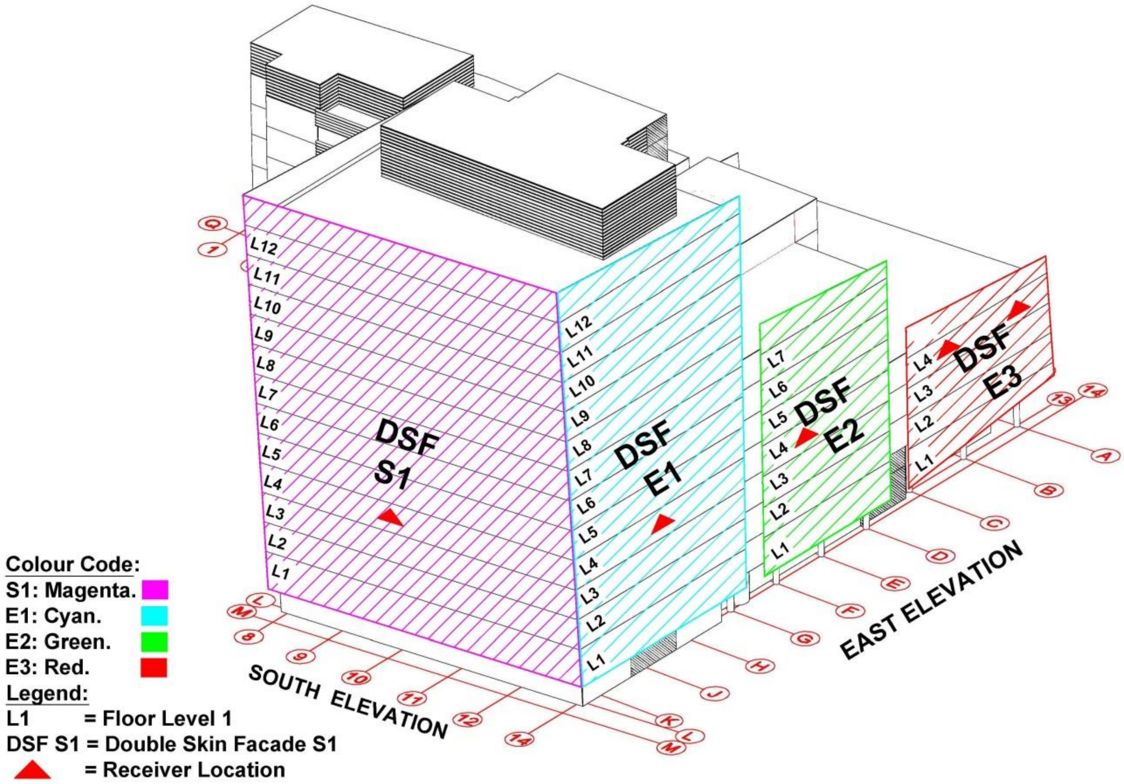


Figure 6.16 Test 2 Receiver Layout

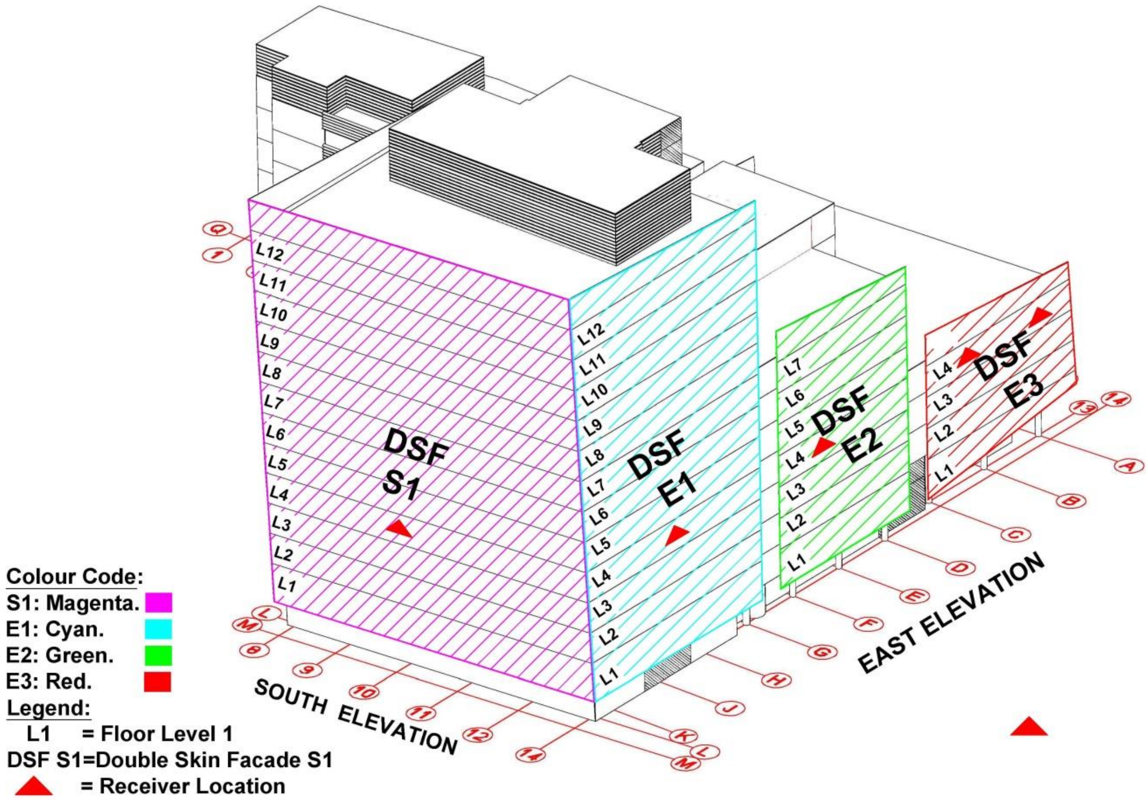


Figure 6.17 Test 2 Receiver locations, South East Corner

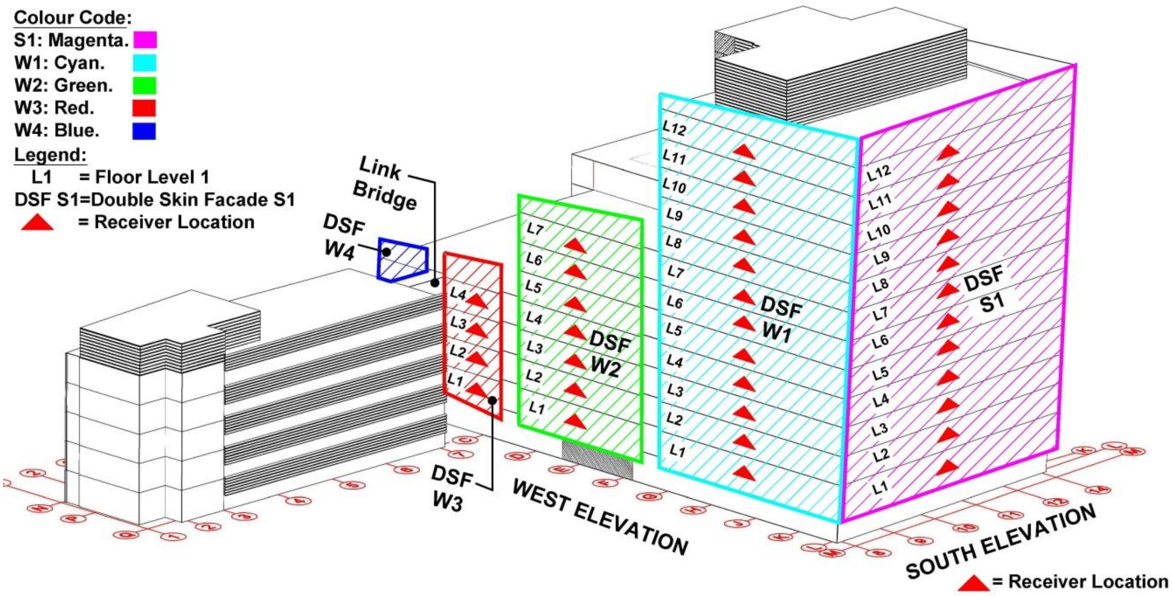


Figure 6.18 Test 2 Receiver Locations, South West Corner

This test resulted in very good data from which parametric modelling could be conducted. It is interesting to note that the level difference between the worst condition (S1 directly beside the main arterial road – figure 6.19) and the best condition (W4 directly behind the link bridge and furthest away from the main arterial motorway – figure 6.20) was 15.5dB.

Figure 6.19 South East corner adjacent main arterial motorway

Figure 6.20 Link Bridge (lowest L_{Aeq} readings taken behind the bridge near the red brick building)

6.2.8.1 SUMMARY OF TEST 2 RESULTS

The test results showed a decrease in SPL as the readings are taken further away from the motorway flyover on the South Elevation. As such the highest SPL levels were on the South Elevation and the lowest were on the West Elevation (W4) behind the link bridge.

This confirms that the link bridge was acting as a barrier to the propagation of sound and as such one would wonder why there is a need for a DSF from an acoustic viewpoint at W4.

The sound level difference between each DSF façade was in the order of 3dB which would be consistent with the line source general rule of a 3 db decay with a doubling of distance. However a more scientific approach would be to analyse the data collected and consider it using common theoretical equations.

The difference between each DSF can be examined when considering the distance from the flyover as the dominant sound source.

Using equation $$Lp = Lw - 20log10 * r - 11dB \quad (3.1),$$

Where L_p = sound pressure at receiver;

L_w = sound power level of source

r = distance between source and receiver

11dB = correction assuming spherical radiation

There is a close relationship with the data collected, allowing for reasonable variations in road traffic levels. S1 was not considered because of the close proximity to the motorway.

The resultant data is tabulated in Table 6.9.

Lp = Lw - 20 log r - 11dB	
Location	Line Source in dB
E3	89.6
W4	89.4
E2	90.3
W3	89.7
W2	91.7
E1	92.3
W1	93.1

Table 6.9 Results from rearranged Equation 6.7

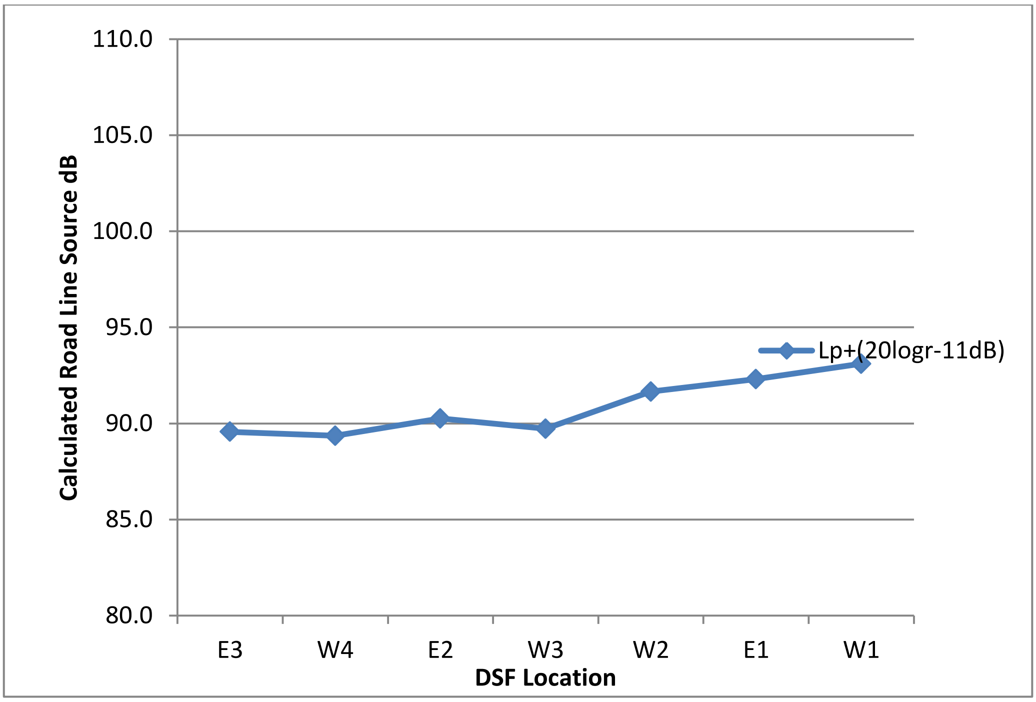


Figure 6.21 Resultant chart using equation 3.1

The resultant values from the equation 3.1 was seen as accurate and validates the data measured and the equation used.

When using a line source it is reasonable to assume variations in road traffic levels up to 3.5dB which was what the results indicated.

The use of barriers were simulated and evaluated in the Chapter 7. Attenuation at the sound point of entry is a worthwhile research topic. If the attenuation is at the bottom of the DSF it may create resistance to airflow however the volumes are so great that it may not be a negative factor.

Test 2 presented data to be compared with the first element in the sound path model illustrated in Figure 1.2. The resultant data validated equation 3.1 with the only questionable aspect of measurement being the consistency of the road traffic sound source.

6.2.9 BUILDING A, LONDON, TESTS 3,4,5 AND 6

6.2.9.1 INTRODUCTION

Tests 3,4,5,6 were carried out using loudspeakers as the source sound. The traffic noise was not sufficient at the time of the testing to satisfactorily test the façade.

A loudspeaker was set up centrally at the bottom of the DSF as the sound source (photo 6.8).

ISO 140-5 states that the loudspeaker source should be 5-7m from the façade however the test procedure needed to deviate and adapt because of site conditions.

The reasons for this deviation from ISO 140-5 are as follows:

- Traffic noise was not sufficient to test effectively - traffic had dissipated after rush hour.
- There was not sufficient distance between the test building and the surrounding roads and buildings to set up the loudspeakers in a safe and proper manner in accordance with ISO 140-5. (see photo 6.19)
- There was a security and safety issue trying to run cables across paths and roadways.
- The decision was made that this method would retrieve accurate data for the decay of sound over distance travelled within the DSF cavity, when repeatability and data acquisition was considered.

Figure 6.22 Setting up loud speakers and calibrating equipment.

- Good simulation and comparison can be made between this method of testing and the resultant data collected, parametric modelling and theoretical calculation.
- There is an element of quick and easy repeatability with this method of testing. This could be utilised when other research is carried out to examine the decay of sound over distance within the DSF cavity on future test sites.

The test consisted of a measurement taken directly above the loudspeaker on each floor for duration of thirty seconds. The measurements were taken in the centre of the DSF in accordance with Figures 6.12 and the distance between floors, and as such, the distance between receivers, was 3.65m.

The data recorded was in the format of L_{Aeq} and was taken across the octave frequency spectrum of 63Hz – 8.0kHz. The D_w and dBa results were also calculated and tabulated for completeness.

6.2.10 BUILDING A, LONDON, TESTS 3

Test 3 was the test on W4 at levels L2, L3 and L4. DSF W4 was the smallest of the DSFs located on the North side of the West Elevation and directly adjacent to the link bridge - see Figures 6.23 and 6.24.

The test was carried out in accordance with the description in section 6.2.8.1 and the abridged results are shown in table 6.10. The full data report is shown in Appendix 13.

The results presented an overall D_w of 8dB. The L_{Aeq} levels were consistent with the other DSFs tested insofar as the L_{Aeq} levels measured were similar to all the other DSFs tested.

The decay of sound over distance was interesting in that the initial decay between the 1st and 2nd receiver was 7dB however for the next doubling of distance the result was 1dB. This result is not consistent with decay of sound for either a point source or line source.

Test 3 - W4 Levels 2-4				
Ref	Level	Dw	LAeq	dBA
W4	Level 2	95	103.3	98.8
W4	Level 3	88	94.9	89.4
W4	Level 4	87	93.3	89

Table 6.10 Summary results from Tests 3

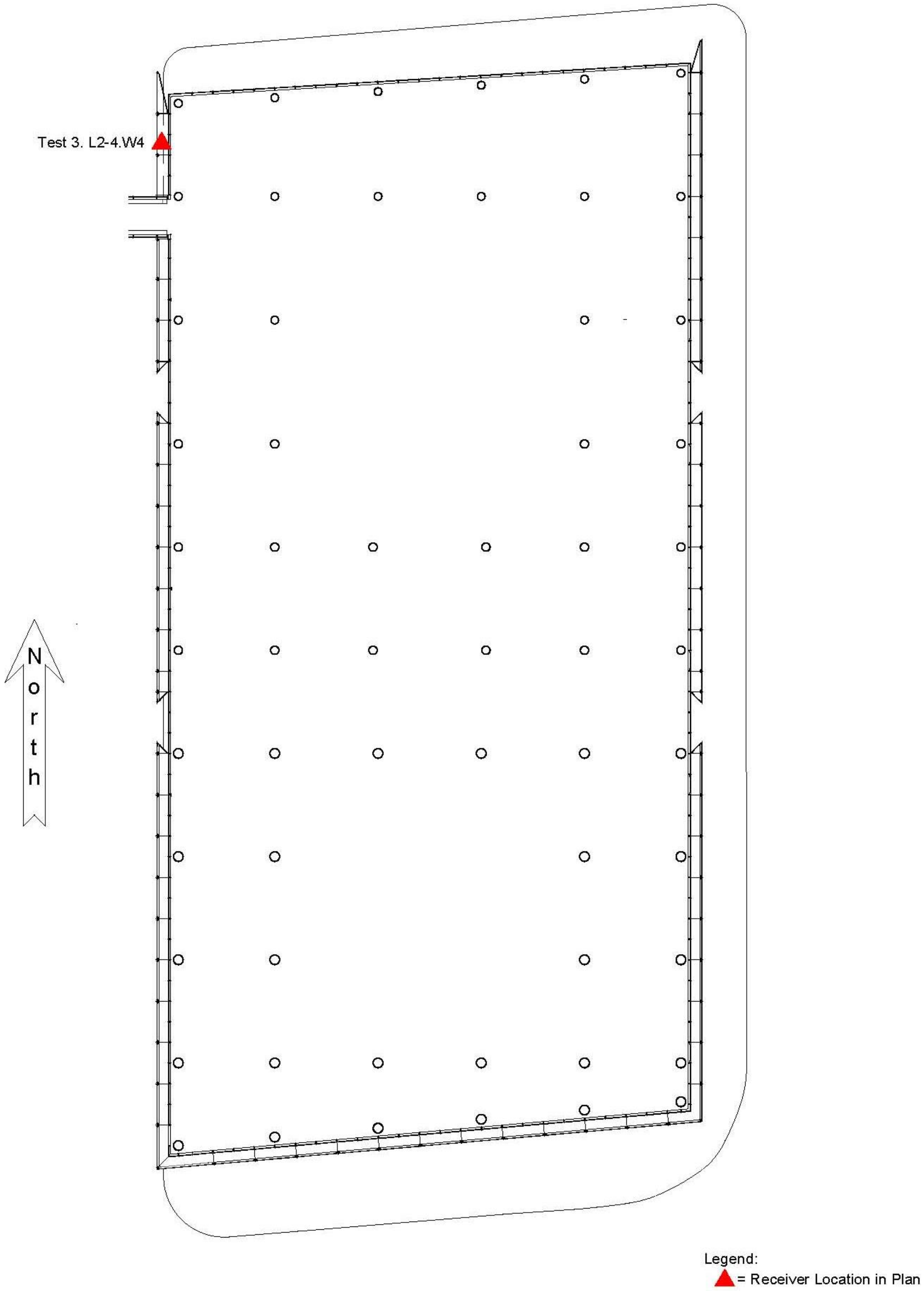


Figure 6.23 Test 3, Plan Layout

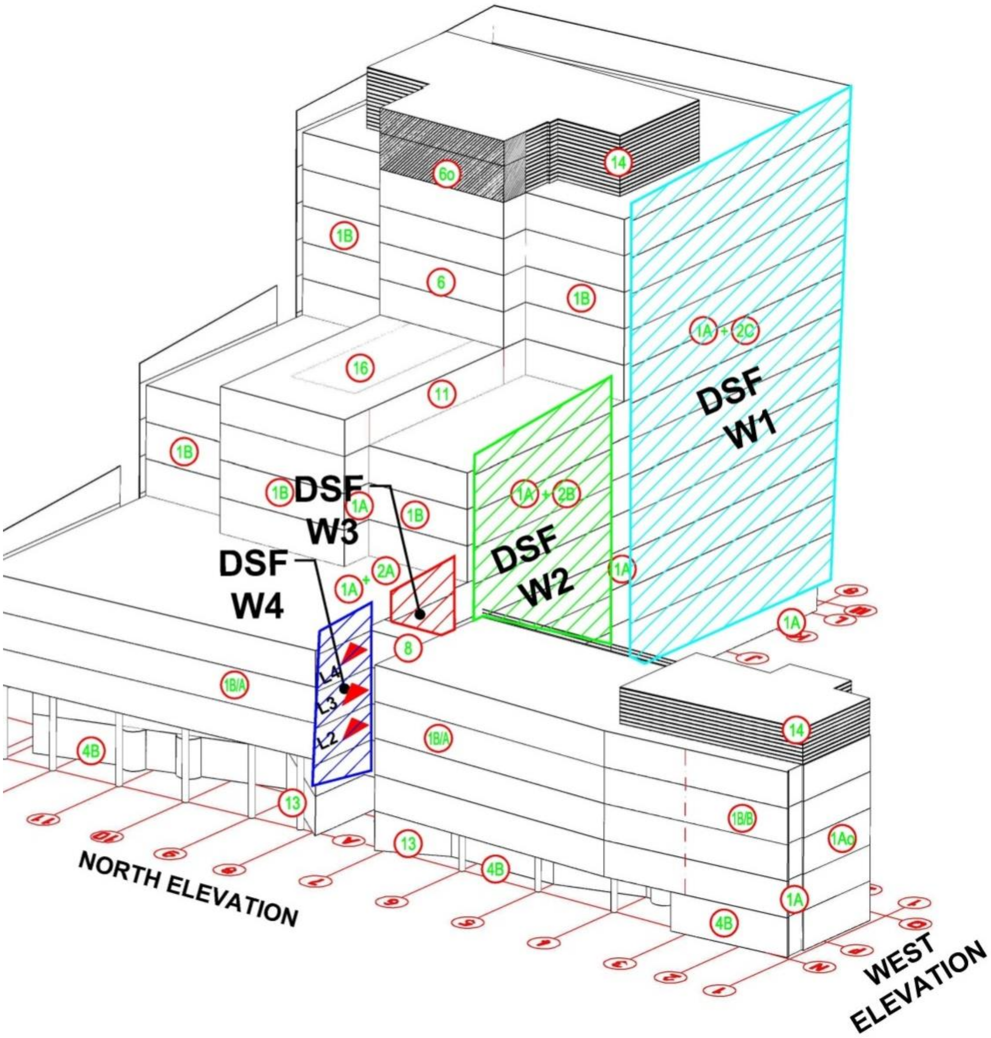


Figure 6.24 Test 3, receiver set out

6.2.10.1 SUMMARY OF TEST 3 RESULTS

Test 3 required more receiver locations to record a larger set of comparative data. The testing procedure itself was good in terms of repeatability for onsite testing of DSFs in urban environments.

The resultant data illustrated an initial large decay of sound (Test 3 being 7dB) with a minimal decay of sound over doubling of distance thereafter – see Figure 6.25.

This result was consistent with the later results of Tests 4,5 & 6, however a larger set of data would have made the result more conclusive.

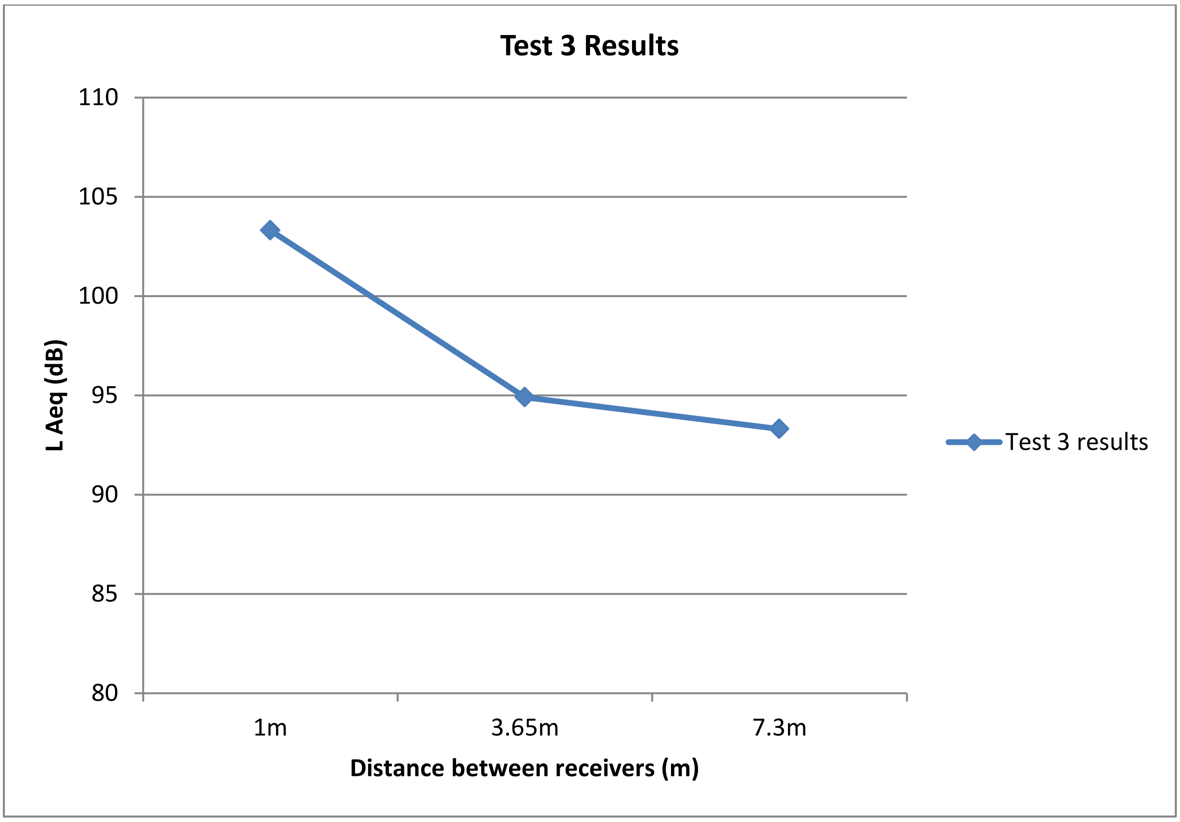


Figure 6.25 Test 3 Results

The minimal decay of sound from the 2nd receiver onwards was not consistent with the anecdotal perception of a DSF giving good sound insulation. There was a 9.8 dB reduction in sound insulation from the bottom of the DSF, Level 2, to the top of the DSF, Level 4.

6.2.11 BUILDING A, LONDON, TESTS 4

Test 4 was the test on W3 at levels L1, L2, L3 and L4. DSF W3 was bigger than DSF W4 but much smaller than DSF 2. It was located on the West Elevation and directly adjacent to the link bridge on the South Side - see Figures 6.26 and 6.27.

The test was carried out in accordance with description in section 6.2.8.1.

The abridged results of Test 4 are shown in table 6.11 and the complete set of data is shown in appendix 13.

Test 4 - W3 Levels 1-4				
Ref	Level	Dw	LAeq	dBA
W3	Level 1	95	103.1	98
W3	Level 2	89	96	90.6
W3	Level 3	87	95.1	90.3
W3	Level 4	87	94.4	88.6

Table 6.11 Test 4 results

As with test 3, the results of test 4 showed an overall D_w of 8dB. The L_{Aeq} levels were consistent with the other DSFs tested insofar as the L_{Aeq} levels measured were similar to all the other DSFs tested.

The decay of sound over distance between the 1st and 2nd receiver was 6dB and 2dB for the next doubling of distance. This was a similar result to Test 3 and a level of consistency was starting to appear between testing regimes.

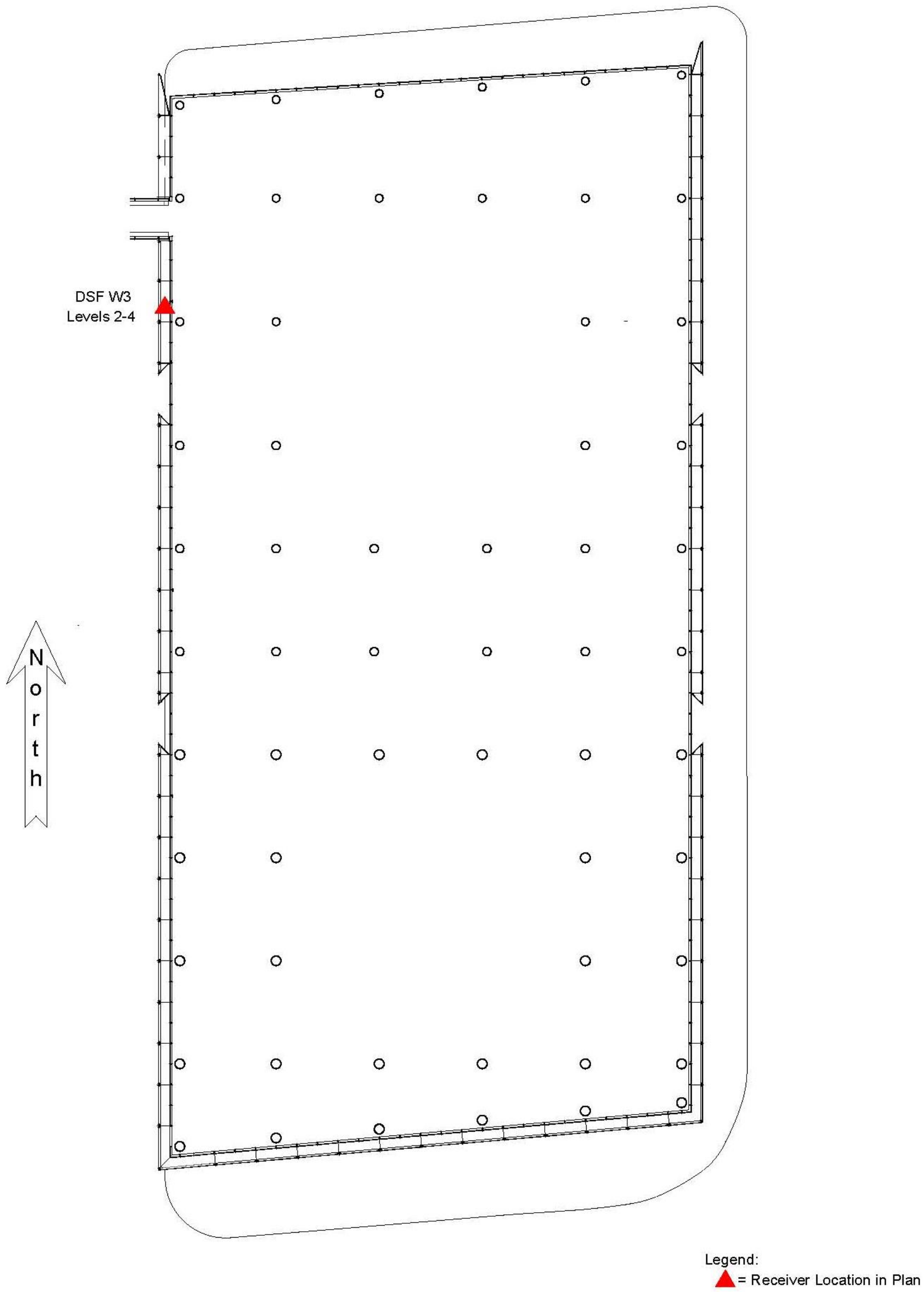


Figure 6.26 Test 4, receiver layout

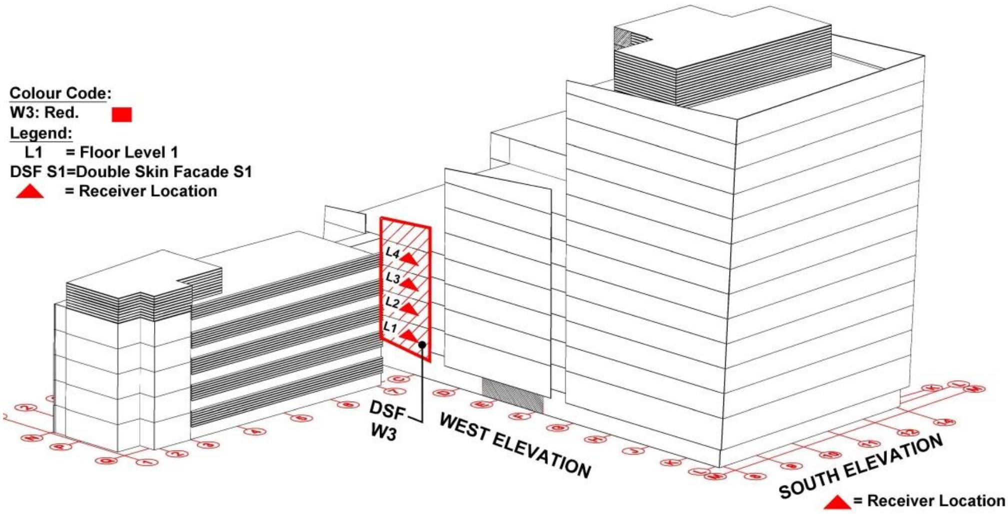


Figure 6.27 Test 4, West Elevation - receiver location

6.2.11.1 TEST 4 - CONCLUSION

Test 4 required more receiver locations to record a larger set of comparative data. The tests only had 1 receiver at each floor level and 3-4 receiver points would have given a much more comprehensive set of data. As was stated in Test 3, the testing procedure itself was good in terms of repeatability for future onsite testing of DSFs in urban environments.

The resultant data illustrated an initial large decay of sound (Test 4 being 6dB) with a minimal decay of sound over doubling of distance thereafter – see Figure 6.28.

This result was consistent with the results of Tests 3,5 & 6, however a larger set of data would have made the result more conclusive.

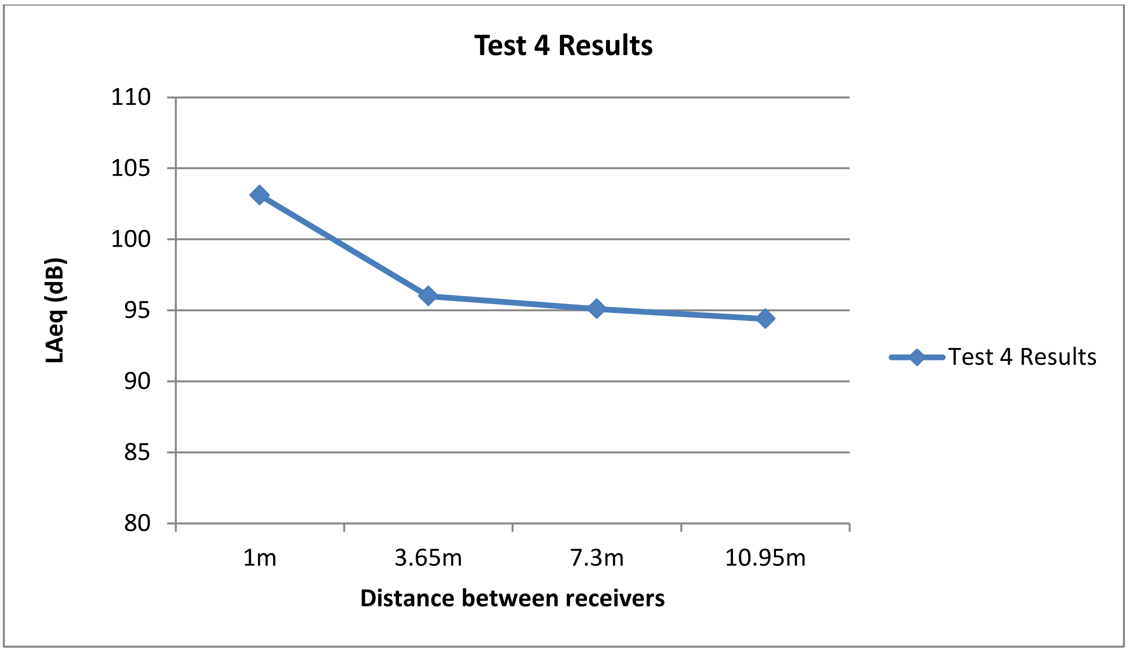


Figure 6.28 – Test 4 results

There was a 9.4 dB reduction in sound insulation from the bottom of the DSF, Level 1, to the top of the DSF, Level 4. W3 (124m³) was twice the volume of W4 (62m³) with the same decay of sound. This result may have been affected by a lack of measured data. It was also not consistent with the perceived and expected result.

6.2.12 BUILDING A, LONDON, TEST 5

Test 5 was the test on W2 at levels L1 – L7. The volume of DSF W3 is 409m³ and it is over 3 times larger than W3. It is located centrally on the West Elevation - see Figures 6.29 and 6.30.

The test was carried out in accordance with description in section 6.2.8.1.

The abridged results of Test 4 are shown in Table 6.12 and the complete set of data is tabulated in appendix 13.

Test 5 - W2 Levels 1-7				
Ref	Level	Dw	LAeq	dBA
W2	Level 1	96	103.8	98.5
W2	Level 2	88	95.8	89.2
W2	Level 3	87	93	89.3
W2	Level 4	84	90.4	85.5
W2	Level 5	82	87.7	83.1
W2	Level 6	82	87.7	83.3
W2	Level 7	81	87.2	82.8

Figure 6.12 Test 5 Abridged Results

As with test 3, the results of test 4 showed an overall D_w of 15dB. The L_{Aeq} levels were consistent with the other DSFs tested insofar as the L_{Aeq} levels measured were similar to all the other DSFs tested.

The decay of sound over distance between the 1st and 2nd receiver was 9dB and for the next doubling of distance the results were 1dB and 6dB. This was a similar result to Tests 3 & 4 and continued the level of consistency between testing regimes.

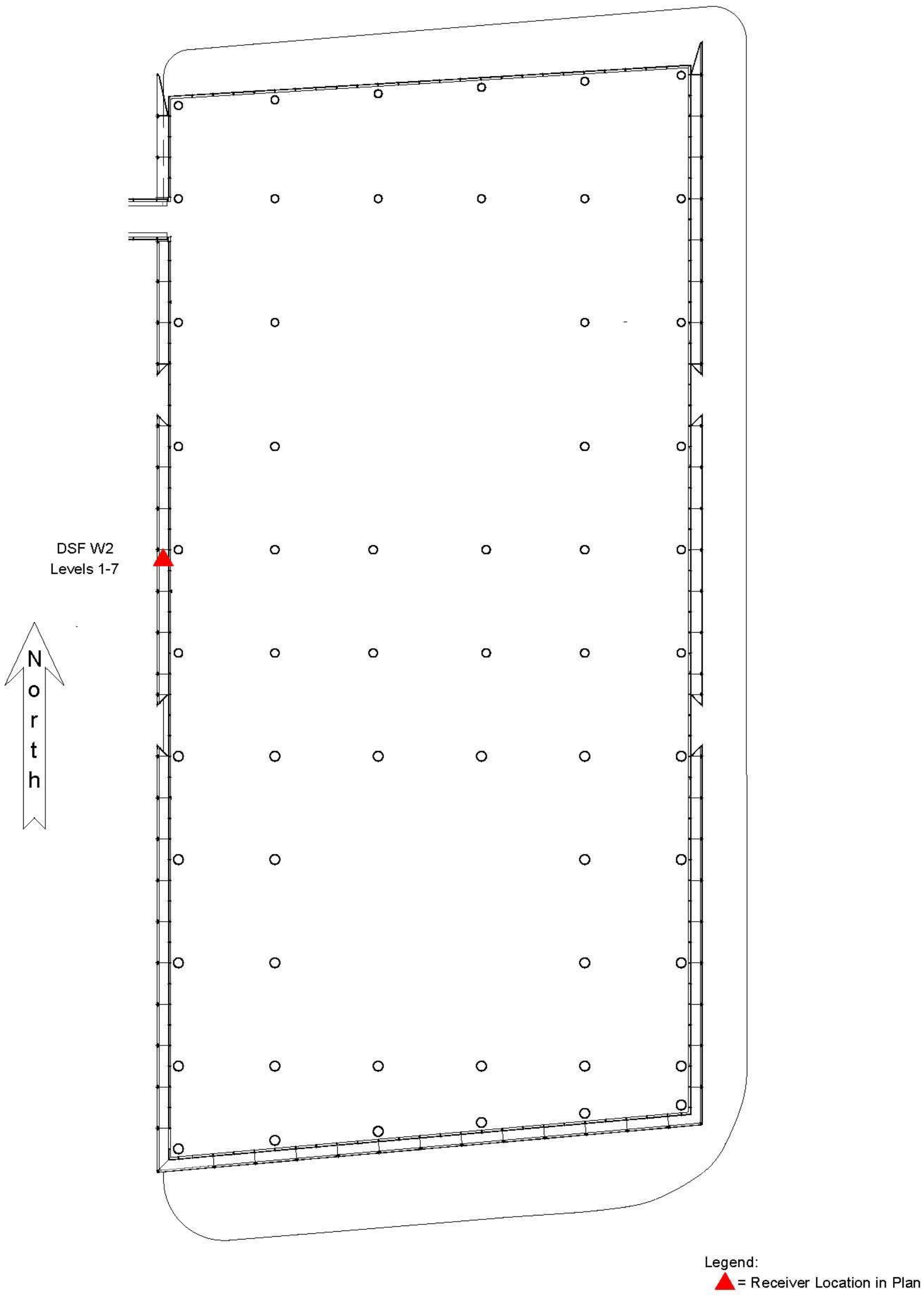


Figure 6.29 – Test 5, Plan receiver set out

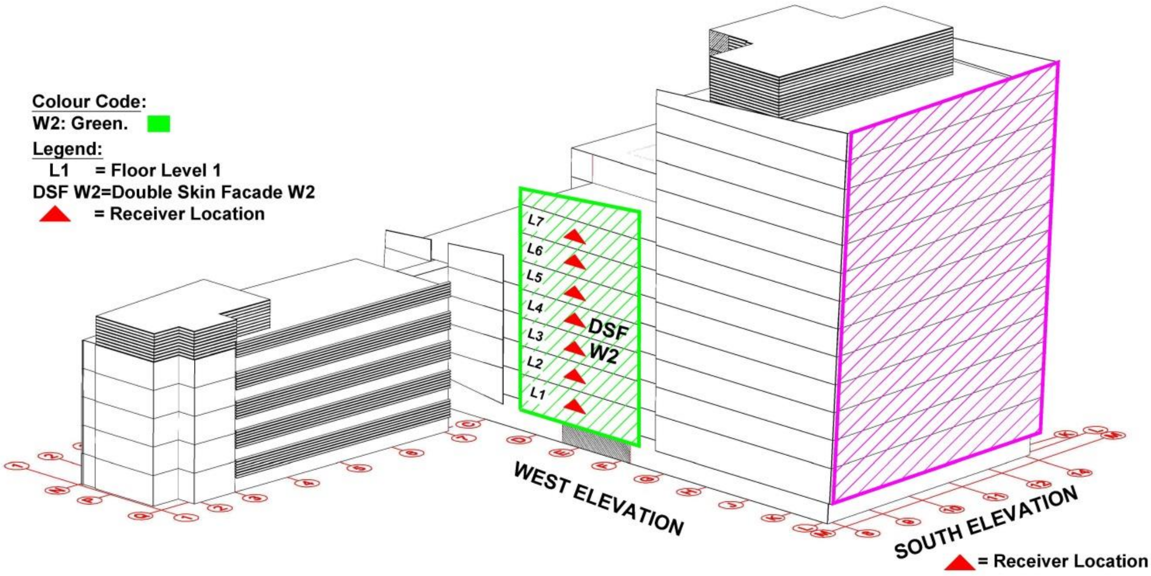


Figure 6.30 – South West Corner, Test 5, receiver set out

6.2.12.1 SUMMARY OF TEST 5

As was stated with tests 3 & 4, test 5 required more receiver locations to record a larger set of comparative data. The tests only had 1 receiver at each floor level and 3-4 receiver points would have given a much more comprehensive set of data. The testing procedure itself was good in terms of repeatability and shows good signs in consistency between tests.

The test 5 resulting data illustrated an initial large decay of sound (Test 5 being 9dB) with a minimal decay of sound over doubling of distance thereafter until level 5 where there was a 6dB drop– see Figure 6.31.

This result was consistent with the results of Tests 3 & 4 with the exception of level 5. This cannot be compared to tests 3 and 4 as it occurs outside the size limits for W4 and W3.

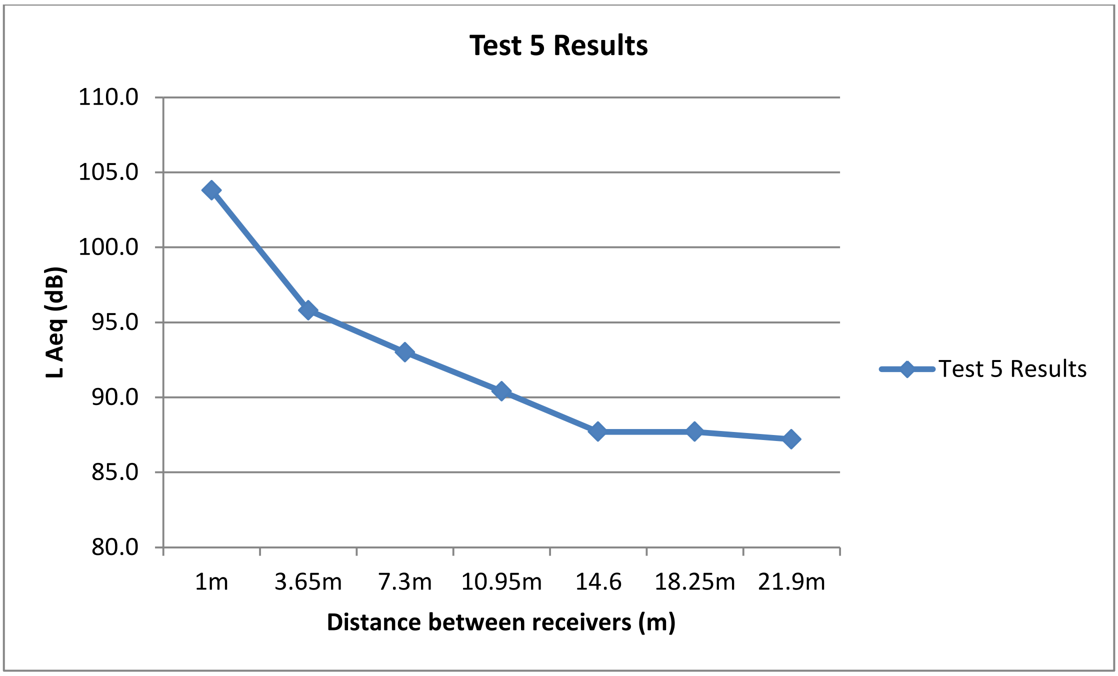


Figure 6.31 Test 5 Results

It was noticeable that there is a minimal decay after Level 5 (14.6m). The initial decay was consistent with Tests 3 and 4.

It is now very apparent that more receiver points on each test would have resulted in very comprehensive comparative data.

6.2.13 BUILDING A, LONDON, TESTS 6

Test 6 was the test conducted on S1 at levels L1 – L12. The volume of DSF S1 was 1460m³ and it was the largest DSF. It was located centrally on the South Elevation facing the flyover - see Figures 6.32 and 6.33.

The test was carried out in accordance with description in section 6.2.8.1.

There were two sets of data taken on S1 to verify the data recorded. The results shown in table 6.13 are a logarithmic average of the two sets of data to weight the results and the complete set of data is shown in appendix 13.

The same criticism is levelled at this test as was made for tests 3,4 and 5 – more receiver points would have produced a better comparative study.

Test 6 - S1 Levels 1-12				
Ref	Level	Dw	LAeq	dBA
S1	Level 1	102	109.5	104.4
S1	Level 2	93	103.4	96.3
S1	Level 3	90	97.3	93.8
S1	Level 4	88	97.1	90.8
S1	Level 5	88	97.9	92.1
S1	Level 6	86	94.9	88.8
S1	Level 7	85	93.0	87.7
S1	Level 8	84	94.3	88.4
S1	Level 9	84	91.4	86.4
S1	Level 10	83	90.2	85.8
S1	Level 11	82	89.1	84.7
S1	Level 12	81	88.2	84.3

Table 6.13 Test 6 Abridged Results

S1 has an overall D_w of 21dB. The L_{Aeq} levels were consistent with the other DSFs tested insofar as the L_{Aeq} levels measured were similar to all the other DSFs tested.

The decay of sound over distance between the 1st and 2nd receiver was 8dB and then 2.5dB, 3dB, 2.5dB and 2dB for the subsequent measurements at doubling of distance. There is an anomaly at Level 5 of -1dB and this may have been due to instrument error. This is the precise reason for having more receiver points during testing – to level out instrument error.

The results from test 6 are more consistent with line source sound decay expectation.

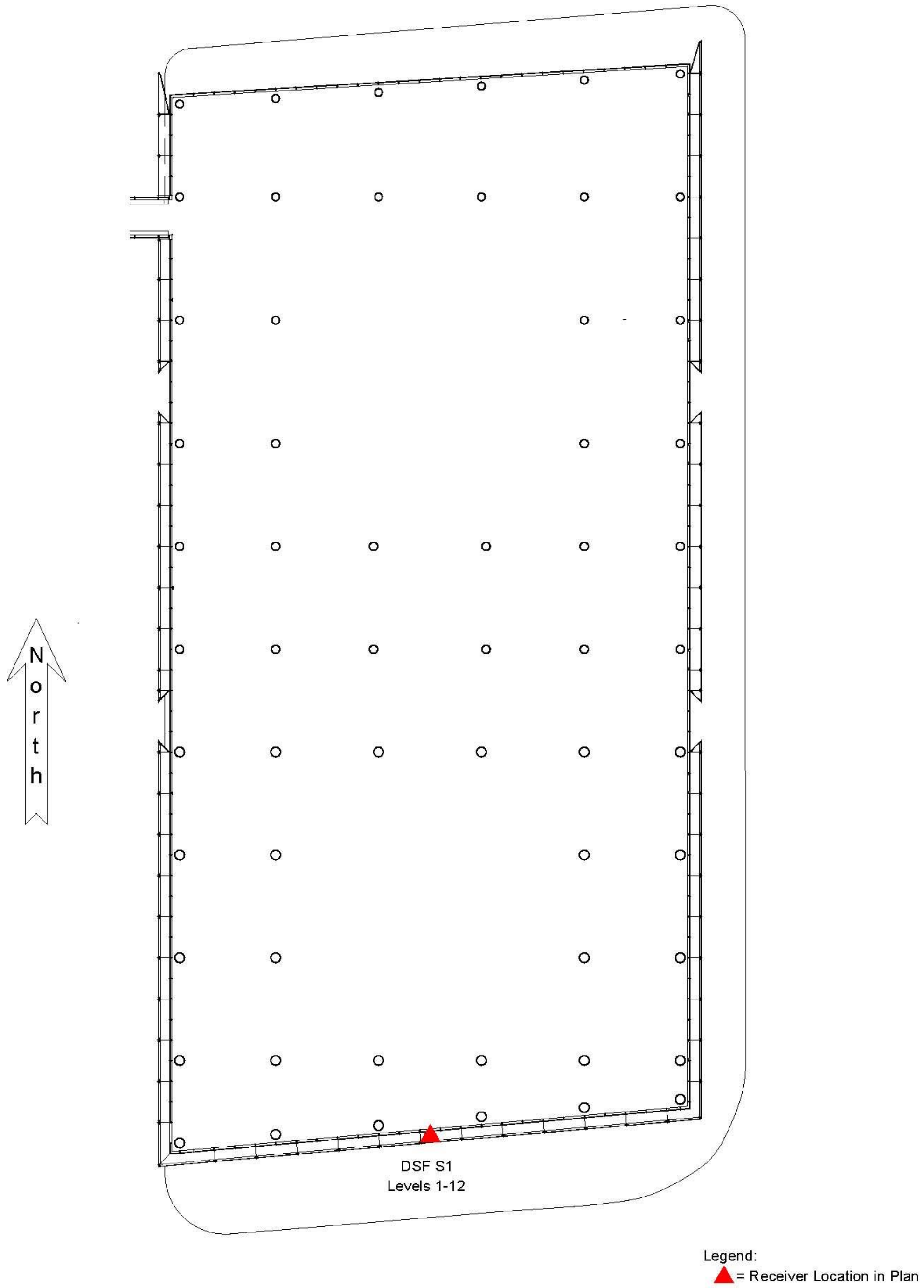


Figure 6.32 Test 6, receiver plan layout

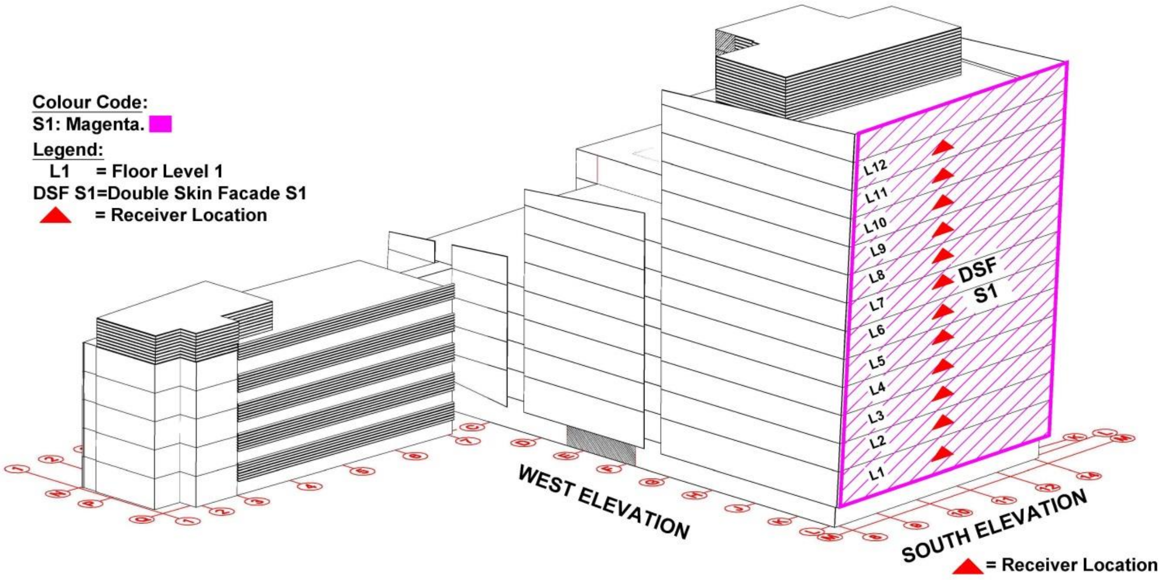


Figure 6.33 South West corner, receiver set out

6.2.13.1 SUMMARY OF TEST 6

As was stated with tests 3,4 & 5, test 6 required more receiver locations to record a larger set of comparative data. All of the tests only had 1 receiver at each floor level and 3-4 receiver points would have given a much more comprehensive set of data. The testing procedure for test 6 was good in terms of repeatability and showed good signs of consistency between tests. The only exception to this was the anomaly in results at level 5. If more receiver points were used at each floor level, the results would identify and level out measurement error.

The test 6 resultant data illustrated an initial large decay of sound (Test 6 being 8.1dB) with a consistent decay of sound over doubling of distance thereafter – see Figure 6.34.

This result was consistent with the other results of Tests 3, 4 & 5 with the exception of level 5. The curves produced on graph were very similar to tests 3,4 & 5. Figure 6.35 shows the results from tests 3,4,5 & 6 and there was consistency in the results.

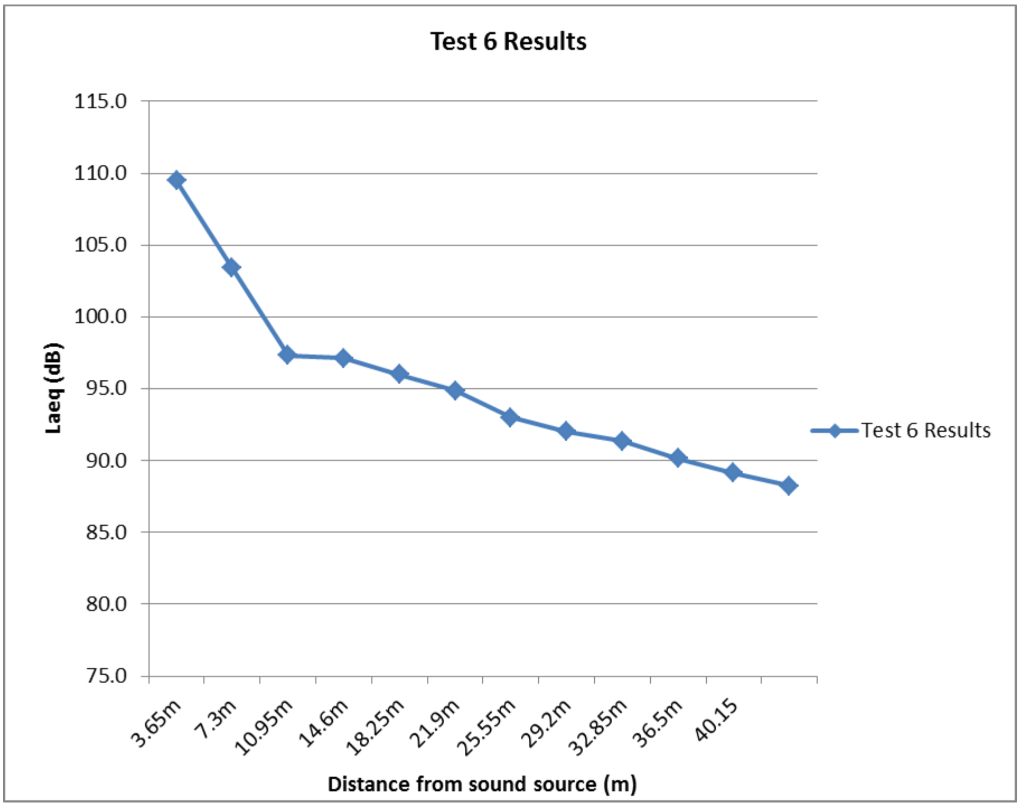


Figure 6.34 **Results graph for Test 6.**

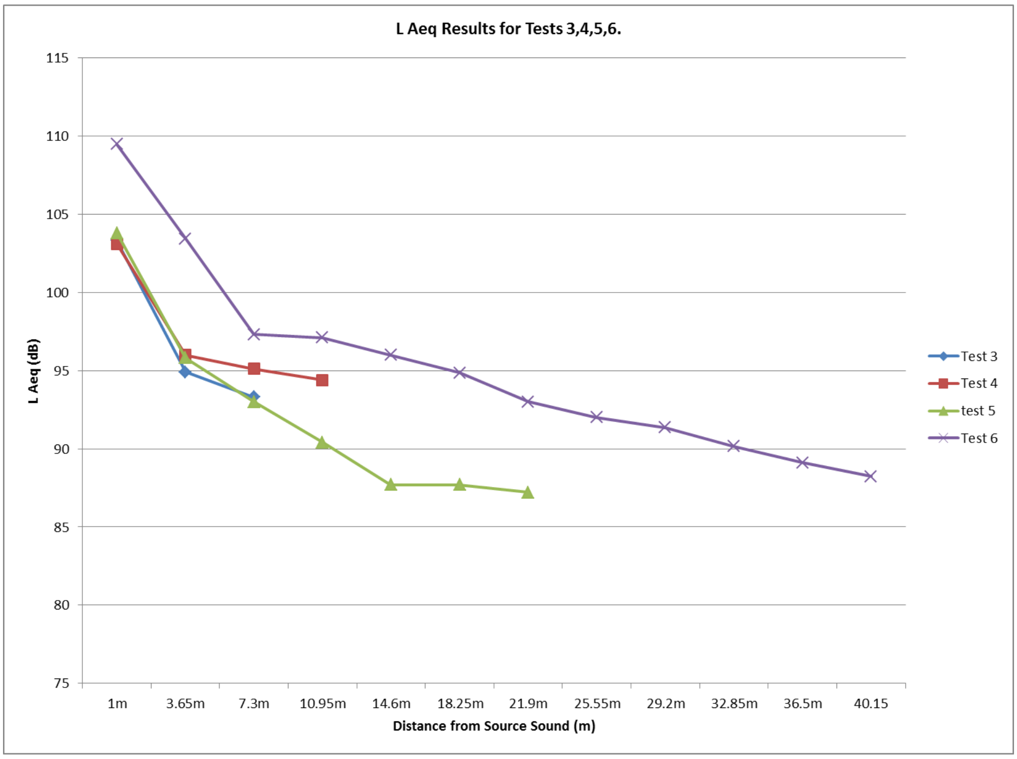


Figure 6.35 **Summary Results graph for Tests 3,4,5 & 6.**

6.2.14 BUILDING A, LONDON, TEST 7 - REVERBERATION TIME

Test 7 was a reverberation test to establish the reverberation time in the DSF cavity. The DSF's tested are shown on figures 6.36, 6.37 and 6.38. The DSFs had varying volumes due to the different widths and heights. Reverberation time is defined as the time taken for the sound energy produced by a source to decay by 60dB after the sound source has been switched off (SRL 1988).

The equipment used was an Olympic 6, 8 shot, 6mm calibre gun and the procedure was to fire the gun and simultaneously record the decay of sound over time. A random selection of DSF receiver locations was chosen. This was the last test to be undertaken due to the sharp and intense sound created by the gun.

The summary data is tabulated in table 6.14

Reverberation Results Test 7	
Reference	T20 (secs)
W3 1st Floor	0.9
W2 1st Floor	0.8
S1 1st Floor	0.8
W1 2nd Floor	0.6
W3 3rd Floor	0.9
W2 4th Floor	0.7
W1 4th Floor	0.7
S1 4th Floor	0.9
W3 7th Floor	0.9
S1 8th Floor	1.0
S1/E1 8th Floor	0.9
S1 12th Floor	0.9
S1/E1 12th Floor	0.8

Table 6.14 Test 7, Reverberation Time Results

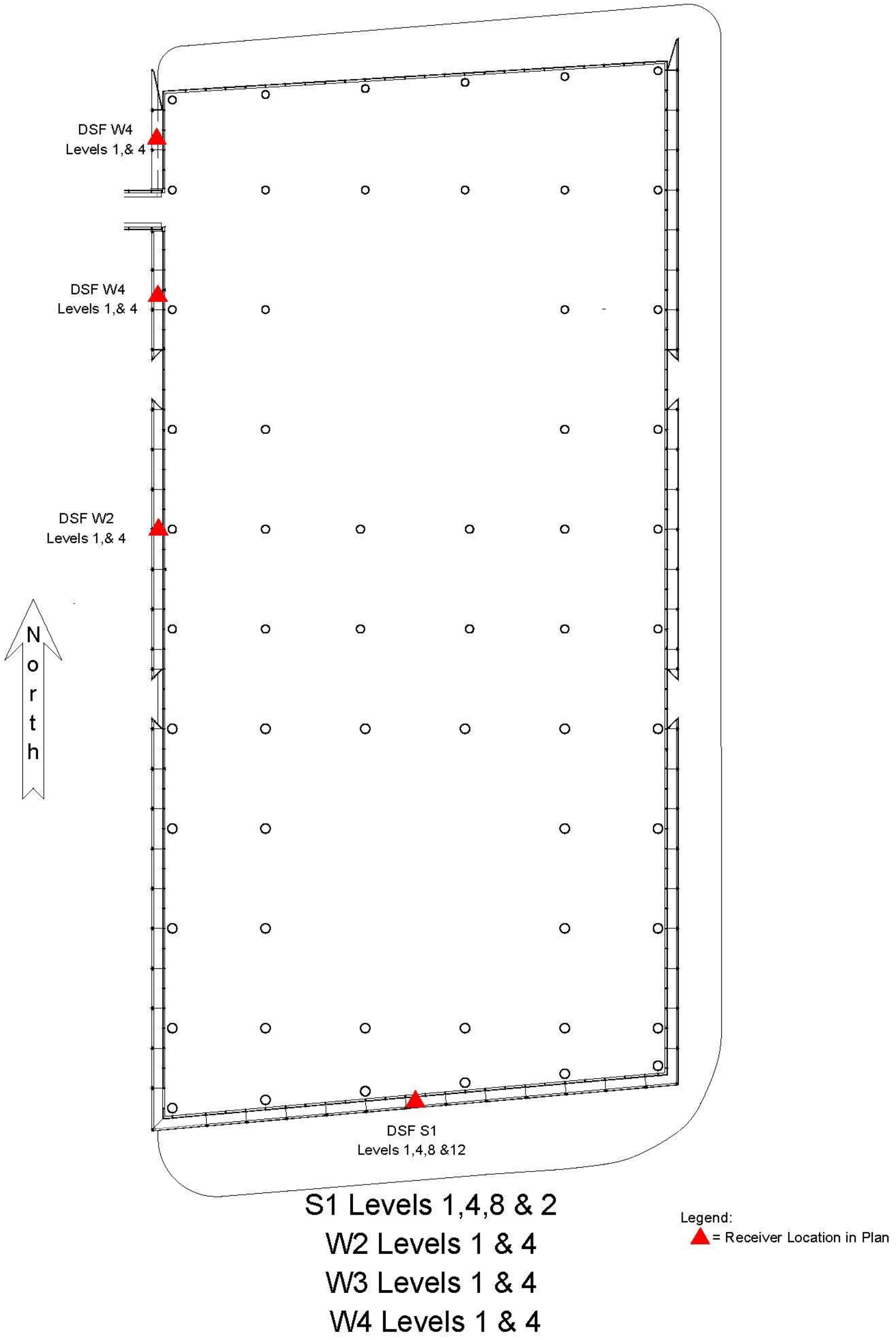


Figure 6.36 - Test 7, Reverberation, Plan set of W1, W2, W3, S1

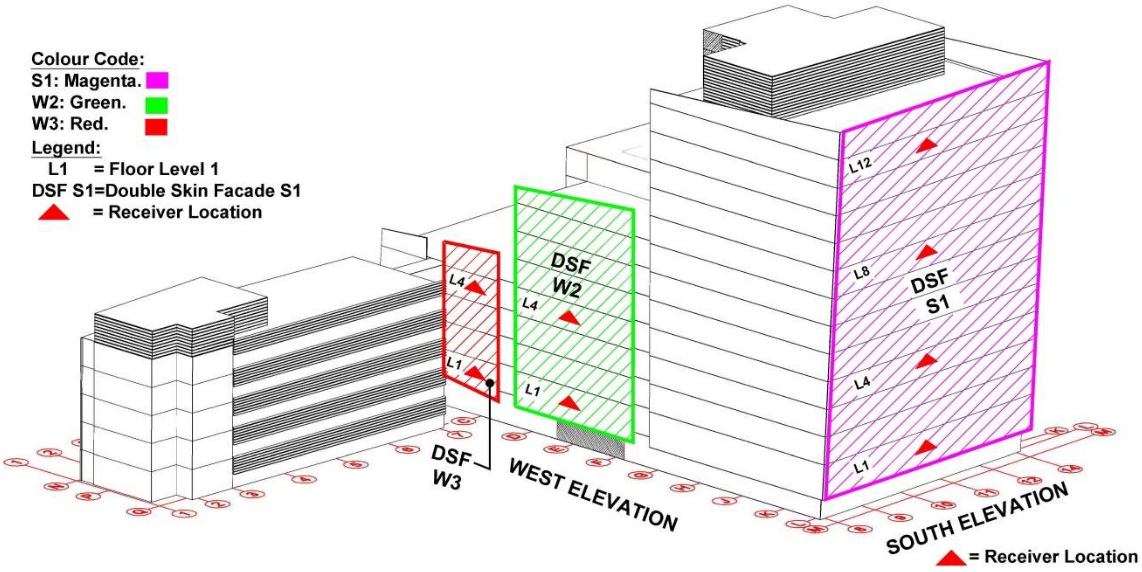


Figure 6.37 - TEST 7, Reverberation, South West Corner, receiver set out

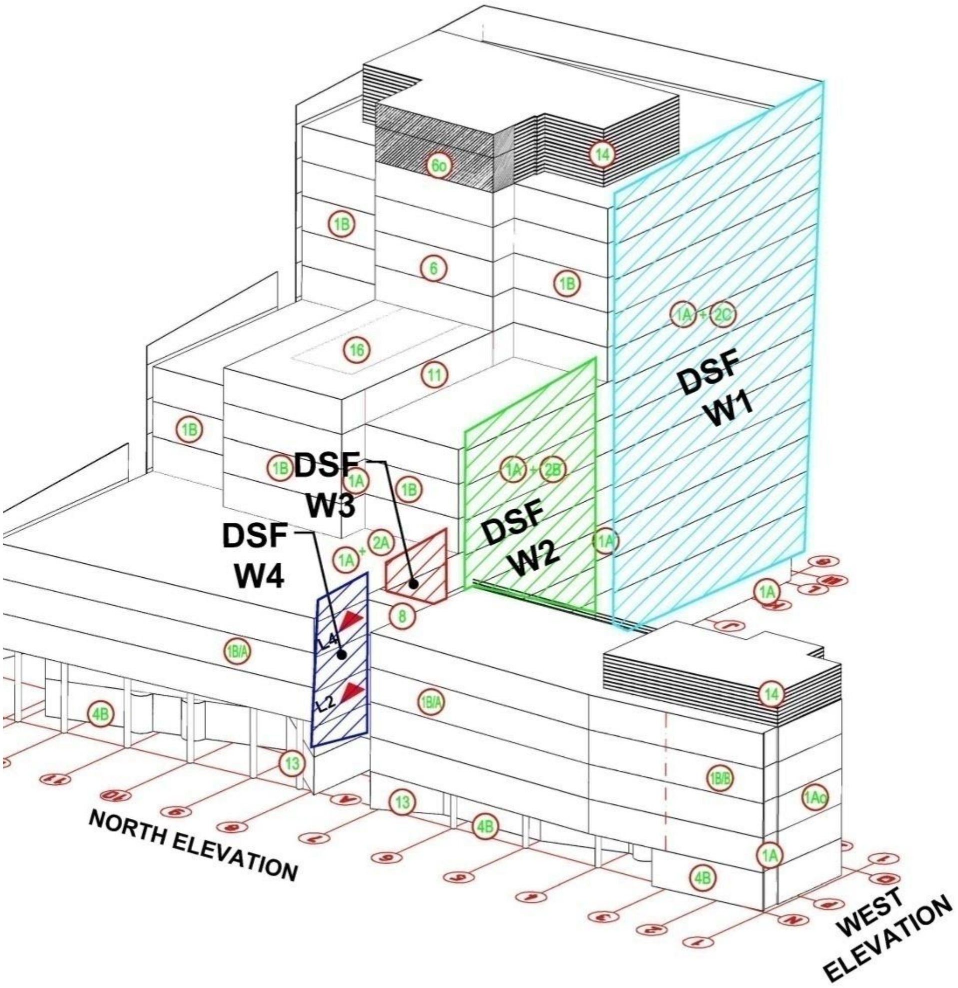


Figure 6.38 - TEST 7, Reverberation, North Elevation, receiver set out W4

6.2.14.1 SUMMARY OF TEST 7 – REVERBERATION TEST

The reverberation test results were contrary to expectation prior to testing. The assumption made before the test was that the NV DSF would be reverberant and, in some manner, would be proportional to the DSF volume. This would follow the relationship developed by W.C. Sabine in Sabine's Formula of:

$$\text{Reverberation Time (R.T.)} = \frac{0.163V}{S\propto} \text{ seconds,} \qquad (6.1)$$

Where, V = room volume (m³), S = room surface area (m²) and $\propto$ = mean absorption coefficient.

This is assuming a diffuse sound field which the DSF is not and the DSF condition is more accurately illustrated by a formula devised by Eyring:

$$\text{R.T.} = \frac{0.163\,V}{-S\,loge(1-\propto)} \text{ seconds.} \qquad (6.2)$$

The Eyring formula reflects a relationship to volume and to material absorption co-efficient. A reverberation time of 1 - 2.5 seconds would not have been unreasonable for Test 7 however the results indicated otherwise.

The results showed a reverberation time in the range of 0.6 – 1.0 seconds. The premise of the smaller volume having a smaller reverberation time holds true in that W4 was 0.6 seconds and S1 was 1.0 second.

The volume of W3 was 124m³ and S1 was 1459m³ (the full table of volumes is given in Table 6.15). When the reverberation data is examined, the relationship of volume to reverberation time is not consistent when assuming all other variables are a constant. The assumption of a constant holds true in that all the materials within the DSF are similar and so the only variables that change are surface area and hence volume. This is an important finding and completely contrary to expected findings.

The DSFs are not reverberant which means that the direct field is dominant, and to some degree, the reverberant sound field becomes less influential.

Using the equation for establishing the reflected field (SRL 1988)

$$Lp\ (direct) = Lw + 10\ logT - 10logV + 14dB \qquad (6.3)$$

And, assuming the direct field as a constant (from the reverb gun), the calculated reflected values are:

S1 46.3dB

W1 45.2dB

W2 41.6dB

W3 36.9dB

The level difference in the reflected field between the largest DSF S1 (1459m³) and the smallest DSF tested for reverberation time W3 (124m³) is 9.4dB.

DSF Volume Calculation				
Reference	Width (m)	Height (m)	Depth (m)	Volume (m^3)
S1	39.65	46	0.8	1459.12
W1	29	46	0.8	1067.2
W2	18.4	27.8	0.8	409.216
W3	9.35	16.6	0.8	124.168
W4	5.975	13	0.8	62.14
E1	27	46	0.8	993.6
E2	18.4	27.8	0.8	409.216
E3	20	16.6	0.8	265.6

Table 6.15 Volume Calculation for Each DSF

It must be assumed then that the area of absorptive material does have a direct relationship on the reflective field over and above Sabines (7.2) and Eyrings (7.3) formulae.

If an average is taken of all the data measured (volume, RT and calculated reflective field) the formula reverts to:-

$$Lp\ (direct) = Lw + 10\ logT - 10logV + 14dB + K,$$

K, being calculated for the data taken, as 0.9 (6.4)

This is an important conclusion which needs to be supported by further research work.

6.2.15 CONCLUSION FOR TESTING CAMPAIGN OF BUILDING A, LONDON

The testing campaign of Building A, London was successful in many respects. It captured important and interesting data, some of which was completely contrary to expectation. The data that has been collected to date starts an important process in the evaluation of the acoustic characteristics of NV DSFs.

There are aspects of the campaign that could have been carried out differently and they will be highlighted in this conclusion.

6.2.15.1 EQUIPMENT AND LOCATION

The equipment used for acoustic testing is expensive. However this testing campaign has highlighted the need for more measurement equipment to be used. In this campaign, only 1 or a maximum of 2 measurement locations were used at each floor level on a test. This was far too few measurement points and a suggested distance between points in the horizontal axis would be 2 - 4m. This would have resulted in 7 receiver points on S1 in contrast to the 2 receiver points used. The increase in sensor location would have improved the sample size sufficiently to examine anomalies in measurement and produce a more accurate selection of data. For instance, the anomaly in measurement at level 5 in Test 6 may have been averaged out with another 5 receiver points. The use of more than one receiver location requires a logarithmic average to be calculated for each location.

An increase in the number of sensor locations results in more cost, more personnel to operate the equipment and a longer timeframe to conduct the test campaign. These are not constraints rather considerations to be taken into account in future testing campaigns.

The equipment used on this test campaign was adequate and most acoustic measurement sensor devices operate across the full frequency spectrum necessary for testing DSF’s. The Norsonic sensors used on this campaign are at the upper end of the quality range.

6.2.15.2 MEASUREMENT PROCESS

Acoustic field testing is challenging and this campaign has highlighted some of the challenges that can be encountered. A perfect scenario would have been to test in accordance with standard norms and analyse in the same way.

The British Standards specify $D_{tr,2m,nT}$ or $D_{ls,2m,nT}$ as the test measurement criteria based on a specific set of procedures. However, site conditions dictated that this testing regime was not possible. Instead, $L_{Aeq,}$ D_w and dBa values have been used and calculated from measurements taken for a 30 second duration.

In general terms, acoustic testing is concerned with comparisons:

- One environment to the other (outside to inside)
- One building to another, to a standard or reference value.
- One glazing system to another

The use of $L_{Aeq,}$ D_w and dBa values is adequate and sufficient for comparison purposes with DSF's. Given the different challenges that site testing in an urban environment may bring, it is reasonable to assume that there may be many circumstances where $D_{tr,2m,nT}$ and $D_{ls,2m,nT}$ may not be used and as such $L_{Aeq,}$ D_w and dBa may even be more suitable for research purposes.

6.2.15.3 SAMPLE AND RECORD RATE

In general, during this campaign of testing, measurements were taken for duration of 30 seconds to capture data. The Norsonic recording devices can record in increments of 1 second up to 3 hours.

The obvious consequence of increasing the recording rate is to increase the overall testing timeframe. It will give a better indication of consistency in noise levels.

However, in hindsight, a better strategy would be to repeat the test as was carried out in test 6. The suggested test procedure would be to repeat each test three times, at the original record rate of measuring at a 30 second duration, and take the algorithmic average of the data measured.

6.2.15.4 DATA ANALYSIS / PROCESSING

Each proprietary sensor had a dedicated memory and software package to convert the captured data to a meaningful set of information.

The Norsonic 181 and 131 both converted the data captured to spread sheet format across the octave and third octave band spectrum.

The data can is then interpreted in accordance with ISO 717-1 and ISO 717-2.

There must be a measure of repeatability which is quite difficult with acoustic testing. In view of this and the inherent challenges of testing in an urban environment, the use of $L_{Aeq,}$ D_w and dBa can be seen as a positive.

If there is the opportunity to obtain $D_{tr,2m,nT}$ and $D_{ls,2m,nT}$, then that is an exceptional result, however it may decrease the likelihood of repeatability.

It is essential that reverberation time is measured as that is a necessary element of calculating D_w in accordance with ISO 717-1 and also generating comparison to the reference curve in Figure 6.9.

6.2.15.5 SUMMARY

The testing campaign was conducted in a competent and professional manner and largely in accordance with best practice. Some of the findings were surprising and offer the opportunity to challenge the conventional views of acoustic performance of NV DSF’s.

The research conducted offers the opportunity to challenge and examine the current parametric methods in acoustic prediction and assess their suitability for use with NV DSFs in Chapter 7, Parametric analysis of double skin façades.

CHAPTER 7

PARAMETRIC ANALYSIS OF DOUBLE SKIN FAÇADES

7.1 INTRODUCTION

The aim of this research is to utilise the predictive acoustic modelling techniques selected in chapter 4, and simulate models based on tested façades from Chapter 6. As described in earlier chapters, the analysis of the sound pressure level has been broken into different elements of the sound path through the DSF. This same procedure is being followed in this chapter so that comparisons, similarities or contrasts can be found with the field testing that has been described in chapter 6.

The software that has been chosen to simulate the façade s are CADNA (Element 1) and CATT (Element 2 and 3).

7.2 ELEMENT 1 (SOURCE TO DSF) – CADNA

Element 1 as shown in Figure 1.2 is the sound path from the sound source to the DSF. In this research the sound path is from a motorway to the DSF, shown in Figure 6.1 – site layout in Chapter 6. The best method of predicting acoustic levels on the face of the DSF is by noise mapping. The description of noise mapping is given in Chapter 3.3.3.

CADNA gives the opportunity to either build a model from first principles or import a plan of the area from another digital source and build the model over that plan. The sound sources are entered from noise data acquired at the model site or an estimate of the sound source.

In this research, a model has been built of the test building from the site layout and section drawings. The test building, Building A, London, and the surrounding buildings were modelled on a combination of site plan, site dimensions and google maps in 3D with all buildings heights inputted from the same information sources.

The resultant model is shown in figure 7.1 with the site outline still included. The colour contour map should be read in conjunction with the colour legend to verify noise levels. The colour legend is a software default setting and as such blue represents noise levels >75dB, red (60dB) and amber (55dB).

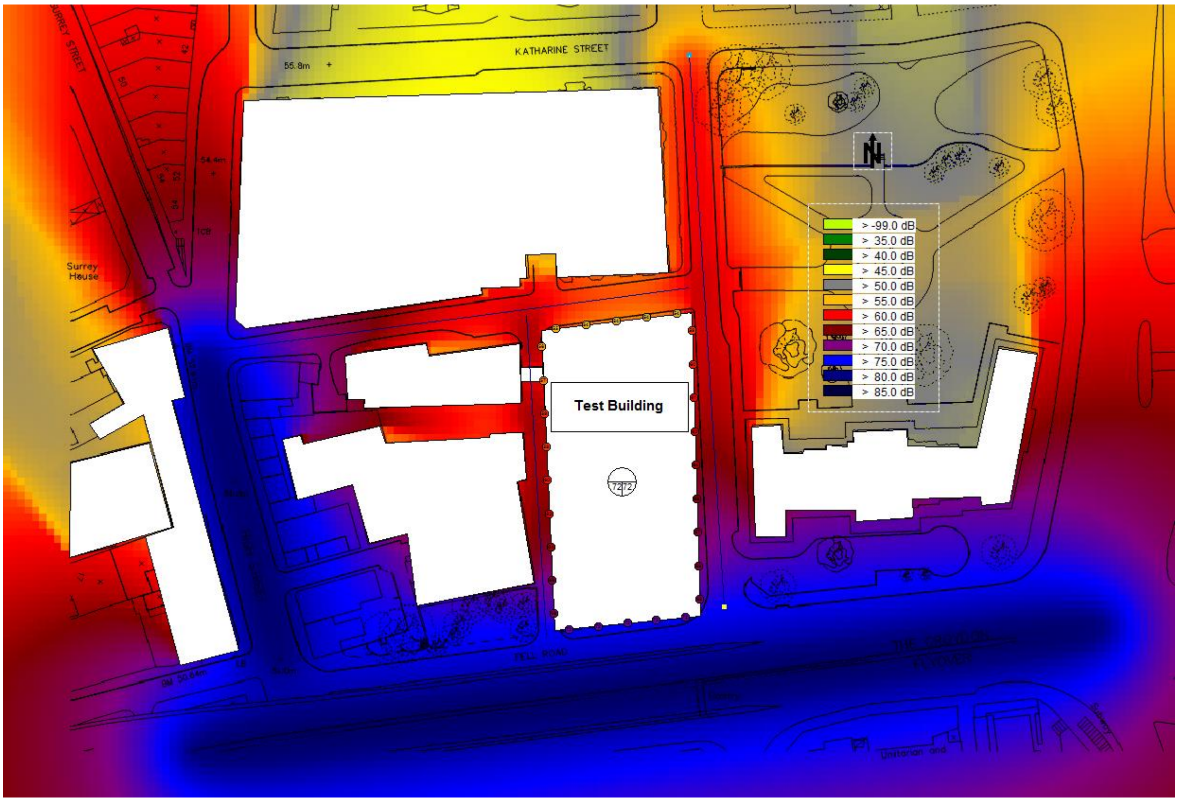


Figure 7.1 Noise Map and Test Building Model

CADNA allows the user to place predictive receivers on the building with x, y and z co-ordinates. In this way, the predicted noise levels can be indicated at every level on the building.

In Chapter 6, field testing, both test 1 and test 2 used road traffic as the sound source. These two tests offered the opportunity to compare the field test and the parametric model data. The simulated results are given in dBA and as such it was imperative that the comparative field test figure used was a dBA value.

7.2.1 PARAMETRIC SIMULATION 1 (compared to field test 1)

Test 1 in the field was an acoustic test using road traffic noise and with receivers placed at levels 1 -12 on DSFs S1 and E1. The receiver positions and layout for site testing were indicated in figures 6.5, 6.7 and 6.8. The results from field test 1 are shown in table 6.7. Receivers were placed both inside and outside the DSF.

Simulation 1 compared the results for noise levels outside the façade (Element 1). Simulation 1 was configured with more receivers on the façade than were used in the field test. This was to obtain more data in the event that Building A, London was to be field tested again. Figure 7.2 shows the comparative results from Simulation 1 with the equivalent receiver positions in Test 1.

A sample of the full data format is given in Figure 7.3. The sample data sheet gives the following information that has been inputted to CADNA:-

1. Level number
2. Receiver height above ground level
3. Road traffic levels
4. Building evaluation in dBA.
5. Predicted noise levels at the façade in dBA.

The Building Evaluation is a logarithmic average of the predicted noise levels simulated. The road traffic levels are a user input from estimated or measured data. In this research the road traffic levels were taken from measured data from the field test. The predicted noise levels produced by CADNA were a single integer value expressed in dBA.

The results from Simulation 1 showed a set of results with a maximum deviation of 4dBA. When the variation in actual tested results was analysed there was found to be a deviation in 3.1dBA. This put the simulated deviation of 4dB compared with actual into perspective. The results were very comparable between actual and simulated in this model.

The contour model of this simulation is shown in Figure 7.4 and the diagram shows the obvious influence of the motorway on DSF S1 and down the two sides of the building.

Test No			dBA	Test No			dBA
1.1	Test E1 - Level 1	L1	65.7	1.2	Test S1 - Level 1	L1	74
	Model E1 - Level 1	L2	69		Model S1 Level 1	L2	76
	Difference	L1-L2	3.3		Difference	L1-L2	2
Test No			dBA	Test No			dBA
1.3	Test E1 - Level 2	L1	65.3	1.4	Test S1 - Level 2	L1	75.9
	Model E1 - Level 2	L2	69		Model S1 - Level 2	L2	76.0
	Difference	L1-L2	3.7		Difference	L1-L2	0.1
Test No			dBA	Test No			dBA
1.5	Test E1 - Level 3	L1	68.2	1.6	Test S1 - Level 3	L1	77.7
	Model E1 - Level 3	L2	69.5		Model S1 - Level 3	L2	75.5
	Difference	L1-L2	1.3		Difference	L1-L2	-2.2
Test No			dBA	Test No			dBA
1.7	Test E1 - Level 4	L1	65.4	1.8	Test S1 - Level 4	L1	78.2
	Model E1 - Level 4	L2	69.3		Model S1 - Level 4	L2	75.1
	Difference	L1-L2	3.9		Difference	L1-L2	-3.1
Test No			dBA	Test No			dBA
1.9	Test E1 - Level 5	L1	70	1.10	Test S1 - Level 5	L1	78.6
	Model E1 - Level 5	L2	69		Model S1 - Level 5	L2	74.4
	Difference	L1-L2	-1		Difference	L1-L2	-4.2
Test No			dBA	Test No			dBA
1.11	Test E1 - Level 6	L1	72.3	1.12	Test S1 - Level 6	L1	74.7
	Model E1 - Level 6	L2	68.3		Model S1 - Level 6	L2	73
	Difference	L1-L2	-4		Difference	L1-L2	-1.7
Test No			dBA	Test No			dBA
1.13	Test E1 - Level 7	L1	68.8	1.14	Test S1 - Level 7	L1	77.1
	Model E1 - Level 7	L2	68.1		Model S1 - Level 7	L2	73.5
	Difference	L1-L2	-0.7		Difference	L1-L2	-3.6
Test No			dBA	Test No			dBA
1.15	Test E1 - Level 8	L1	68.6	1.16	Test S1 - Level 8	L1	72.5
	Model E1 - Level 8	L2	68		Model S1 - Level 8	L2	73
	Difference	L1-L2	-0.6		Difference	L1-L2	0.5
Test No			dBA	Test No			dBA
1.17	Test E1 - Level 9	L1	69.1	1.18	Test S1 - Level 9	L1	75
	Model E1 - Level 9	L2	68		Model S1 - Level 9	L2	72.5
	Difference	L1-L2	-1.1		Difference	L1-L2	-2.5
Test No			dBA	Test No			dBA
1.19	Test E1 - Level 10	L1	68.2	1.20	Test S1 - Level 10	L1	74.7
	Model E1 - Level 10	L2	67.7		Model S1 - Level 10	L2	72.3
	Difference	L1-L2	-0.5		Difference	L1-L2	-2.4
Test No			dBA	Test No			dBA
1.21	Test E1 - Level 11	L1	68.1	1.22	Test S1 - Level 11	L1	73.7
	Model E1 - Level 11	L2	67.5		Model S1 - Level 11	L2	71.6
	Difference	L1-L2	-0.6		Difference	L1-L2	-2.1
Test No			dBA	Test No			dBA
1.23	Test E1 - Level 12	L1	64.5	1.24	Test S1 - Level 12	L1	75
	Model E1 - Level 12	L2	66.5		Model S1 - Level 12	L2	71.5
	Difference	L1-L2	2		Difference	L1-L2	-3.5

Figure 7.2 Test 1 compared to Simulation 1 - Data results

Level no	**1**			**Receiver Level**	**5.7m**				
				Building Evaluation	**76**				

Road Traffic Levels			
S	E	W	N
88	85	85	80

Predicted Levels at Facade

South	1	2	3	4	5				
	75	75	76	76	76				
East	1	2	3	4	5	6	7	8	9
	73	71	69	67	63	62	62	59	60
West	1	2	3	4	5	6	7	8	9
	72	70	67	64	63	62	62	59	60
North	1	2	3	4	5				
	58	57	56	56	57				

Figure 7.3 Sample Data results Simulation 1

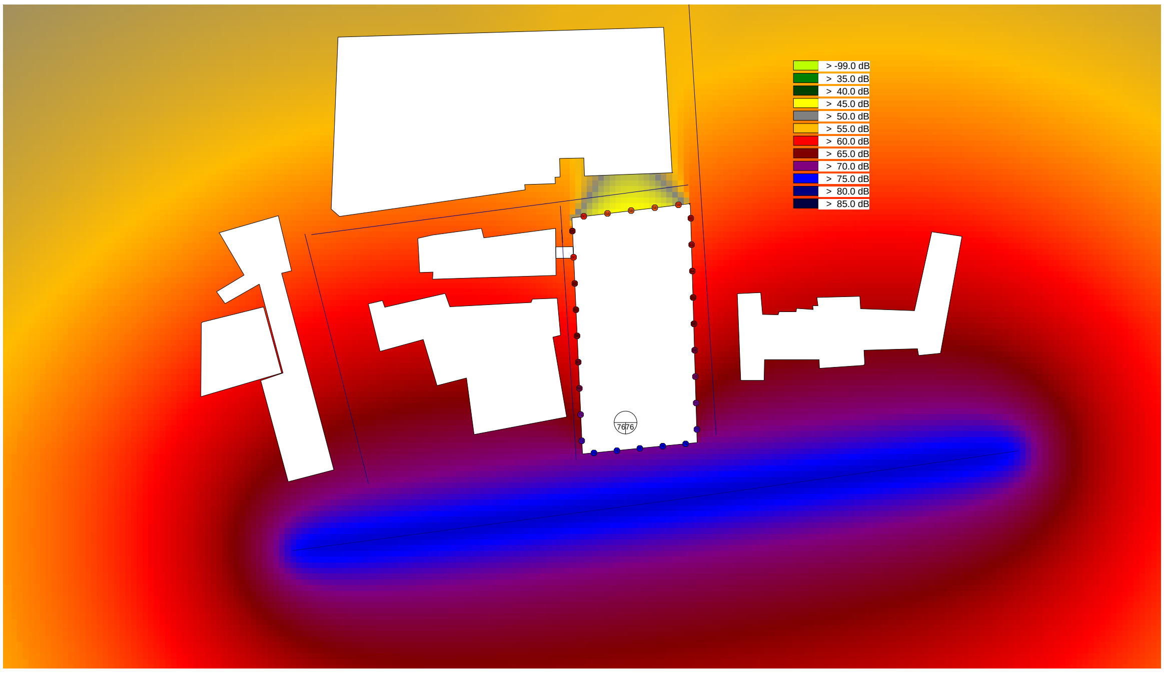


Figure 7.4 Contour Diagram, Simulation 1 – Level 1

7.2.2 PARAMETRIC SIMULATION 2 (compared to field test 2)

Test 2 in the field was an acoustic test using road traffic noise and with receivers placed at level 4 on each DSF around the building. The receiver positions and layout for site testing were in accordance with figures 6.5, 6.10, 6.11, and 6.12. The results from field test 2 are shown in table 6.8.

The Simulation 2 input replicated the receiver positions. The data results for simulation 2 are shown in Figure 7.5. The simulation 2 results are given in dBA.

Test 2			Simulation 2			Deviation
Ref	Level	dBA	Ref	Level	dBA	
E3	L4	59	E3	L4	59.8	-0.8
E3	L4	60.9	E3	L4	60.7	0.2
E2	L4	62.6	E2	L4	61.7	0.9
E1	L4	69.5	E1	L4	68.5	1
S1	L4	73.6	S1	L4	74.1	-0.5
S1	L4	73.9	S1	L4	74.1	-0.2
S1	L4	74.1	S1	L4	74.2	-0.1
W1	L4	70.4	W1	L4	69.2	1.2
W1	L4	66.6	W1	L4	65.5	1.1
W2	L4	64	W2	L4	63	1
W3	L4	60.1	W3	L4	60.5	-0.4
W4	L4	57.7	W4	L4	57.4	0.3

Figure 7.5 Simulation 2 results compared to Test 2

The comparison between test 2 and simulation 2 show a very small deviation between -0.8 to 1.2 dBA, which considering the possible fluctuation in road traffic noise in the test scenario, would appear to be a very satisfactory result.

Within this simulation it was decided to introduce an acoustic screen in front of the building at 4m high, 4m in front of the building and the width of the building. The bottom of the DSF starts 4m off ground level and as such the intention was to investigate the noise level at L1. The results are shown in figure 7.6 and show on average a 2dBA drop not just on the elevation with the screen but on all elevations. It was concluded that low level attenuation at the sound entry position is an important design detail that needs particular attention during design.

Level no 1 with acoustic screen					Receiver Level		5.7m
					Building Evaluation		74

Road Traffic Levels			
S	E	W	N
88	85	85	80

Predicted Levels at Facade

South	1	2	3	4	5				
	75	75	76	76	76				
East	1	2	3	4	5	6	7	8	9
	71	70	68	67	64	63	61	60	59
West	1	2	3	4	5	6	7	8	9
	71	70	66	63	61	61	61	58	57
North	1	2	3	4	5				
	56	56	55	55	56				

Figure 7.6 Simulation 2 result with 4m high acoustic screen

7.2.3 SUMMARY – CADNA PREDICTIVE MODELLING

CADNA, as a form of predictive modelling for element 1 of this research, has performed well. The deviation in results did not appear excessive given the nature of the sound source that it was being measured against. The computational time was 20 minutes per model which was not excessive, considering the area and size of model utilised.

CADNA would not be suitable to simulate elements 2 and 3 of the sound path. The model algorithms are not suitable to model the intricacies of a small DSF cavity/room.

As such, the decision to just use CADNA for element 1 was appropriate.

7.3 CATT ACOUSTICS – ELEMENT 2 (PROPOGATION OF SOUND THROUGH THE DSF)

7.3.1 INTRODUCTION

The background to the choice of CATT acoustics is given in Chapter 3. It is a predictive acoustic software tool that utilises ray tracing and image sourcing. CATT acoustics is designed for simulation of acoustics in rooms and as such the DSF is being treated as a long flat room or duct.

The CATT models were simulated by creating a room/box/DSF and then placing the room within a much larger box or environment. All surfaces both internal and external were assigned absorbent coefficients by the user. CATT enables the user to build a model using an external sketch software package (e.g. Google SketchUp) and export to CATT. CATT identifies all planes and geometries by co-ordinates. The sound source and receivers are inserted into the model by co-ordinates. CATT calculates the amount of rays to be used but will allow the user to reduce this amount if the calculation time is excessive. The models in this research have been calculated with 172,000 rays per model resulting in a simulation calculation period of 1 hour.

Models have been constructed for tests 2-7 as categorised by Chapter 6 compared to the field test results.

The absorption coefficient used for simulations 2-7 are set out in Figure 7.7. A different coefficient was used for the outer and inner skins and the data used is taken from published SAINT GOBAIN acoustic data for glass types.

Absorption Coefficients Used In Models 2-7.						
Hz	125	250	500	1	2	4
Outer Skin	28	29	32	33	37	47
Inner Skin	25	28	38	47	49	57

Figure 7.7 Absorption Coefficients used in simulations 2-7.

7.3.2 TIME TRACING

Time tracing was not discussed in Chapter 4. It is a function within CATT that enables the user to illustrate and view the path of sound rays through the model in time steps of milliseconds. The user can input a number of options to develop this model function, such as the number of rays to be included, the time frame in milliseconds and the number of image reflections. The rays are shown in the 1 kHz frequency band and the legend maps colour with SPL.

Time tracing is a very useful visual aid and some examples are shown to illustrate various models. Simulation 2 was used to produce time trace snapshots using different input options.

Figure 7.8 uses 1000 rays over 200 ms, with a maximum order of 3 to produce a snapshot at 16.0 ms. The sound rays can be seen leaving the source and starting to propagate through the DSF in a spherical manner.

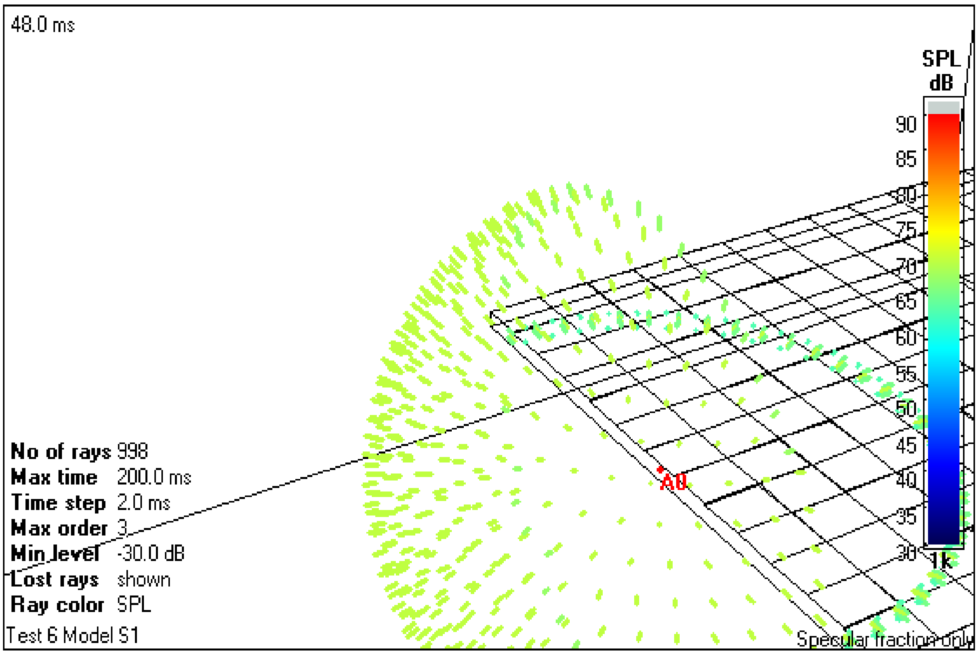


Figure 7.8 Time Trace at 16ms using 1000 rays.

Figure 7.9 shows the same model, using the original input data, with a snapshot at 46ms. The rays reflected off the sides of the DSF and continued their path through the DSF.

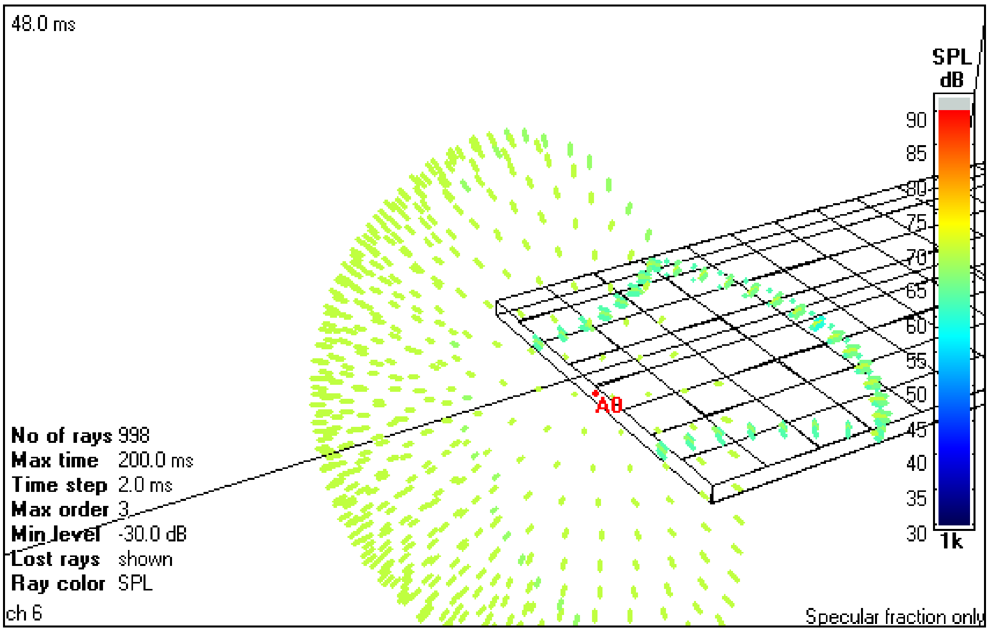


Figure 7.9 Trace Trace at 48ms using 1000 rays.

The number of rays used in Figure 7.10 were increased to 50,000 and a snapshot was taken at 46ms. Figure 7.10 demonstrates a more dense concentration of rays illustrating a clearer depiction of the ray profile.

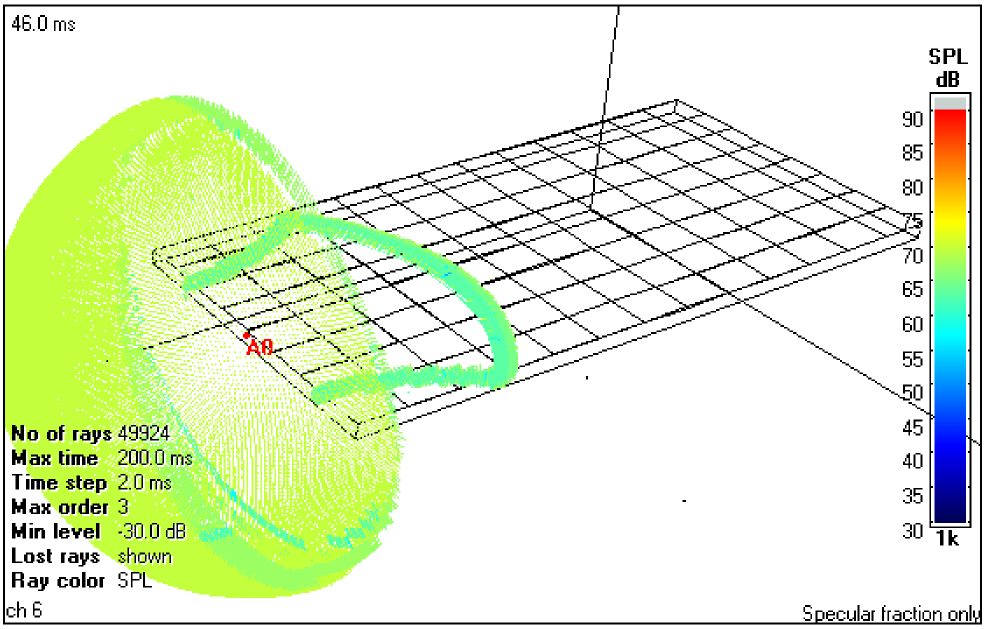


Figure 7.10 Trace Trace at 46ms using 50000 rays.

When the ray count is increased to 100,000 the snapshot becomes more defined as shown in Figure 7.11.

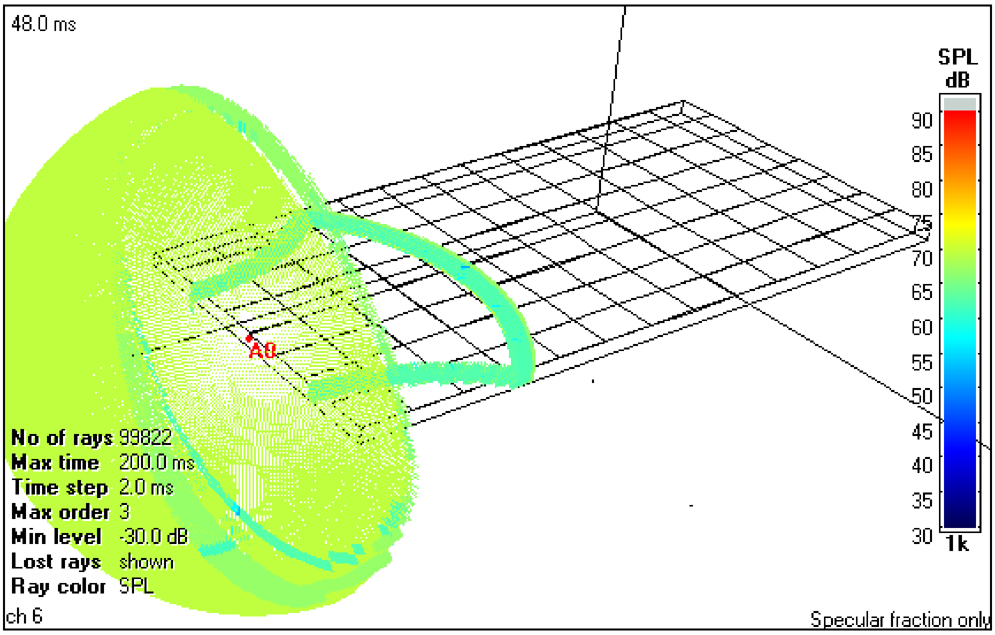


Figure 7.11 Trace Trace at 48ms using 100000 rays.

As the time trace continues the snapshots illustrate 'end reflection'. This is the technical acoustic description of the rays reflecting off the end of a duct. Figures 7.12 and 7.13 illustrate end reflection and this is an important phenomenon in the acoustic analysis of a DSF.

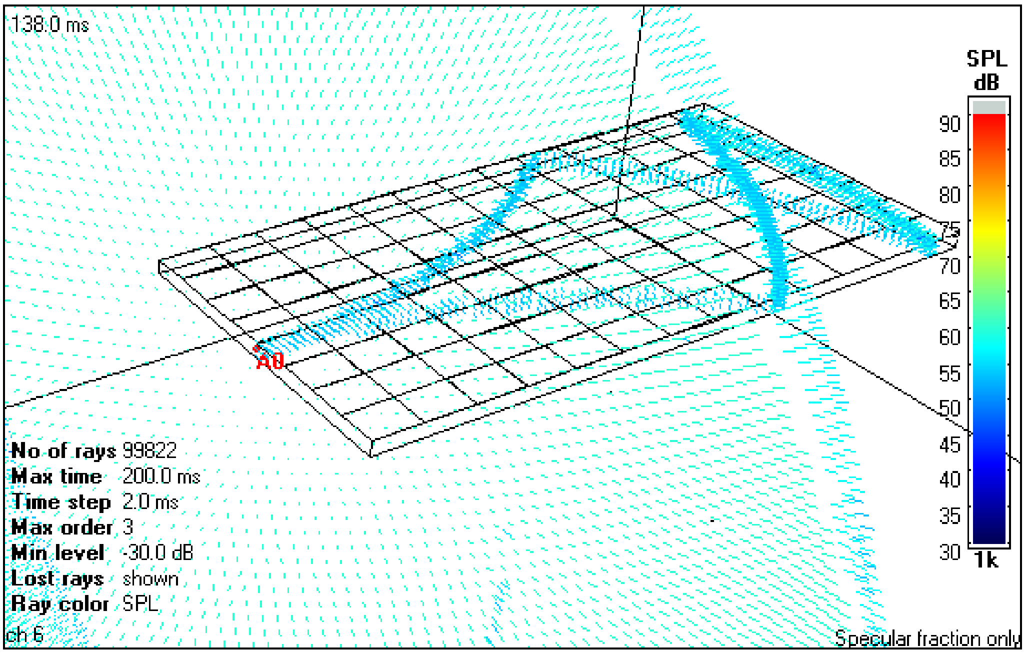


Figure 7.12 Trace Trace at 138ms using 100000 rays.

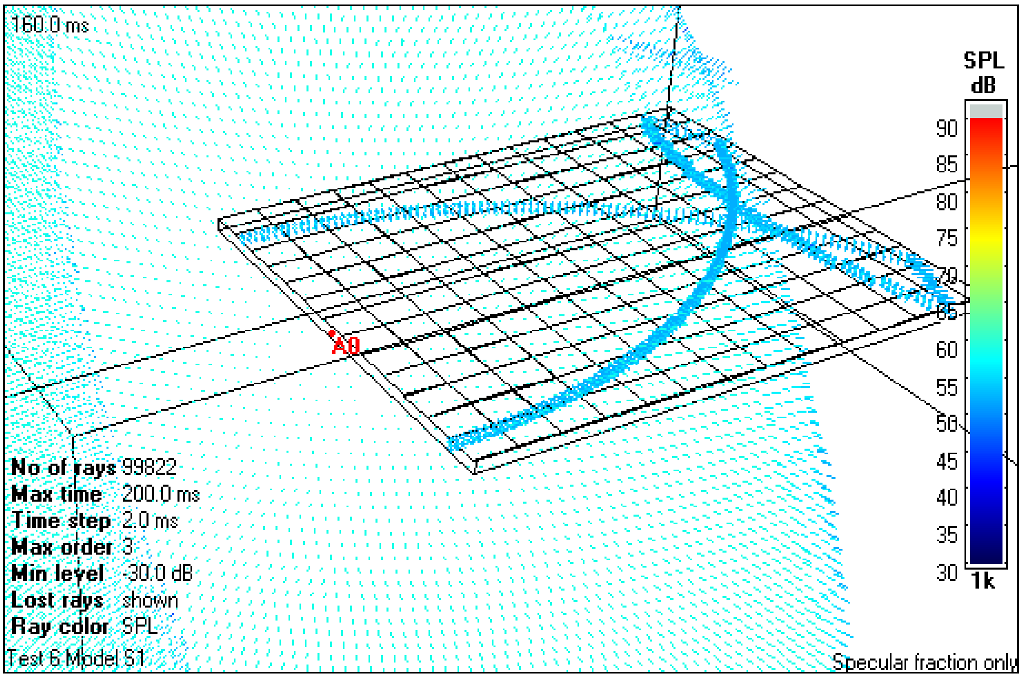


Figure 7.13 Time Trace at 160ms using 100000 rays.

7.3.3 SIMULATION 2

Simulation 2 examined DSFs E3, E2, E1, S1, W3, W3, W2 and W1 at Level 4, with a sound source placed at the bottom of the DSF and receivers placed within the DSF to replicate Test 2 receiver positions. The receiver position coordinates were calculated from the origin in the model.

The Google SketchUp model for Simulation 2 Model E2 is shown in Figure 7.14.

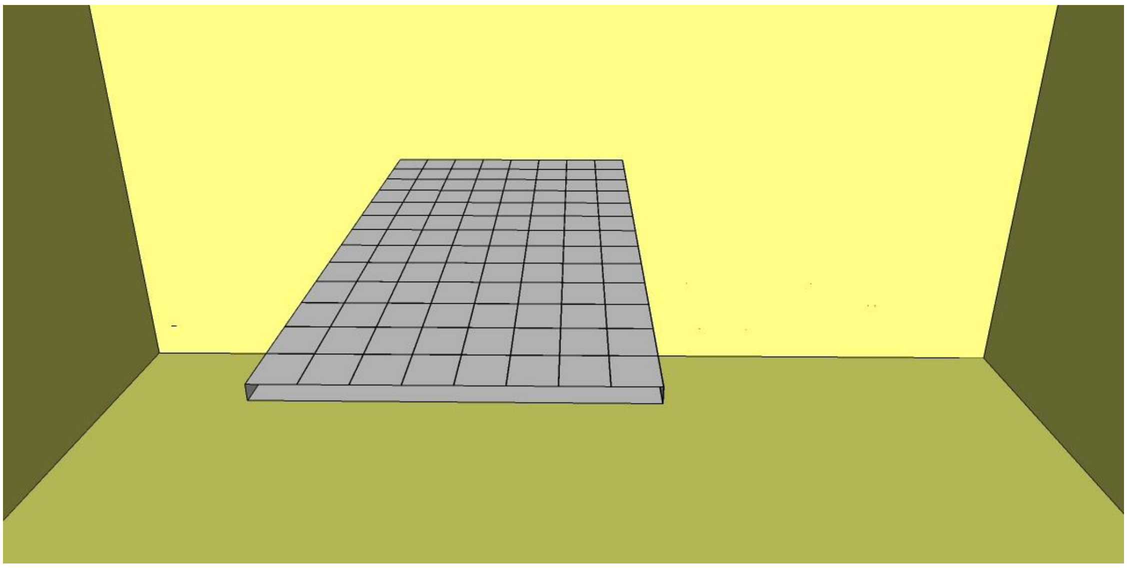


Figure 7.14 Simulation 2 Model E2 from Google SketchUp

The imported model when viewed in CATT is shown in Figure 7.15. The source and receiver positions were verified by viewing in this mode. It is possible to zoom and rotate as shown in Figure 7.16. If a source cannot be viewed by a receiver then a default error message will be displayed. The user can override this error if the model is correct.

The results for this simulation are shown in Figure 7.17 and were compared against the results in Test 2. The deviation in results was -0.8dB to 1.2dB.

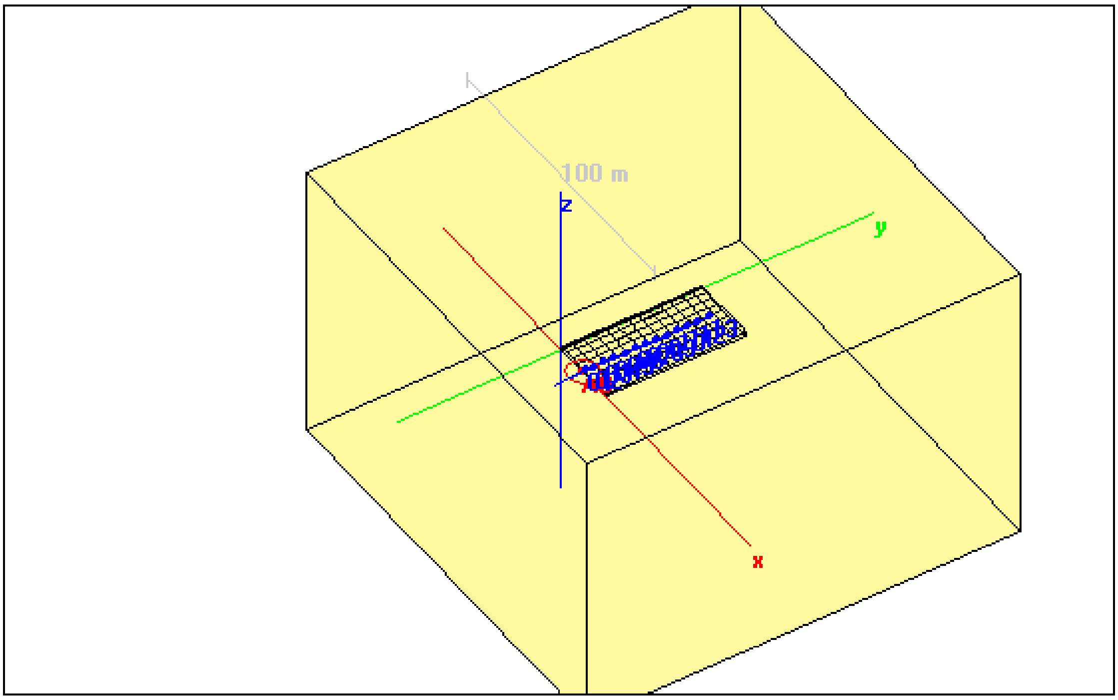


Figure 7.15 Simulation 2 Model E2 viewed in CATT

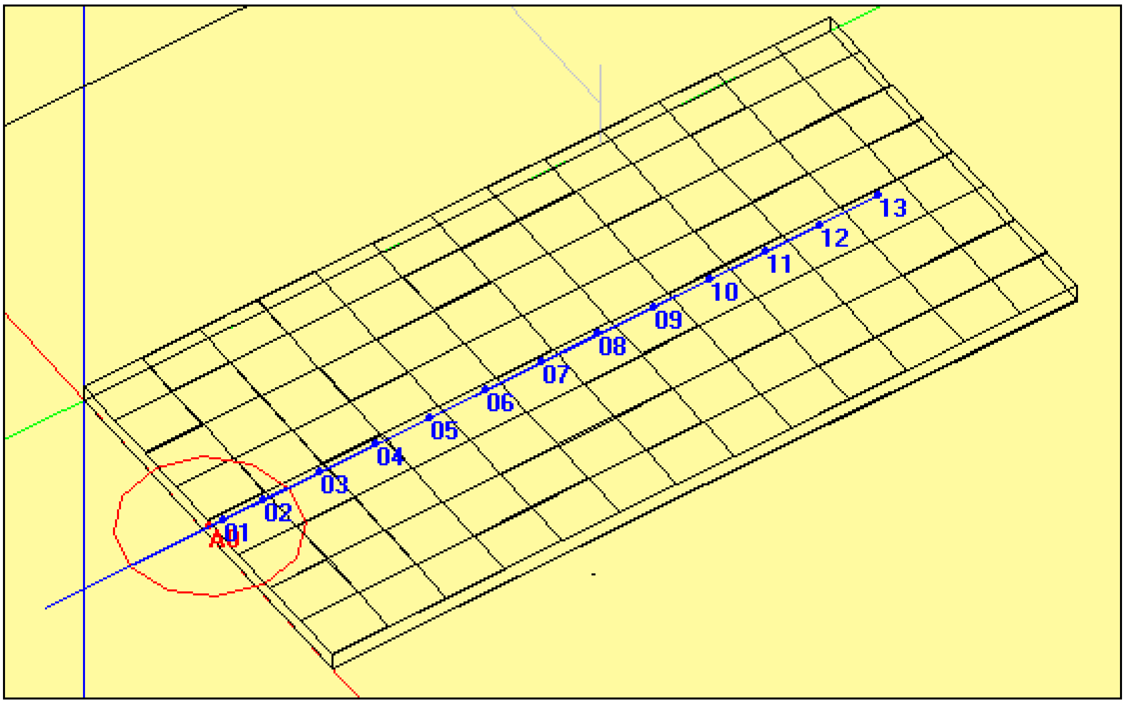


Figure 7.16 Simulation 2 Model E2 Exploded view in CATT

Test 2			Simulation 2			Deviation (dB)
Ref	Level	dB	Ref	Level	dB	
E3	L4	59	E3	L4	59.8	-0.8
E3	L4	60.9	E3	L4	60.7	0.2
E2	L4	62.6	E2	L4	61.7	0.9
E1	L4	69.5	E1	L4	68.5	1
S1	L4	73.6	S1	L4	74.1	-0.5
S1	L4	73.9	S1	L4	74.1	-0.2
S1	L4	74.1	S1	L4	74.2	-0.1
W1	L4	70.4	W1	L4	69.2	1.2
W1	L4	66.6	W1	L4	65.5	1.1
W2	L4	64	W2	L4	63	1
W3	L4	60.1	W3	L4	60.5	-0.4
W4	L4	57.7	W4	L4	57.4	0.3

Figure 7.17 Simulation 2 Results V Test 2 Results

7.3.4 SIMULATION 3

Simulation 3 replicated the test on W4 at levels L2, L3 and L4. The model is shown in Figure 7.18.

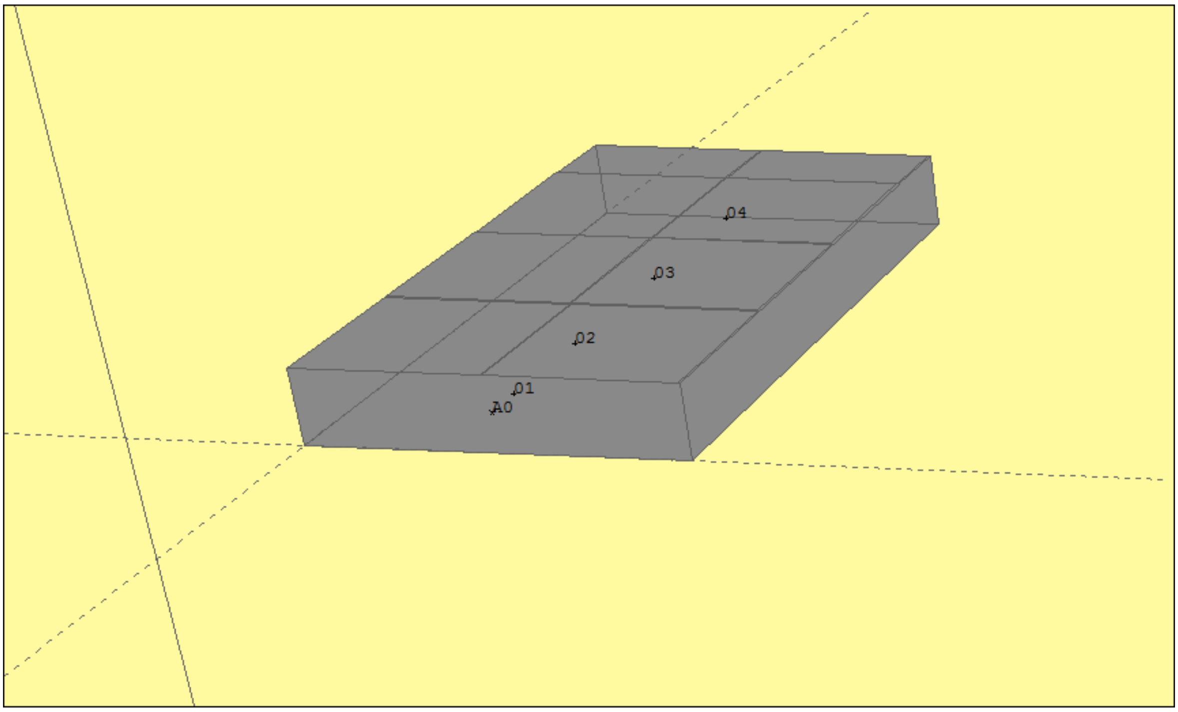


Figure 7.18 Simulation 3 Model in CATT

The simulation 3 results are shown in Figure 7.19 and examined in relation to the equivalent D_W value from Test 3. The resulting deviations of -1db to 3db are shown in figure 7.20.

	Ref	Level	Dw		Ref	Level	Dw	Deviation
Test 3	W4	Level 2	95	Model W3	W4	Level 2	92	3.0
	W4	Level 3	88		W4	Level 3	89	-1.0
	W4	Level 4	87		W4	Level 4	87	0.0

Figure 7.19 Simulation 3 Results V Test 3 results

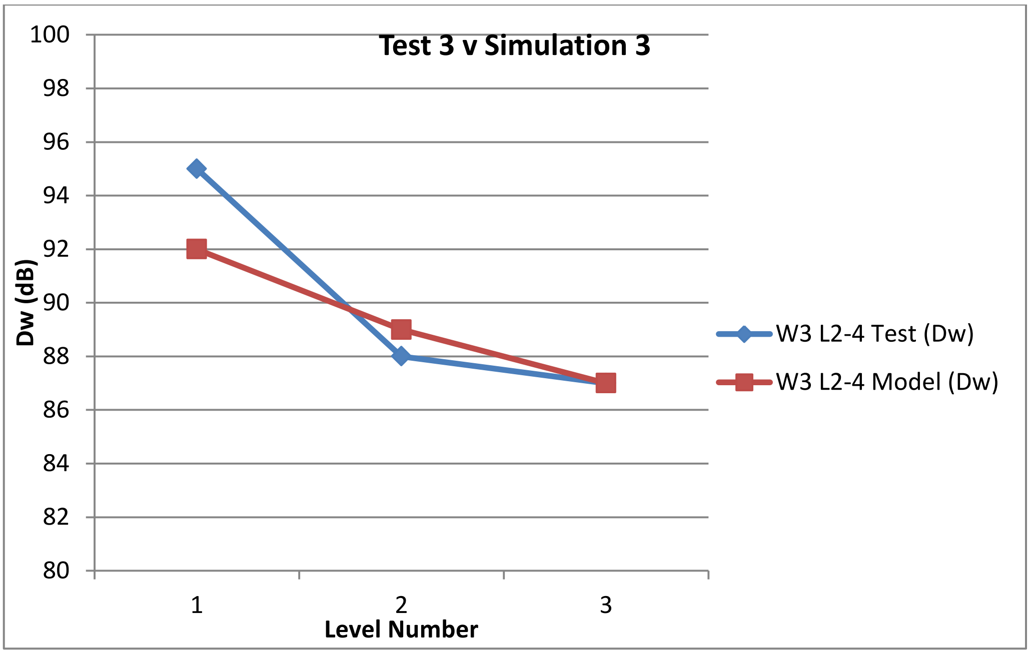


Figure 7.20 Graph of Test 3 and Model 3 results

7.3.5 SIMULATION 4

Simulation 4 replicated field test 4 - W3 on levels 1-4. The simulation model is shown in Figure 7.21. The results are shown in Figure 7.22 with a deviation in results of 2dB as shown in Figure 7.23. As the DSFs become bigger in scale, the similarities in results are becoming more apparent from a graphical perspective.

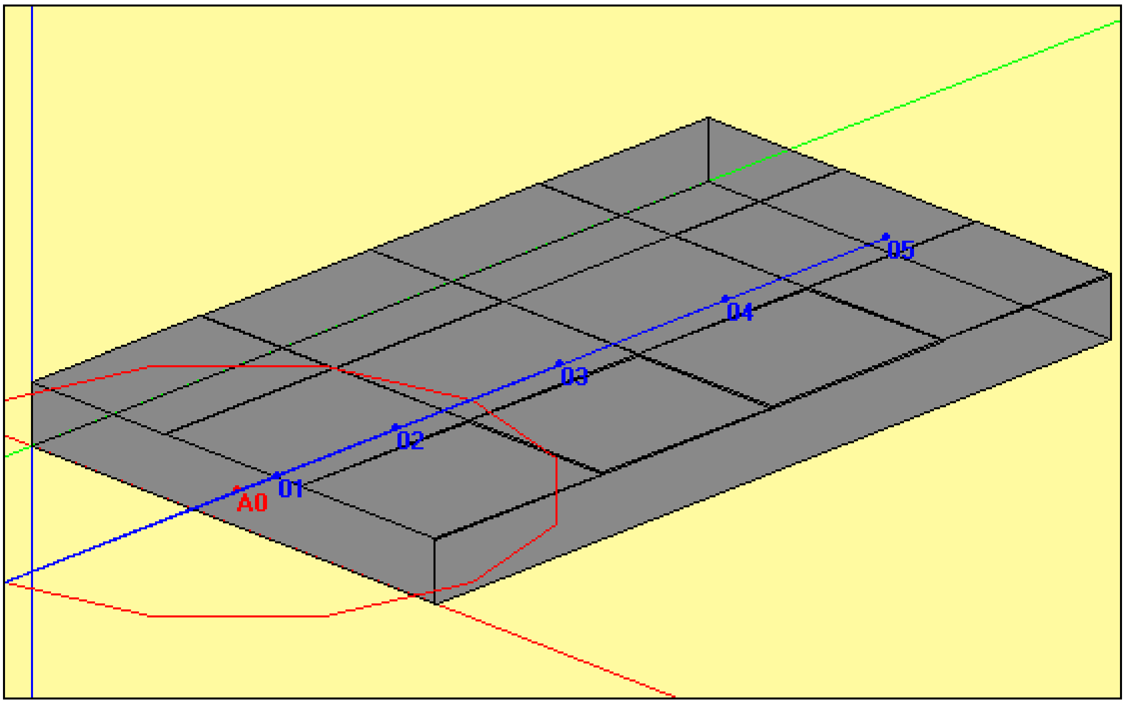


Figure 7.21 Simulation Model 4

	Ref	Level	Dw		Ref	Level	Dw	Deviation (Dw)
Test 4	W3	Level 1	95	Model 4	W3	Level 1	93	2
	W3	Level 2	89		W3	Level 2	88	1
	W3	Level 3	87		W3	Level 3	86	1
	W3	Level 4	87		W3	Level 4	87	0

Figure 7.22 Simulation results of Test 4 and Model 4 results

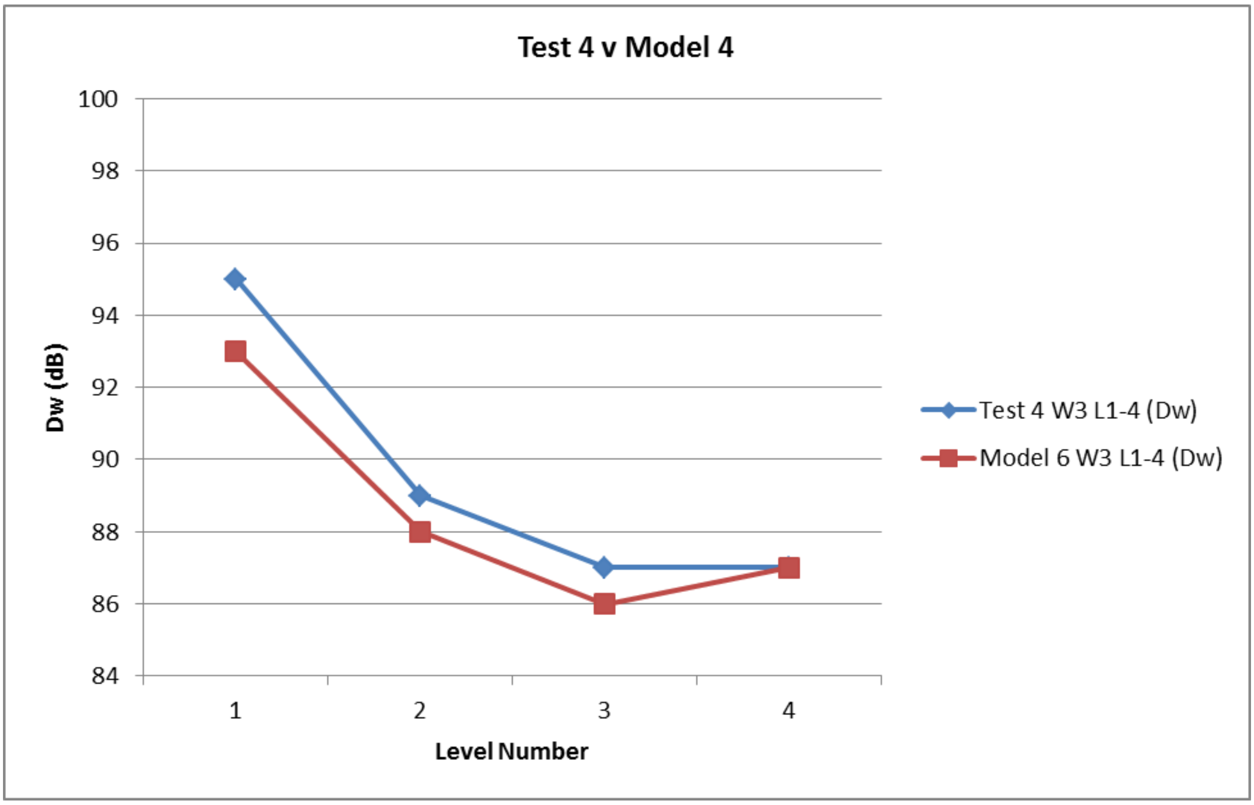


Figure 7.23 Graph of Model Test 4 and Model 4 results

7.3.6 SIMULATION 5

Test 5 was the field test on W2 at levels L1 – L7. DSF W3 was located centrally on the West Elevation - see Figures 7.18 and 7.19. The model for Simulation 5 is shown in figure 7.24 with the results and graph in figures 7.25 and 7.26 respectively. The deviation in results between testing and simulation are -3dB to 1dB.

The computation time for the larger models (simulation 5 and 6) using 172,000 rays was in excess of 1 hour. The time trace at 124ms is shown in Figure 7.27 shows the 1st order reflection quite clearly with the end reflection just about to take place.

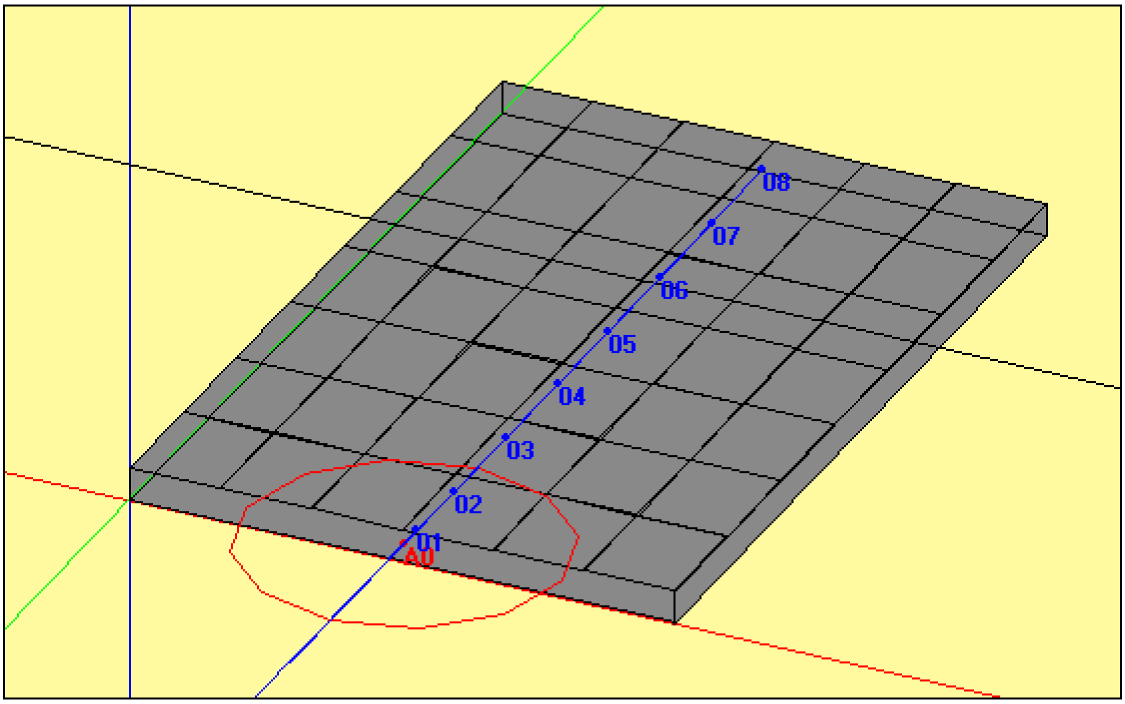


Figure 7.24 Simulation Model 5

	Ref	Level	Dw		Ref	Level	Dw	Deviation
Test 5	W1	Level 1	96	Model 5	W1	Level 1	95	1
	W1	Level 2	88		W1	Level 2	91	-3
	W1	Level 3	87		W1	Level 3	88	-1
	W1	Level 4	84		W1	Level 4	86	-2
	W1	Level 5	82		W1	Level 5	85	-3
	W1	Level 6	82		W1	Level 6	85	-3
	W1	Level 7	81		W1	Level 7	84	-3

Figure 7.25 Simulation results of Test 5 and Model 5 results

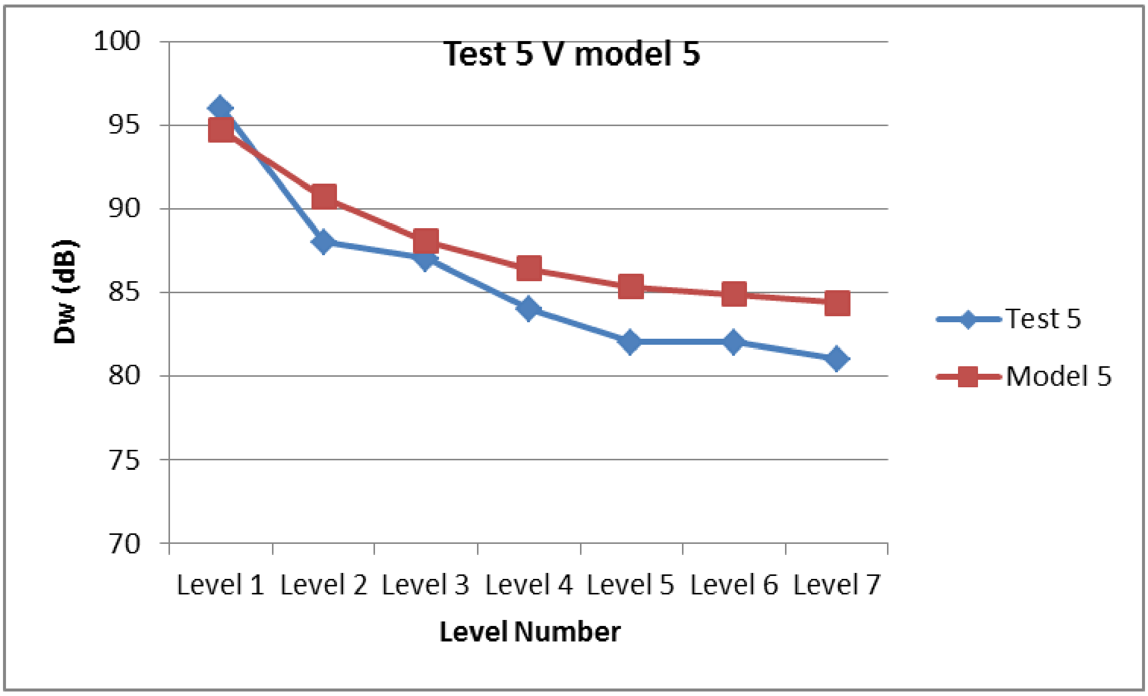


Figure 7.26 Graph of Test 5 and Model 5 results

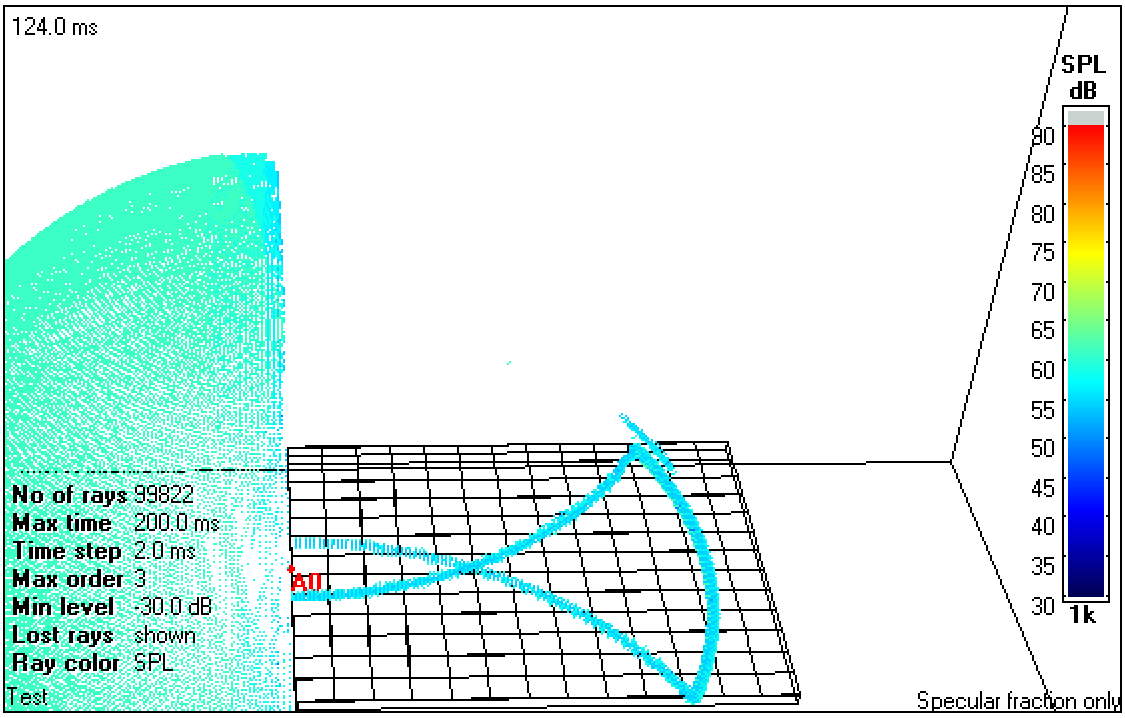


Figure 7.27 Time trace snapshop at 124ms in Model 5

7.3.6 SIMULATION 6

Test 6 was the test conducted on S1 at levels L1 – L12. DSF S1 is located centrally on the South Elevation facing the flyover - see Figures 6.20 and 6.21. The simulation model is shown in Figure 7.28 with the results and graph shown in figures 7.29 and 7.30 respectively. The deviation in result between test and simulation was in the range of -2.4 to 1.5 dB. The time trace snapshot is shown in Figure 7.31 at 166ms with the end reflection having just taken place.

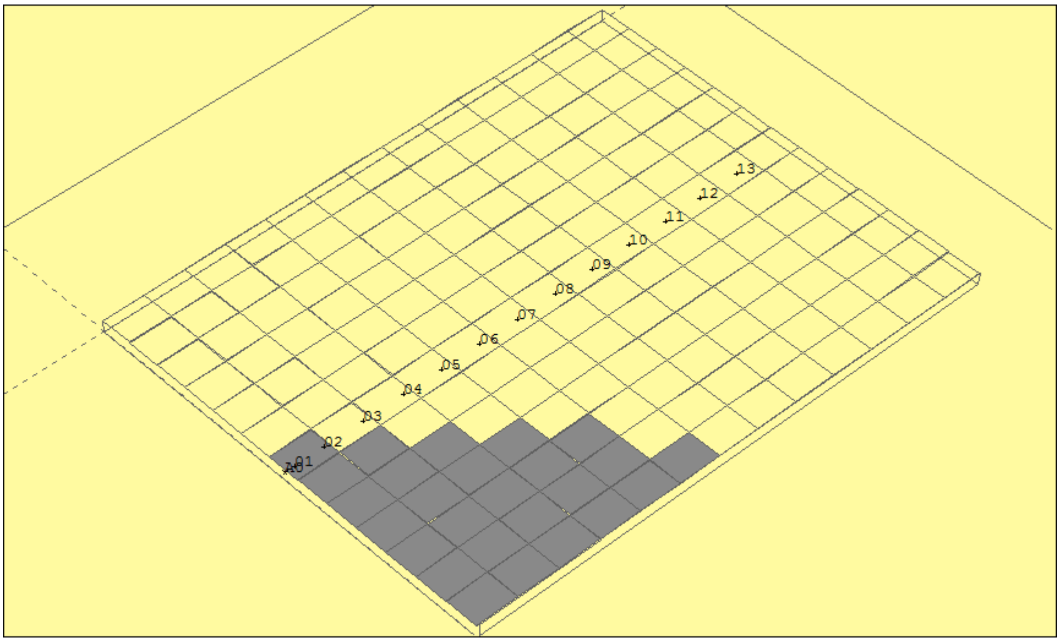


Figure 7.28 Simulation 6

	Ref	Level	Dw		Ref	Level	Dw	Deviation
Test 6	S1	Level 1	102	Model 6	S1	Level 1	100.5	1.5
	S1	Level 2	93		S1	Level 2	95.4	-2.4
	S1	Level 3	90		S1	Level 3	92	-2
	S1	Level 4	88		S1	Level 4	89.8	-1.8
	S1	Level 5	88		S1	Level 5	87.2	0.8
	S1	Level 6	86		S1	Level 6	86.4	-0.4
	S1	Level 7	85		S1	Level 7	84.8	0.2
	S1	Level 8	84		S1	Level 8	84.3	-0.3
	S1	Level 9	84		S1	Level 9	85	-1
	S1	Level 10	83		S1	Level 10	82.8	0.2
	S1	Level 11	82		S1	Level 11	83.2	-1.2
	S1	Level 12	81		S1	Level 12	82.6	-1.6

Figure 7.29 Simulation results of Test 6 and Model 6 results

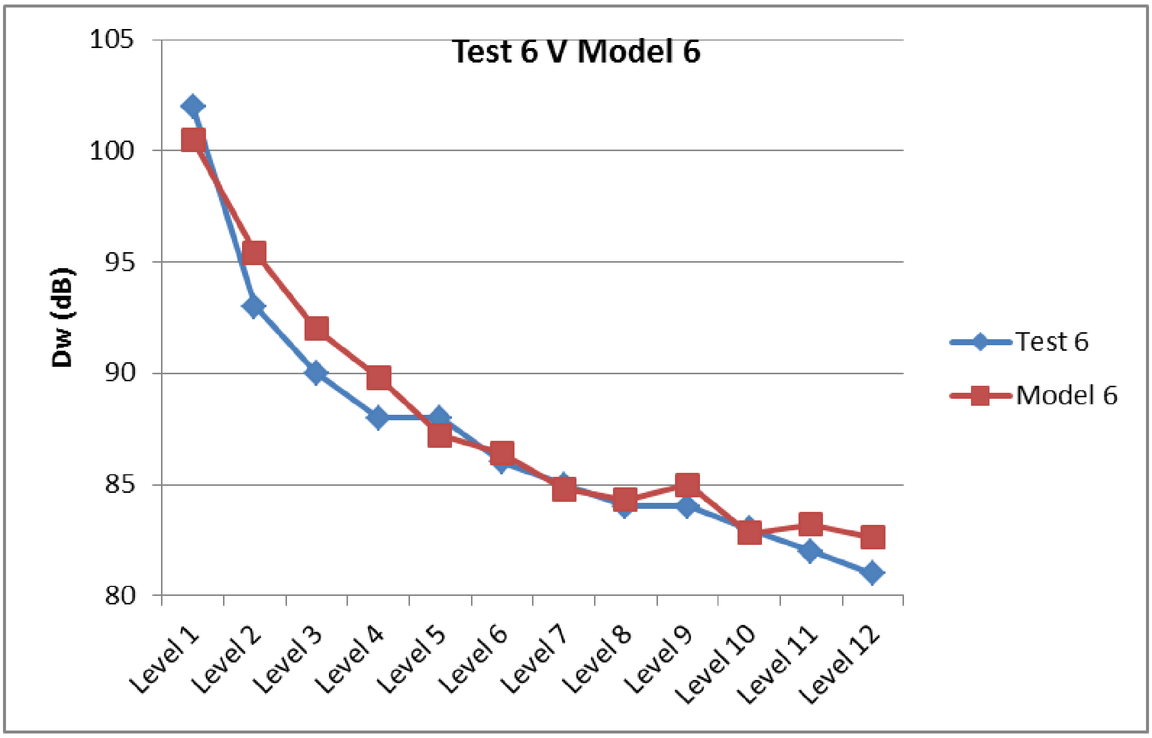


Figure 7.30 Graph of Test 6 and Simulation 6 results

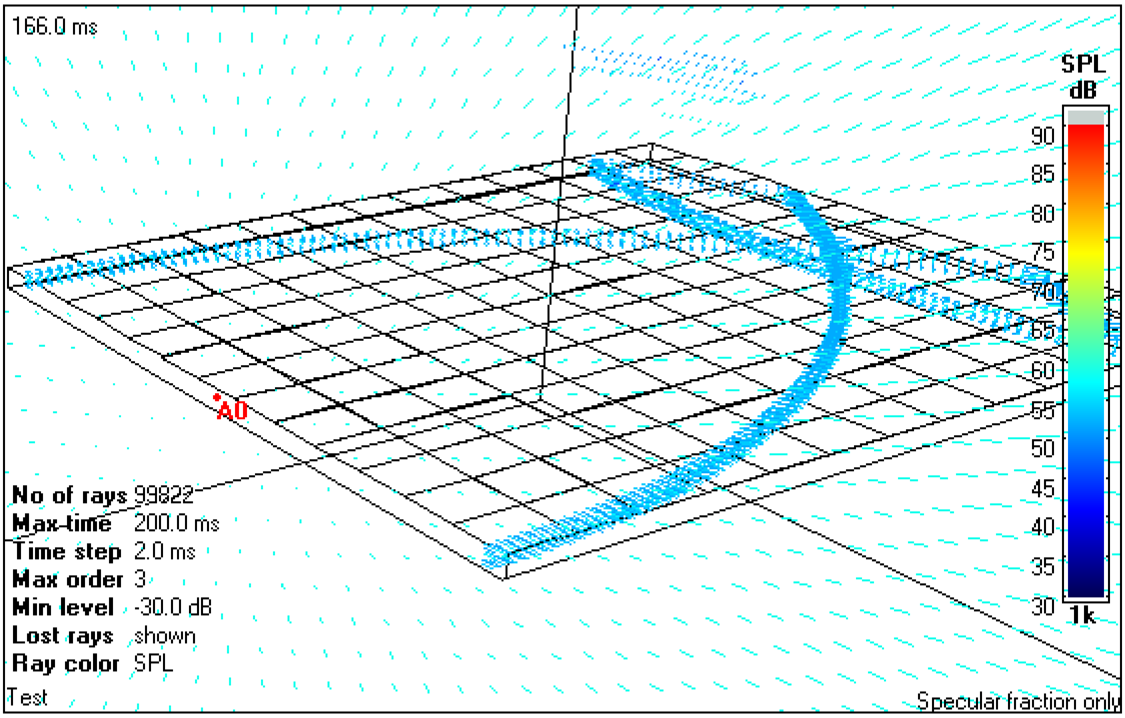


Figure 7.31 Time trace snapshop at 124ms in Model 6

7.3.8 SIMULATION 7 - REVERBERATION TIME

Test 7 was a reverberation test to establish the reverberation time in the DSF cavity. The DSF's tested are shown on figures 6.22, 6.23 and 6.24. CATT runs RT in each simulation and will give T20 and T30 values. The abridged data is given in Figure 7.32 and the full data is recorded in appendix 15. A snap shot is provided in Figure 7.33 of how CATT produced it's results within the software.

In this simulation, the deviation between test and model is in the range of -0.57 seconds to 0.45 seconds. There appeared to be two anomalies in S1 Level 4 and W4 Level 2. It was obvious from the abridged results and more so from analysing the full data that an error occurred in these simulations. The errors have been highlighted in red within figure 7.32.

Reference	T20 Av Test (sec)	T20 Av Model (sec)	Deviation
W2 Level 1	0.93	0.77	0.16
W2 Level 3	0.91	0.74	0.17
W2 Level 7	0.86	0.53	0.33
S1 Level 1	0.76	0.84	-0.08
S1 Level 4	0.95	4.39	-3.44
S1 Level 8	0.98	0.93	0.04
W3 Level 4	0.70	10.03	-9.33
W3 Level 1	0.81	0.72	0.09
W4 Level 4	0.65	1.22	-0.57
W4 Level 2	0.64	0.19	0.45

Figure 7.32 Abridged Simulation 7 RT Data compared to field test

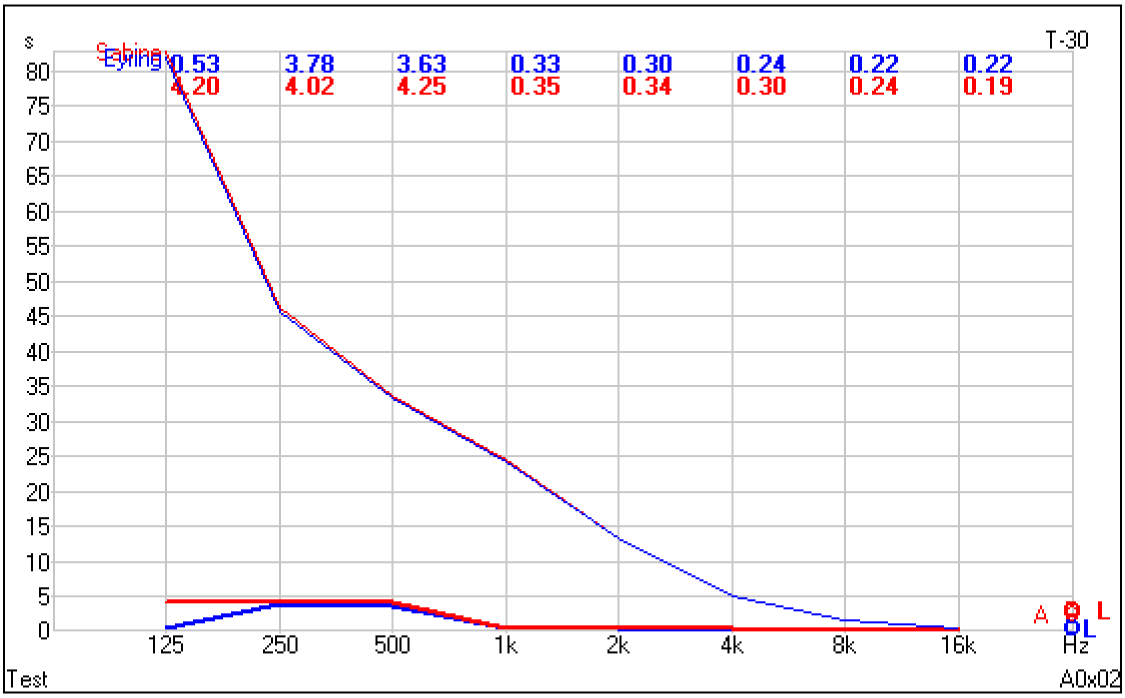


Figure 7.33 T30 snapshot of W3 Level 4

7.3.9 CONCLUSION – ELEMENT 2, CATT SIMULATION

The CATT predictive software has been very successful in the prediction of the acoustic attenuation of the modelled DSFs. There were differences in the deviations through tests 2-7 when compared to field tested data which had fluctuations in traffic noise.

The CATT algorithms that are designed for rooms do appear to suit this form of predictive model and the overall conclusion would be that CATT is suitable for further DSF examination.

7.4 ELEMENT 3 (Sound propagation from DSF through open windows into the building)

This Element was not included in the field testing because there were no opening sashes as part of the DSF system on that project.

A comparison can be made with the Napier University and Fuller and Lurcock research papers from Chapter 2.

The Napier University research investigated window opening widths of 50mm, 100mm and 200mm. The intention of this section is to simulate the propagation of sound through an open window in a DSF. Figure 7.34 illustrates the Google SketchUp model viewed from the bottom.

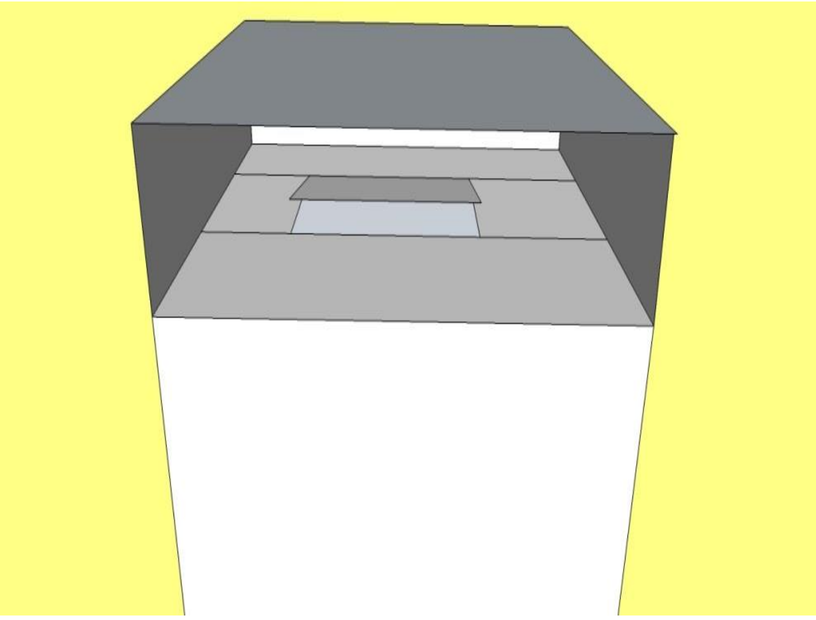


Figure 7.34 Element 3, model view from bottom of the DSF.

The simulation will use window opening widths of 50mm, 100mm and 200mm as per the Napier research with an additional opening of 25mm.

Figures 7.35 and 7.36 show the simulated model and the receiver positions in CATT. The receivers are set at a height of 1.07m above FFL, the same height above finished floor level (FFL) that Napier used. Figure 7.37 is a time trace snapshot taken at 28.0 ms illustrating the sounds rays beginning to propagate through the open window. The abridged resultant data is tabulated in Figure 7.38 and illustrated graphically in Figure 7.39. The full dataset across 63Hz to 16kHz frequency range can viewed in Appendix 16.

The Napier research concluded that the estimated apparent sound reduction index for an open residential window could be expressed as:

$$y = -5.8\ Log_{10}\,(x) + 13.2 \qquad (7.1)$$

The results from this research yield equations in a range from -8LogN to -10.5LogN. The equations extracted from Figure 7.39 are:

$$y = -8.6\ Log_{10}\,(x) + 93.3 \qquad \text{(25mm opening)} \qquad (7.2)$$

$$y = -10.5\ Log_{10}\,(x) + 97 \qquad \text{(50mm opening)} \qquad (7.3)$$

$$y = -10.2\ Log\,(x) + 96.5 \qquad \text{(100mm opening)} \qquad (7.4)$$

$$y = -8.0\ Log_{10}\,(x) + 90.9 \qquad \text{(200mm opening)} \qquad (7.5)$$

This suggests that there is potential to develop a series of equations for opening widths and window types, rather than having one simple equation.

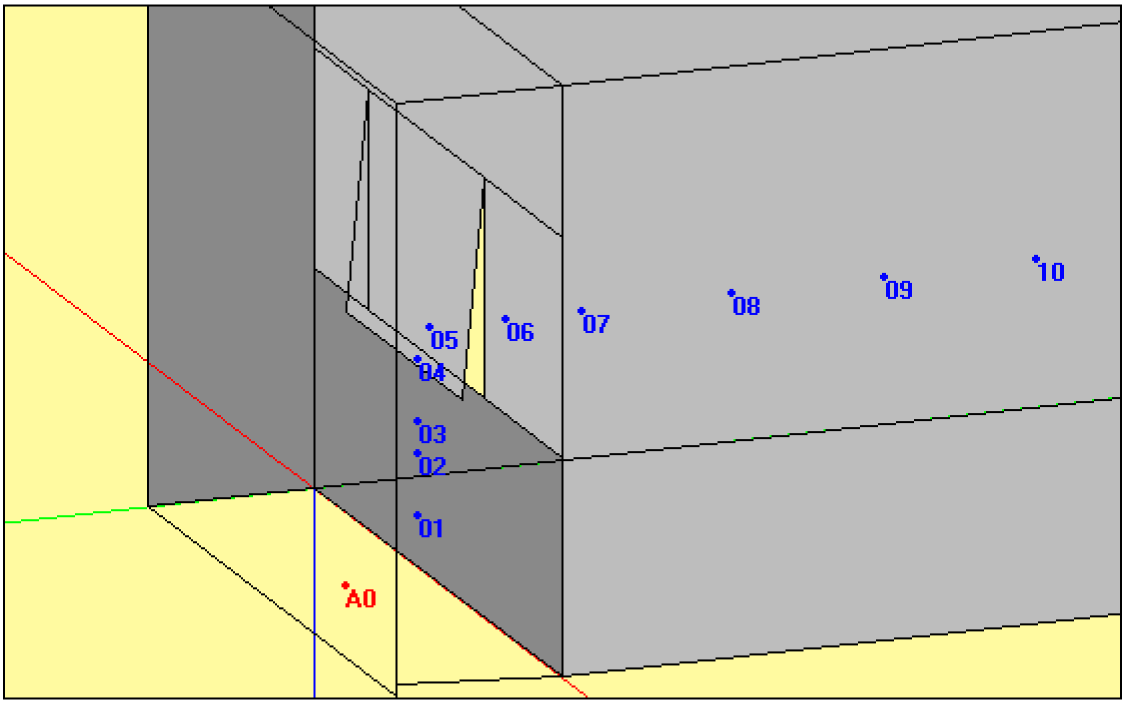


Figure 7.35 Element 3, model view from side as seen in CATT.

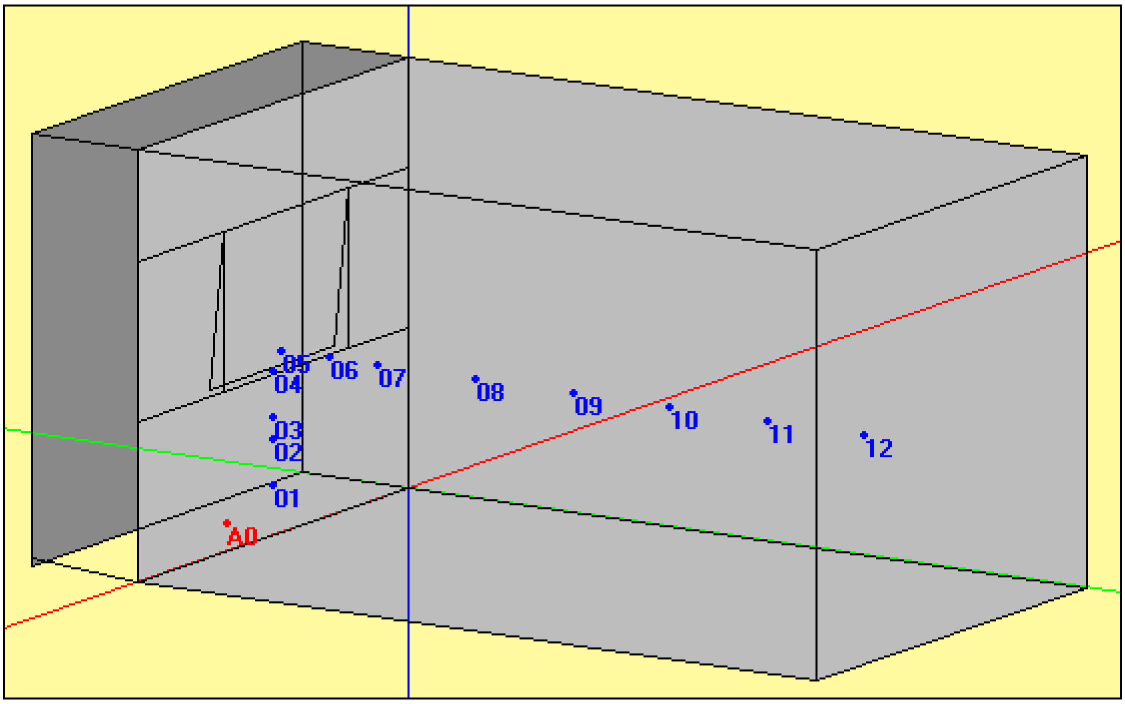


Figure 7.36 Element 3, model view from back as seen in CATT.

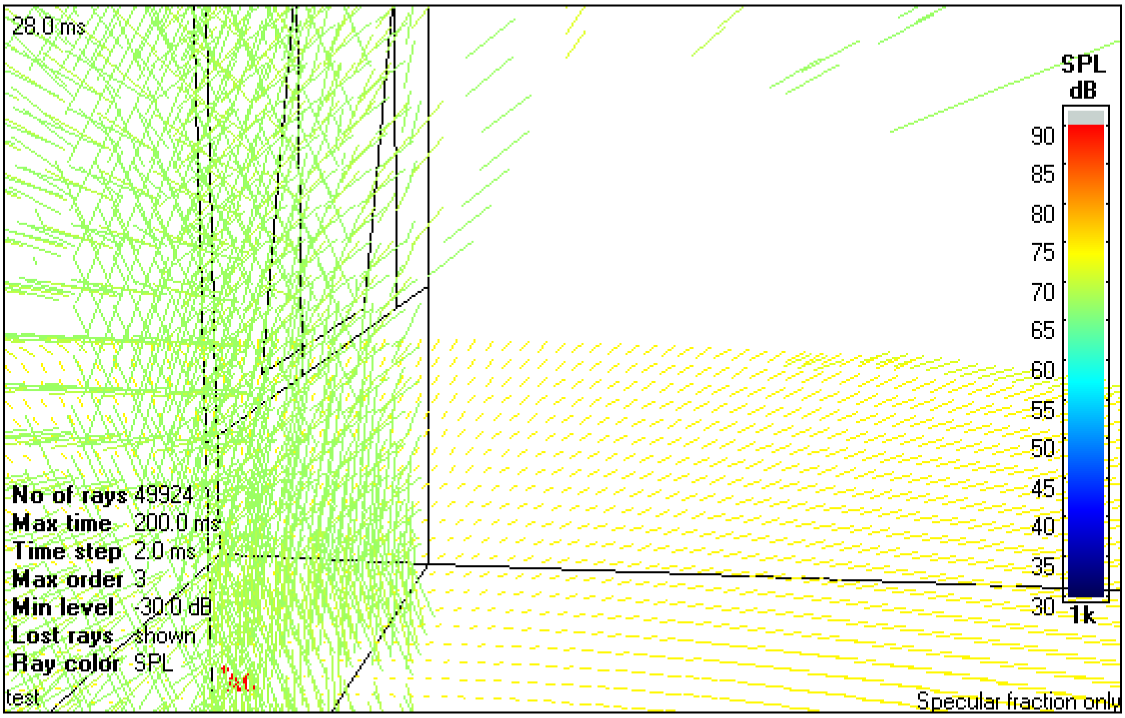


Figure 7.37 Element 3, time trace snapshot.

Component 3 Abridged Results				
Receiver Number	Opening Width			
	25mm (dB)	50mm (dB0	100mm (dB)	200mm (dB)
Receiver 1	101.6	102.6	101.5	101.7
Receiver 2	99.2	99.3	99.2	99.2
Receiver 3	99.7	98.2	98.0	98.2
Receiver 4	95.2	96.7	95.8	96.3
Receiver 5	83.8	91.6	91.7	91.6
Receiver 6	83.8	83.9	84.0	84.0
Receiver 7	82.5	82.5	82.5	82.6
Receiver 8	80.2	80.2	80.2	80.2
Receiver 9	78.3	78.3	78.3	78.3
Receiver 10	76.7	76.7	76.7	76.7
Receiver 11	75.3	75.4	75.4	75.4
Receiver 12	74.2	74.2	74.2	74.2

Figure 7.38 Element 3, data results.

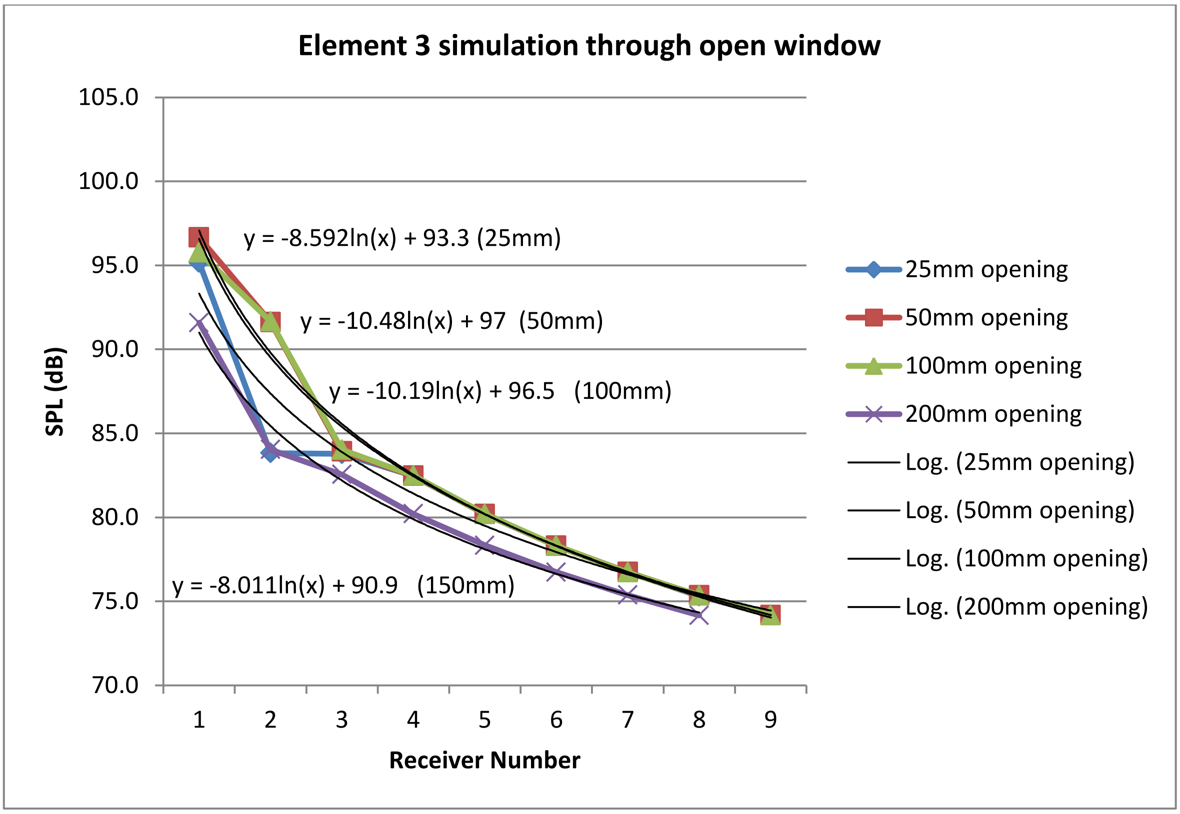


Figure 7.39 Element 3, graph of the resultant dataset from simulation.

7.4.1 CONCLUSION – ELEMENT 3, CATT SIMULATION

The process of simulating element 2 was very successful. CATT is a very effective tool for quick and simple acoustic analysis of rooms and is suited to simulating Element 3.

The results show a 9.6 dB drop from directly outside the façade (receiver 5) to a receiver 6m inside the room. A 14dB drop is calculated to 4m inside the room from receiver 5. Whilst different to the Napier University equation, there may be validity in providing a set of equations for different window types. Napier provided one equation for all scenarios however this may well be too general. It could be construed that the concluding Napier equation maybe as general as the originating 10-15dB drop hypothesis that they were attempting to correct.

The validity of the equations derived from the CATT predictions would require extensive research to provide comparative data against which the true accuracy could be measured.

7.5 SUMMARY OF PREDICTIVE ACOUSTIC ANALYSIS OF DSF

The predictive acoustic analysis comparison to the test building has produced interesting results.

In general the deviation between simulated and measured has been small and shows that there is validity in further research in this area. The deviations seem particularly samll when fluctuation in traffic noise levels is considered.

The selected software programs are adequate for the elements of the sound path they were selected to simulate. Computational times can be kept to a moderate timeframe whilst achieving accurate results. Greater computational time will most likely achieve closer results to that measured.

7.5.1 ELEMENT 1

Noise mapping Element 1 was a very accurate acoustic method of predicting noise levels from source to the face of the DSF. In addition to being able to predict the noise levels it also enables the user to investigate the effects of screening on the façade. The conclusion was that any commercially available acoustic noise mapping predictive software package would yield adequate results.

7.5.2 ELEMENT 2

Element 2 was by far the most important and complicated process within this study. This research did not conclusively in determine whether ray tracing was an accurate method of acoustic prediction within the DSF. The comparison to field tests needs to be broadened and investigated further but the deviation between predicted and measured results was close enough to warrant further research.

The CATT algorithms designed for rooms do appear to suit this form of predictive model and the overall conclusion was that CATT would be suitable for further DSF examination subject to further verification against more field tested projects.

7.5.3 ELEMENT 3

In the past a 10-15 dB reduction was recommended as the transmission loss through open windows. The research of Napier, Fuller and Lurcock advanced the available data however there has been very little predictive research in this area.

This dissertation has found CATT to be very versatile in it’s ability to simulate this scenario and proposes that a selection of research is necessary to verify ray tracing models against laboratory tested windows.

There is no reason to discount the validity of the element 3 data in this research. The resultant data did not accurately fit the current empirical calculations provided by Napier, Fuller et al, however, comparison to other predictive data is required and is another area of potential future research.

CHAPTER 8

CONCLUSION

The overall aim of this study was to investigate whether field testing could support and validate parametric models to enable the façade industry to characterise DSFs more accurately. The metric for judging the success of this study is measured by how successfully each objective was achieved. They are reviewed as follows.

8.1 A Review of regulations and DSF parameters.

The desk based review of acoustic field testing standards and regulations discovered that there were no specific acoustic calculation methods for DSFs. This supported the need to explore the acoustic attenuation of DSFs along the sound path using an elemental approach.

8.2 Characterise the DSF configuration

In chapter 3 the DSF was characterised in terms of geometry and typology. This review was taken in terms of the boundaries and limits set in chapter 1 and as such the review concentrated on NV DSFs. The characterisation of NV DSFs revealed that acoustics is widely cited as an advantage with NV DSF designs. However, these generalisations are anecdotal and could not be validated by research. It is conclusive that acoustics is one of the least researched building physics elements of naturally ventilated façade design including NV DSFs.

8.3 Review parametric modelling procedures

A review of parametric modelling techniques was undertaken in Chapter 3. The modelling typology was mapped to the relevant sound path elements and commercial software packages were selected to simulate each element of the tested buildings.

8.4 Identify selected NV DSF projects and devise acoustic monitoring strategy

In chapter 6, the selected building for onsite acoustic testing was introduced and described in detail. The aim of this study was to select a number of buildings to test but difficulties arose with building owners and developers in relation to commercial confidentiality.

After the study was completed there was one project available that could be tested. The acoustic testing of a multi storey building in an urban environment was challenging. The testing phase posed difficulties that were mostly in relation to the testing methodology. These difficulties were overcome by making decisions with the appropriate justification (table 6.4) for amendments to the testing methodology.

The resulting data was comprehensive however the provision of more receiver points would have provided a more robust set of data. The constraints of time, cost and personnel were underestimated on a study of this magnitude and are relevant issues for future testing and research.

8.5 Parametric Analysis

Acoustic parametric analysis of the field tested facades was undertaken in chapter 7. The selected techniques from chapter 3 were used to simulate all of the selected facades. The simulation was successful in replicating on site tests in all cases. The deviation between field and simulation was noted in each case and showed that overall the deviations were less than 4dB. A larger set of field test data would provide more insight into these deviations.

8.6 Select most effective and useful analysed data to present to the Industry.

The field testing and parametric analysis data was mapped to theoretical hypotheses in chapter 5. The chosen hypotheses for each element of the sound path were combined in a simplistic calculation sheet (Figure 5.15) that could be used by designers if parametric software was not available.

8.7 Recommendations for future work

8.7.1 *Development of an international acoustic technical review committee to produce a comprehensive and integrated framework for research in acoustics applied to façades.*

8.7.2 *Review of current acoustic standards to reflect the current technological advances in double skin façade construction.*

8.7.3 *Development of a simple acoustic calculation sheet for DSF construction and validation with further laboratory and field testing.*

8.7.4 *Development of an integrated acoustic predictive software package for the façade industry. Current acoustic predictive methods require combining the results of separate simulations to reach a conclusive result. There is the possibility of this being an 'add-on' to current predictive environmental software packages.*

8.7.5 *University of Bath to formalise a strategic approach to complete the volume of research outlined in this study.*

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Appendix

Contents

APPENDIX 2 International standards harmonized stage codes

STAGE	SUBSTAGE						
				90 Decision Substages			
	00 Registration	20 Start of main action	60 Completion of main action	92 Repeat an earlier phase	93 Repeat current phase	98 Abandon	99 Proceed
00 Preliminary stage	00.00 Proposal for new project received	00.20 Proposal for new project under review	00.60 Close of review			00.98 Proposal for new project abandoned	00.99 Approval to ballot proposal for new project
10 Proposal stage	10.00 Proposal for new project registered	10.20 New project ballot initiated	10.60 Close of voting	10.92 Proposal returned to submitter for further definition		10.98 New project rejected	10.99 New project approved
20 Preparatory stage	20.00 New project registered in TC/SC work programme	20.20 Working draft (WD) study initiated	20.60 Close of comment period			20.98 Project deleted	20.99 WD approved for registration as CD
30 Committee stage	30.00 Committee draft (CD) registered	30.20 CD study/ballot initiated	30.60 Close of voting/ comment period	30.92 CD referred back to Working Group		30.98 Project deleted	30.99 CD approved for registration as DIS
40 Enquiry stage	40.00 DIS registered	40.20 DIS ballot initiated: 5 *months*	40.60 Close of voting	40.92 Full report circulated: DIS referred back to TC or SC	40.93 Full report circulated: decision for new DIS ballot	40.98 Project deleted	40.99 Full report circulated: DIS approved for registration as FDIS
50 Approval stage	50.00 FDIS registered for formal approval	50.20 FDIS ballot initiated: 2 *months*. Proof sent to secretariat	50.60 Close of voting. Proof returned by secretariat	50.92 FDIS referred back to TC or SC		50.98 Project deleted	50.99 FDIS approved for publication
60 Publication stage	60.00 International Standard under publication		60.60 International Standard published				
90 Review stage		90.20 International Standard under periodical review	90.60 Close of review	90.92 International Standard to be revised	90.93 International Standard confirmed		90.99 Withdrawal of International Standard proposed by TC or SC
95 Withdrawal stage		95.20 Withdrawal ballot initiated	95.60 Close of voting	95.92 Decision not to withdraw International Standard			95.99 Withdrawal of International Standard

Appendix 3 Method Statement (MS01)

John Downes, MSc Façade Engineering Method Statement (MS01)

MS 01 - Method Statement for Acoustic Testing of Façade Elements			
Project		Method Statement Number	MS 01-1-01
Method Statement Description	Acoustic Façade Testing	Status	
Prepared By		Date	
Accepted By (if required)		Date	
Scope of Work	The scope of work includes the acoustic testing of the glazed double skin façade		
Access and Egress	Access to ground level externally. Access to DSF cavity and rooms within the building		
Lighting	None		
Plant and Equipment General	Equipment will be digital source airborne noise, amplifier, loudspeaker and microphones. All test equipment is calibrated annually and will have labels indicating test date.		
Plant and Equipment PPE Power Working Platform			
Materials	None		

John Downes, MSc Façade Engineering Method Statement (MS01)

Sequence of work	
Training	All testers are trained to carry out testing in accordance with ISO 140-5.
Supervision	Testing will be supervised by an experienced and competent tester.
Housekeeping	We do not envisage any waste or scrap material during testing, however, if there is any, operatives will gather up an either dispose of same in appropriate receptacles or bring waste away.
Induction / Briefing Register	Prior to operatives commencing any testing on site, they will receive any induction that they client deems appropriate. If there is no induction by the client the operatives will have a tool box talk to discuss proper procedure in accordance with this method statement (MS01) and Risk assessment (RS01).
Appendices	1. 2. 3. 4.

Appendix 4 Risk Assessment Form (RS01)

UNIVERSITY OF BATH AR50247, John Downes SOP 04	Project: ____ John Downes, MSc Façade Engineering Dissertation RISK ASSESSMENT FORM		RA Nº ____ Page: 1 of ___
Prepared or Reviewed by (name, title and signature)	Accepted for use by Project/Departmental Manager/nominee	Accepted by Employer (if required)	Date
			___/___/___

Risk Assessment for:

Item	Operations	Hazard	Risk	Risk Class	Nºs at Risk	Preventive Measures	Final Risk Class

Key: L = Low M = Medium H = High

Appendix 5 Norsonic Precision Sound Analyser Type 131 with Norsonic Type 1207 Pre-amplifier, Norsonic Type 1228 microphone

Norsonic

PD 131 Ed.2 Rev.0 English 06.07

SPECIFICATIONS:

(Common for both models unless noted.)
The Nor130 series of SLM fulfil the following standards: IEC60651, IEC60804, IEC61672, IEC61260, ANSI S1.4, ANSI S1.11, and ANSI S1.43.
The Nor131 instrument meets the Class1 requirements while the Nor132 instrument is to the Class 2 requirements.

Measured Parameters:
Simultaneous measurement of SPL, L_{eq}, L_{Max}, L_{Min}, L_E and L_{Peak} (plus the T_{max5} for Germany only).

Time weighting functions:
Fast, Slow or Impulse.

Spectral weighting functions:
Simultaneously measurement of A and C or Z-weighting. Additionally the 1/1 octave real time filters covering all bands from 8 Hz to 16K Hz (option 1) or 1/3-octave covering all bands from 6,3Hz to 20kHz (option 4).

Statistical calculations (option 2)
7 fixed percentiles $L_{1\%}$, $L_{5\%}$, $L_{10\%}$, $L_{50\%}$, $L_{90\%}$, $L_{95\%}$, and $L_{99\%}$ plus one user defined value (f.ex. $L_{0.1\%}$). The statistical calculation is performed in real time within each frequency band if the filter option 1 is installed.

Measurement range:
One range covering 120dB without any range adjustments

Self noise measured with microphone:	17dBA (25dBA for Nor132)
Maximum RMS level	137dBA
Maximum Peak level	140dB PeakC

Levels up to 174dB can be measured by use of a suitable 1/4" microphone.

Battery / power consumption:
4 IEC LR6 (AA sized). Separate display showing battery voltage and run time on battery since last battery change. Nominal operation time on one set of batteries is >8 hours. Nominal 11-15V external DC voltage. If external supply drops below 9 volt, it switches uninterrupted to internal batteries.

Datastorage:
5MB internal memory equals to 2.5 million values which typically holds all measured functions from up to 10,000 individual measurements.

Datatransfer:
Data transfer via USB 2.0 interface.

Microphone and preamplifier:
Detachable ICP preamplifier on Nor131 which allows up to 30 meter of extension cable to be used without loss of performance. 100 m for SPL level less than 130 dB and 300 m for SPL level less than 120 dB. Nor132 has a fixed ICPpreamplifier. The microphones are free field electret types. A build in random incidence correction network can be selected. A built in optional correction network for the windscreen can also be selected.

Analogue output:
AC output, 100mV for full scale deflection.

Specifications subject to changes without notice.

Norsonic
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Tel.: +47 3285 8900 Fax.: +47 3285 2208
info@norsonic.com www.norsonic.com

Distributor:

Calibrators Nor1251/52/53 Specifications

	Nor1253	Nor1251	Nor1252
IEC60942 Classification	Class L (Previous Class 0)	Class 1	Class 2
Complies with ANSI S1.40	Yes	Yes	Yes
Sound pressure level (re: 20µPa)	124.0±0.2dB	114.0±0.2dB	114.0±0.4dB
Frequency	250Hz±0.2% or 1000Hz±0.2%	1000Hz±0.2%	1000Hz±0.2%
Distortion	<1%	<1%	<1%
Sensitivity to change in the load volume	-0.00002dB/mm3 (250Hz) +0.0003dB/mm3 (1000Hz)	+0.0003dB/mm3	+0.0003dB/mm3
Typical change in SPL per year	<0.01dB	<0.02dB	<0.02dB
Time for level to stabilise	<2 sec.	<2 sec.	<2 sec.
Microphone cartridge size	1", ½", ¼"	1", ½", ¼"	½", ¼"
Controls	Power-on pushbutton with green LED indication Automatic shut-off when the microphone is removed (except for ¼")		
Temperature range	-10°C to +50°C	-10°C to +50°C	-10°C to +50°C
Ambient pressure range	65--108kPa	65--108kPa	65--108kPa
Humidity range	10--90%RH	10--90%RH	10--90%RH
Battery type	9V 6LR61	9V 6LR61	9V 6LR61
Battery life-time	9V 6LR61	9V 6LR61	9V 6LR61
Battery life-time	>20 hours	>30 hours	>30 hours
External supply voltage	7.5--15Vdc. Automatic shut-off when Vbatt<7.5Vdc		
CE classification, EMC	EN50081-1, EN 50082-1		
Safety	EN61010-1, 1993 portable equipment pollution category 2		
Size	L: 109.5mm; Ø: 40mm		
Weight	185g with battery		

Appendix 5   JBL Powered Loudspeakers (X2) PRX512M

JBL

PRX512M

12" 2-Way Multipurpose Self-Powered Sound Reinforcement System

Features:

- Dual angle enclosure for both front-of-house and floor monitor applications
- Optimized EQ for monitor or front-of-house applications
- JBL Differential Drive® woofer
- 1.5" annual polymer diaphragm compression driver
- Class-D, Crown® digital amplifier: lightweight, compact, multi channel, heritage
- DSP input section, crossover, dynamic limiting, component optimization, selectable system EQ
- Professional XLR line and ¼" Mic/Instrument inputs, with loop through.
- Illuminated logo for clear Power-On status
- Dual angle pole mount socket
- DuraFlex™ coated plywood construction

Application:

PRX512M is the most compact and versatile speaker in the PRX500 Series. It has been designed to deliver the most performance for its weight and size as both a stage monitor and a front of house main PA. Two user selectable EQ settings are provided to optimize the system for either application. With a dual socket pole mount the PRX512M is a perfect match with a PRX518S subwoofer, offering a high performance self-powered sub/sat system.

The PRX512M is a self-powered, lightweight two-way multipurpose loudspeaker system. The PRX512M is comprised of a 262F 305 mm (12") Differential Drive® woofer, a 2408H 37.5 mm (1.5 in) annular polymer diaphragm, neodymium compression driver mounted to a 70° by 70° horn, all driven by a multi-channel Crown International Class-D digital power amplifier. A propriety DSP chip is at the core of a fully featured input section, providing user selectable system EQ, protection, input sensitivity selection, cross-over functionality, dynamic limiting and discrete component optimization.

The enclosure is constructed of quality plywood and coated in JBL's rugged DuraFlex™ finish. An integrated dual angle pole mount on the bottom enables easy deployment and aiming. The CNC-machined steel grille wraps around the sides of the enclosure so there are no protruding lips on the front of the box to create acoustical interference. The grille is also lined with an acoustically transparent foam to provide additional driver protection.

The amplifier input panel offers XLR or ¼ inch jack compatibility and a sensitivity switch provides extra flexibility, making it possible to connect literally any sound source without using a mixer. Signal present and overload lights indicate the system status and assist in setting the optimum level, via the level control knob.

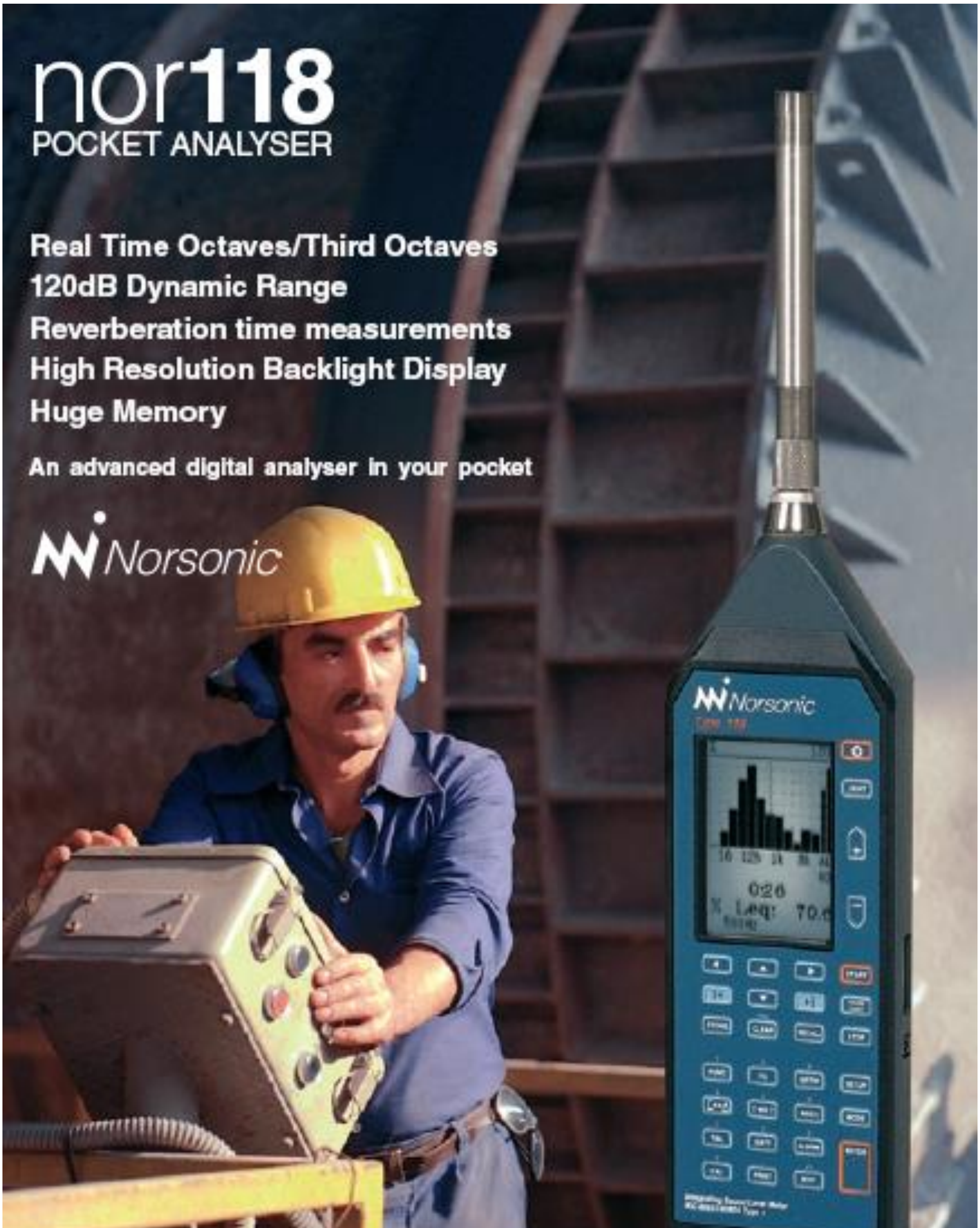
Preliminary Specifications:

System Type:	Self powered 12", two-way, bass-reflex,
Frequency Range (-10 dB):	46 Hz – 20 kHz (EQ in main position) 60 Hz – 20 kHz (EQ in monitor position)
Frequency Response (±3 dB):	76 Hz – 20 kHz (EQ in main position) 90 Hz – 20 kHz (EQ in monitor position)
Coverage Pattern:	70° x 70° nominal
Directivity Index (DI):	10.2 dB
Directivity Factor (Q):	10.8
Crossover Modes:	DSP controlled 48 dB filter slope
Crossover Frequency:	1.6 kHz
System Power Rating	500 W continuous, 1000 W peak
LF Power amp	Class-D, 400 Watt (continuous) at driver impedance
HF Power amp	Class-D, 100 Watt (continuous) at driver impedance
Distortion:	Less than 0.1% at rated power
Maximum Peak Output*:	135 dB SPL
Signal Indicators:	Overload: Red LED indicates input overload condition Signal: Green LED indicates signal presents
Input sensitivity:	Mic position: –25 dBu to 0 dBu Line position: +20 dBu to +10 dBu
Input Impedance:	64 K Ohms (balanced), 32 K Ohms (unbalanced)
EQ:	Presets for Main and Monitor position
LF Driver:	1 x JBL 262F 380 mm (12 in) Differential Drive® woofer
HF Driver:	1 x JBL 2408H 37.5 mm (1.5 in) annular polymer diaphragm, neodymium compression driver
Enclosure:	Trapezoidal, 18 mm, plywood
Suspension / Mounting:	Dual 36 mm pole socket
Transport:	Integrated handle with backing cup
Finish:	Anthracite DuraFlex™ finish
Grille:	Powder coated, Anthracite black, 18 gauge perforated steel with acoustically transparent black foam backing.
Input Connectors:	Balanced XLR / ¼ inch combo jack with XLR loop through,
Dimensions (H x W x D):	650 mm x 380 mm x 350 mm (25.5 in x 15 in x 14 in)
Net Weight:	18 kg (40 lb)

* Maximum Peak output measured with IEC pink noise at 1 meter in front of speaker baffle under free space conditions. Measurement instrument set to peak hold. Speaker tested and calibrated at full power, recording maximum peak level.

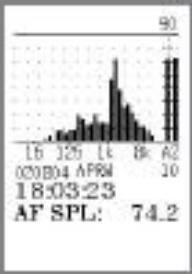
JBL continually engages in research related to product improvement. Some materials, production methods and design refinements are introduced into existing products without notice as a routine expression of that philosophy. For this reason, any current JBL product may differ in some respect from its published description, but will always equal or exceed the original design specifications unless otherwise stated.

Appendix 8 Norsonic Precision Sound Analyser Type 118

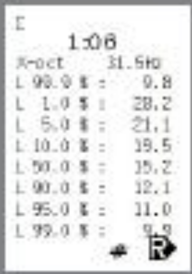


Typical screen displays

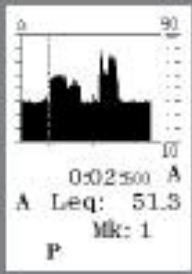
Sound level meter display mode



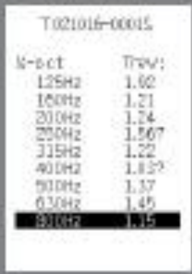
Real time octave and third octave analysis. To view the A-weighted spectrum press the A-PREW button



Real time statistics, even in octaves and third octaves



Electronic level recorder with markers



Reverberation time in octaves and third octaves

Specifications

IEC60651 type 1, IEC60804 type 1 and IEC61672-1 class 1. IEC 61260 class 1 in octaves/third octave bands

Dimensions: 76 × 234 × 32 [mm] (W×H×D). Height is 365mm with preamplifier and microphone cartridge.

Weight: 630g, 1,4lbs with batteries

Display: High resolution backlight LCD. 160 × 240 pixels

Simultaneous measurement of: SPL, L_{max}, L_{min}, L_{eq}, SEL, L_{peak}, L[illegible]

Spectral weighting: Simultaneous measurement of A and C or Z weighting and octaves or third octaves (third octave filters are optional)

Octave filters: 8, 16, ..., 16000Hz class 1 digital filters

Third octave filters: 6.3, 8, 10, ..., 20000Hz class 1 digital filters

Dynamic range: 120dB

Power: Batteries 4 cells type AA or 12V external DC

Data storage: 5MB = 2.5 million values in L(1) mode

Also available: Nor-Protector, MS-Windows® based software for hearing protector selection based on the measured levels.

Norsonic

For full brochure and further details please contact:
Norsonic AS, P.O.Box 24,
N-3421 Lierskogen, Norway
Telephone: +47 3285 8900
Facsimile: +47 3285 2208
info@norsonic.com www.norsonic.com

Distributor

Campbell Associates

Appendix 9 Olympic 6 Reverberation Time Test Gun

Specifications

Item Features:

Caliber : .22 Short Crimps

Finish: Black

Length: 7" Overall, 2" Barrel

Weight: 13 oz

Rounds: 8

Grips: Plastic Black

Action: Single & Double

The Olympic 6 is an affordable starter pistol and dog training pistol. It fires single or double action. The cylinder swings open to accept eight (8) .22 caliber short crimped blanks only.

This replica gun cannot be converted to fire live ammo. The barrel is plugged and has a red dot at the end in compliance with ATF regulations. No federal license required.

Appendix 10 Test 1 S1/E1 Levels 1-12 Complete Dataset

Location	Test No		LAeq	63 Hz	125 Hz	250 Hz	500 Hz	1.0 kHz	2.0 kHz	4.0 kHz	8.0 kHz
E1_Level 1_Out	**1,1**	**L1**	65.7	73.3	68.3	65.4	61.8	62.7	55.1	48.5	38.8
E1_Level 1_In		**L2**	63.9	78.3	67.2	61.3	59.7	60.9	54	44.1	33
		L1-L2	1.8	-5	1.1	4.1	2.1	1.8	1.1	4.4	5.8
		RT	0.2	0.2	1.0	0.6	0.7	0.8	0.6	0.5	0.8
S1_Level 1_Out	**1,2**	**L1**	74	80.4	71.8	72.1	70.2	70.9	64.8	58.6	51.5
S1_Level 1_In		**L2**	71.5	84.9	71.2	64.8	66.7	69	62.1	54.7	46
		L1-L2	2.5	-4.5	0.6	7.3	3.5	1.9	2.7	3.9	5.5
		RT	2.3	0.2	0.7	0.9	0.9	0.9	0.7	0.4	0.8
E1_Level 2_Out	**1,3**	**L1**	65.3	70.5	65.5	63.4	61.1	62.5	55.8	49.1	40.1
E1_Level 2_In		**L2**	63.4	74.5	67.5	62.7	58.7	60.4	53.5	43.9	33.3
		L1-L2	1.9	-4	-2	0.7	2.4	2.1	2.3	5.2	6.8
		RT	2	0.5	1.1	1	0.8	0.8	0.7	0.6	0.9
S1_Level 2_Out	**1,4**	**L1**	75.9	74.4	72.5	73.7	71.9	72.9	67.4	59.3	51.6
S1_Level 2_In		**L2**	72.9	79.3	71	68	68	70.7	63.8	54.9	45.1
		L1-L2	3	-4.9	1.5	5.7	3.9	2.2	3.6	4.4	6.5
		RT	2.9	0.7	0.7	1	1	1	0.8	0.5	0.9
E1_Level 3_Out	**1,5**	**L1**	68.2	71.4	64.8	64.1	63.2	66.2	58.3	50.1	40.6
E1_Level 3_In		**L2**	64.7	76.1	64.4	61.2	59.9	62.2	55.5	46.1	34.8
		L1-L2	3.5	-4.7	0.4	2.9	3.3	4	2.8	4	5.8
		RT	4	0.7	1.2	1.1	0.9	0.9	0.8	0.6	0.9
S1_Level 3_Out	**1,6**	**L1**	77.7	77.1	72.8	73.1	72.8	75.6	68.6	59.3	49.9
S1_Level 3_In		**L2**	73.9	82.9	70	66.3	68.1	72.3	64.3	53.4	41.4
		L1-L2	3.8	-5.8	2.8	6.8	4.7	3.3	4.3	5.9	8.5
		RT	4.2	0.7	1.3	1.1	1.0	1.0	0.9	0.6	1.0
E1_Level 4_Out	**1,7**	**L1**	65.4	69.4	65.5	62.7	60.7	62.9	56.1	47.4	37.7
E1_Level 4_In		**L2**	63.7	73.6	63.9	61.6	58.7	61.1	54.1	43.2	31.6
		L1-L2	1.7	-4.2	1.6	1.1	2	1.8	2	4.2	6.1
		RT	3.9	0.8	1.0	1.1	1.0	0.9	0.8	0.6	0.9
S1_Level 4_Out	**1,8**	**L1**	78.2	73.9	71.5	72.8	73.4	76.3	68.2	58.9	49.5
S1_Level 4_In		**L2**	74.3	77.3	68.7	65.4	68.5	72.7	64.6	53	41
		L1-L2	3.9	-3.4	2.8	7.4	4.9	3.6	3.6	5.9	8.5
		RT	1.4	0.4	1.1	1.1	1.0	1.0	0.9	0.6	1.0
E1_Level 5_Out	**1,9**	**L1**	70	70.3	65.5	65.8	65.2	67.9	60.1	51.1	41.9
E1_Level 5_In		**L2**	67.1	74.6	65.5	63.3	62.5	64.8	57.8	46.9	35.5
		L1-L2	2.9	-4.3	0	2.5	2.7	3.1	2.3	4.2	6.4
		RT	1.5	0.7	1.5	1.1	1	1	0.7	0.8	0.9
S1_Level 5_Out	**1,10**	**L1**	78.6	76	71.4	72.9	73.6	76.8	68.8	58.8	50.5
S1_Level 5_In		**L2**	74.4	80.7	71.5	65.6	68.5	72.8	65	53.9	42.3
		L1-L2	4.2	-4.7	-0.1	7.3	5.1	4	3.8	4.9	8.2
		RT	1.2	0.5	1.1	1.1	1.0	1.0	0.9	0.7	1.0
E1_Level 6_Out	**1,11**	**L1**	72.3	73.9	71.9	72.7	69.6	68.9	62.3	54.8	44.9
E1_Level 6_In		**L2**	68.3	77	69.5	68	65.4	65.1	58.7	48.9	36.4
		L1-L2	4	-3.1	2.4	4.7	4.2	3.8	3.6	5.9	8.5
		RT	3	0.5	1.1	1	0.9	0.8	0.8	0.6	0.8
S1_Level 6_Out	**1,12**	**L1**	74.7	73.5	68.9	70.1	70.2	72.7	64.8	55.9	47.1
S1_Level 6_In		**L2**	70.6	77.5	68.5	63.7	65.2	68.8	60.8	50.6	38.5
		L1-L2	4.1	-4	0.4	6.4	5	3.9	4	5.3	8.6
		RT	3.1	0.5	1.2	1.1	1.0	0.9	0.9	0.6	0.9

E1_Level 7_Out	**1,13**	**L1**	68.8	72.3	68.1	64.5	64.5	66	59.9	55.9	46.6
E1_Level 7_In		**L2**	65.9	75.5	66.6	61.3	61.1	63	57.8	50.4	38.2
		L1-L2	2.9	-3.2	1.5	3.2	3.4	3	2.1	5.5	8.4
		RT	3	0.5	0.9	1.2	1.2	1	0.9	0.7	1
S1_Level 7_Out	**1,14**	**L1**	77.1	74.1	70.9	71.7	72	75.3	67.4	57	47.1
S1_Level 7_In		**L2**	73	78.8	68.3	65.1	67	71.4	63.8	52	38.8
		L1-L2	4.1	-4.7	2.6	6.6	5	3.9	3.6	5	8.3
		RT	3.1	0.5	0.9	1.2	1.2	1.0	0.9	0.7	1.0
E1_Level 8_Out	**1,15**	**L1**	68.6	70.1	64.8	65.4	64.2	66.4	58.5	49.3	39.2
E1_Level 8_In		**L2**	65.8	75.3	64.1	62.4	61.3	63.5	56.2	45.1	31.9
		L1-L2	2.8	-5.2	0.7	3	2.9	2.9	2.3	4.2	7.3
		RT	2.2	1.2	0.9	1.2	1.1	1	0.9	0.7	1
S1_Level 8_Out	**1,16**	**L1**	72.5	71.2	73.6	70.1	68.9	69.8	62.6	52	43
S1_Level 8_In		**L2**	68.6	76.6	76	66	64.1	65.6	58.1	48.8	35.1
		L1-L2	3.9	-5.4	-2.4	4.1	4.8	4.2	4.5	3.2	7.9
		RT	2.5	1.2	0.8	1.2	1.1	1.0	0.9	0.7	1.0
E1_Level 9_Out	**1,17**	**L1**	69.1	71.9	68.3	66.1	64.9	66.5	59.7	51.4	41.9
E1_Level 9_In		**L2**	66.2	76.7	68	62.7	62	63.4	57.2	47	34
		L1-L2	2.8	-5.2	0.7	3	2.9	2.9	2.3	4.2	7.3
		RT	2.9	1.5	0.7	0.8	0.9	0.9	0.8	0.7	0.8
S1_Level 9_Out	**1,18**	**L1**	75	76.3	69.1	69.3	70.4	72.9	65.8	55.7	44.8
S1_Level 9_In		**L2**	71.8	77	67.3	63	65.9	70.1	62.6	50.8	36.5
		L1-L2	3.2	-0.7	1.8	6.3	4.5	2.8	3.2	4.9	8.3
		RT	3.8	1.6	0.7	0.9	0.9	0.9	0.9	0.7	0.9
E1_Level 10_Out	**1,19**	**L1**	68.2	70.8	65.8	64.5	64	65.8	58.9	49.9	39.5
E1_Level 10_In		**L2**	65.6	72.9	65.9	62.7	61.4	63.1	56.2	45.6	32.3
		L1-L2	2.6	-2.1	-0.1	1.8	2.6	2.7	2.7	4.3	7.2
		RT	3	1.7	0.9	0.9	0.9	0.9	0.8	0.7	0.9
S1_Level 10_Out	**1,20**	**L1**	74.7	81	72.9	69.9	70	72.7	65	54	43.5
S1_Level 10_In		**L2**	71.4	85.9	75.4	64.7	65	69.3	61.8	49.5	35
		L1-L2	3.3	-4.9	-2.5	5.2	5	3.4	3.2	4.5	8.5
		RT	3.5	1.9	1.0	0.9	0.9	0.9	0.8	0.7	0.9
E1_Level 11_Out	**1,21**	**L1**	68.1	70.3	64.8	64.6	63.6	65.9	58.2	49.7	39.2
E1_Level 11_In		**L2**	65.1	74.9	64.4	61.4	60.4	62.7	56	45.7	31.7
		L1-L2	3	-4.6	0.4	3.2	3.2	3.2	2.2	4	7.5
		RT	2.7	1.8	0.9	0.8	0.9	0.9	0.8	0.7	0.9
S1_Level 11_Out	**1,22**	**L1**	73.7	79.1	72.3	68.7	69.4	71.5	63.8	54.1	43.8
S1_Level 11_In		**L2**	70.5	81.1	69.9	63.9	65.6	68.5	60.7	49.7	35.8
		L1-L2	3.2	-2	2.4	4.8	3.8	3	3.1	4.4	8
		RT	2.8	1.8	0.9	0.9	0.9	0.9	0.8	0.6	0.9
E1_Level 12_Out	**1,23**	**L1**	64.5	68.6	67.8	64.6	60.4	61.6	53.4	43.9	33
E1_Level 12_In		**L2**	61.5	72.2	64.1	60.1	57.7	58.6	51.1	40.2	27.6
		L1-L2	3	-3.6	3.7	4.5	2.7	3	2.3	3.7	5.4
		RT	2.6	1.7	0.8	1	0.9	0.9	0.8	0.7	0.8
S1_Level 12_Out	**1,24**	**L1**	75	72.7	69.3	70.3	70.9	72.9	64.7	54.8	44.7
S1_Level 12_In		**L2**	71.4	78	70.7	65.3	66.7	69.5	61.8	50.8	36.8
		L1-L2	3.6	-5.3	-1.4	5	4.2	3.4	2.9	4	7.9
		RT	2.7	1.8	0.9	1.0	0.9	0.9	0.8	0.7	0.9

Appendix 11 Test 1 S1/E1 Levels 1-12 Graphs for 1.2-1.24

Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

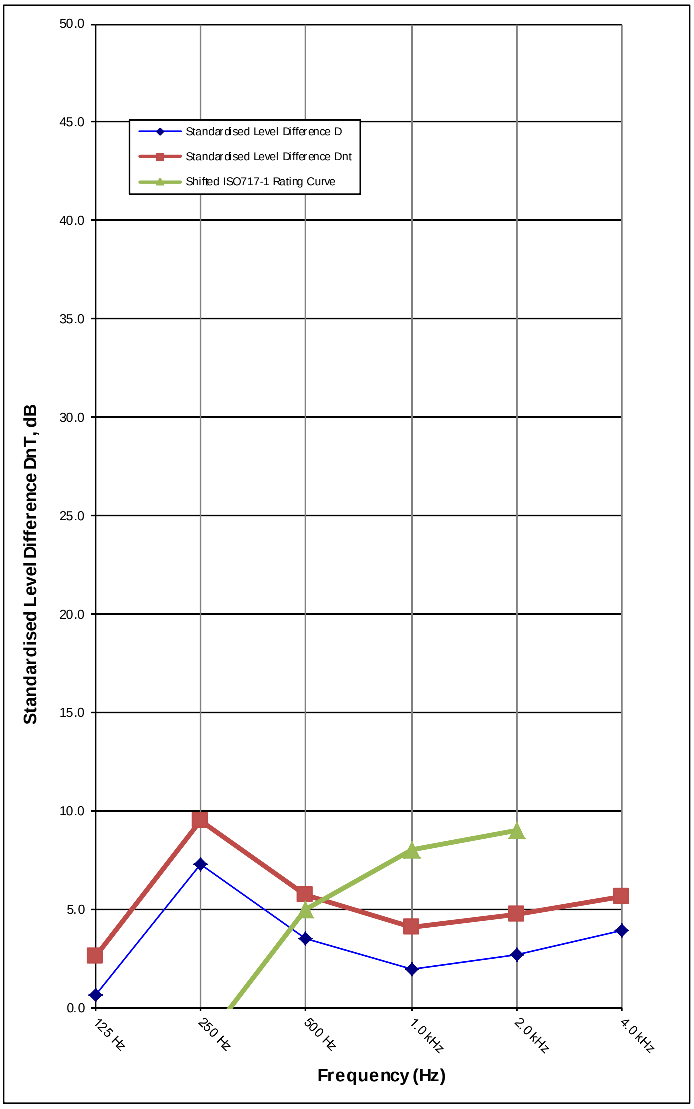
Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 2**

Site: Building A, London

Source room : S1_Level 1_Environment_181 Receiver room : S1_Level 1_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-4.5	-3.0
125	0.6	2.6
250	7.3	9.5
500	3.5	5.7
1k	1.9	4.1
2k	2.7	4.7
4k	3.9	5.6



Rating according to ISO 717-1

$D_{nT,w}$ = 5 dB **$D_{w=}$** **3 dB** N/A

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

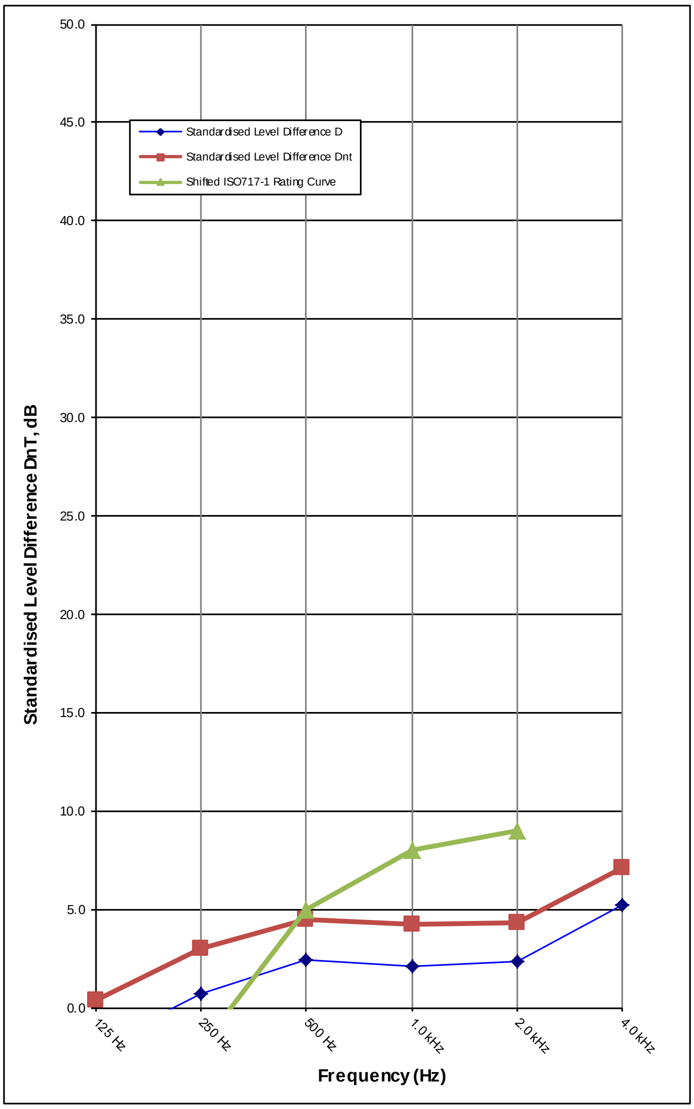
Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 3**

Site: Building A, London

Source room : E1_Level 2_Environment_181 Receiver room : E1_Level 2_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-4.0	-2.2
125	-2.0	0.4
250	0.7	3.0
500	2.4	4.5
1k	2.1	4.2
2k	2.3	4.3
4k	5.2	7.1



Rating according to ISO 717-1

$D_{nT,w}$ = 5 dB **$D_{w=}$** **3 dB** N/A

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

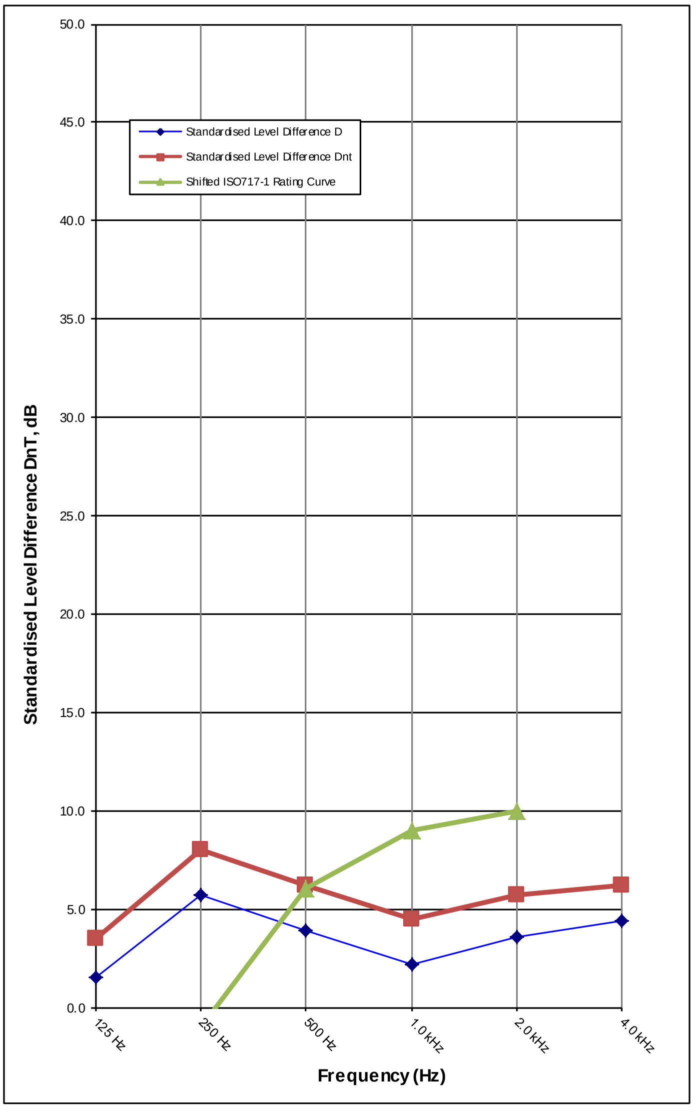
Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 4**

Site: Building A, London

Source room : S1_Level 2_Environment_181 Receiver room : S1_Level 2_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-4.9	-2.9
125	1.5	3.5
250	5.7	8.0
500	3.9	6.2
1k	2.2	4.5
2k	3.6	5.7
4k	4.4	6.2



Rating according to ISO 717-1

$D_{nT,w}$ = 6 dB **$D_{w=}$** **4 dB** N/A

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

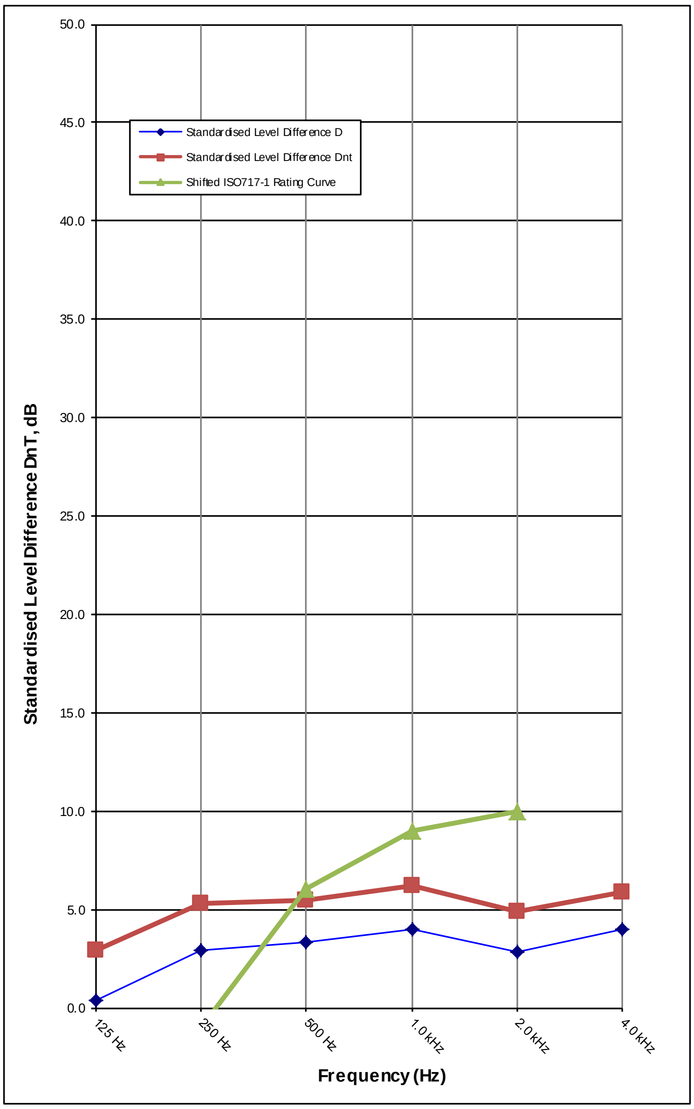
Client: John Dow nes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 5**

Site: Building A, London

Source room : E1_Level 3_Environment_181 Receiver room : E1_Level 3_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-4.7	-2.7
125	0.4	2.9
250	2.9	5.3
500	3.3	5.5
1k	4.0	6.2
2k	2.8	4.9
4k	4.0	5.9



Rating according to ISO 717-1

$D_{nT,w}$ = 6 dB **D_{w}=** **4 dB** N/A

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

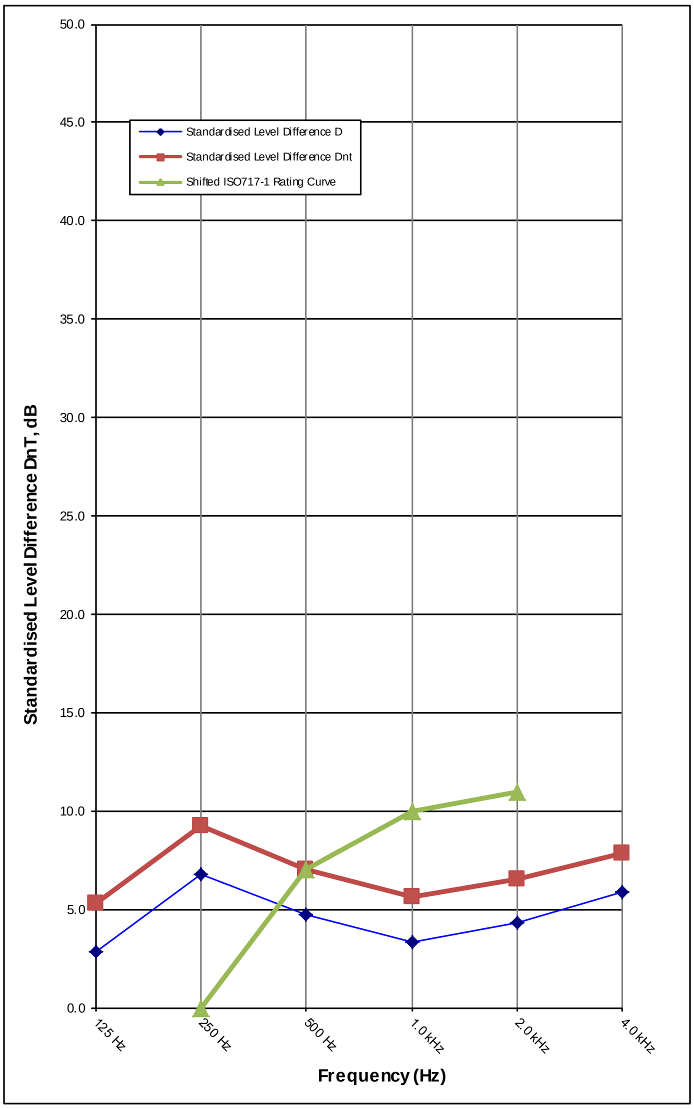
Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 6**
Site: Building A, London

Source room : S1_Level 3_Environment_181 Receiver room : S1_Level 3_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-5.8	-3.8
125	2.8	5.3
250	6.8	9.2
500	4.7	7.0
1k	3.3	5.6
2k	4.3	6.5
4k	5.9	7.8



Rating according to ISO 717-1

$D_{nT,w}$ = 7 dB **$D_{w=}$** **5 dB** N/A

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

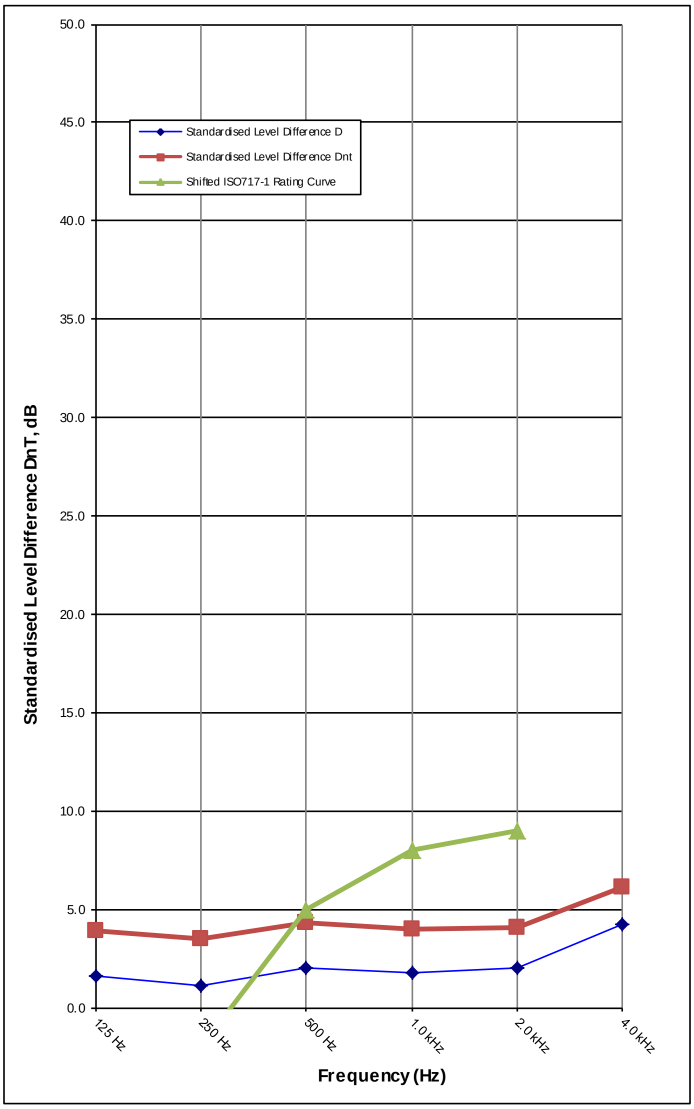
Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 7**
Site: Building A, London

Source room : E1_Level 4_Environment_181 Receiver room : E1_Level 4_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-4.2	-2.1
125	1.6	3.9
250	1.1	3.5
500	2.0	4.3
1k	1.8	4.0
2k	2.0	4.1
4k	4.2	6.1



Rating according to ISO 717-1

$D_{nT,w}$ = 5 dB **D_{w}=** **2 dB** N/A

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

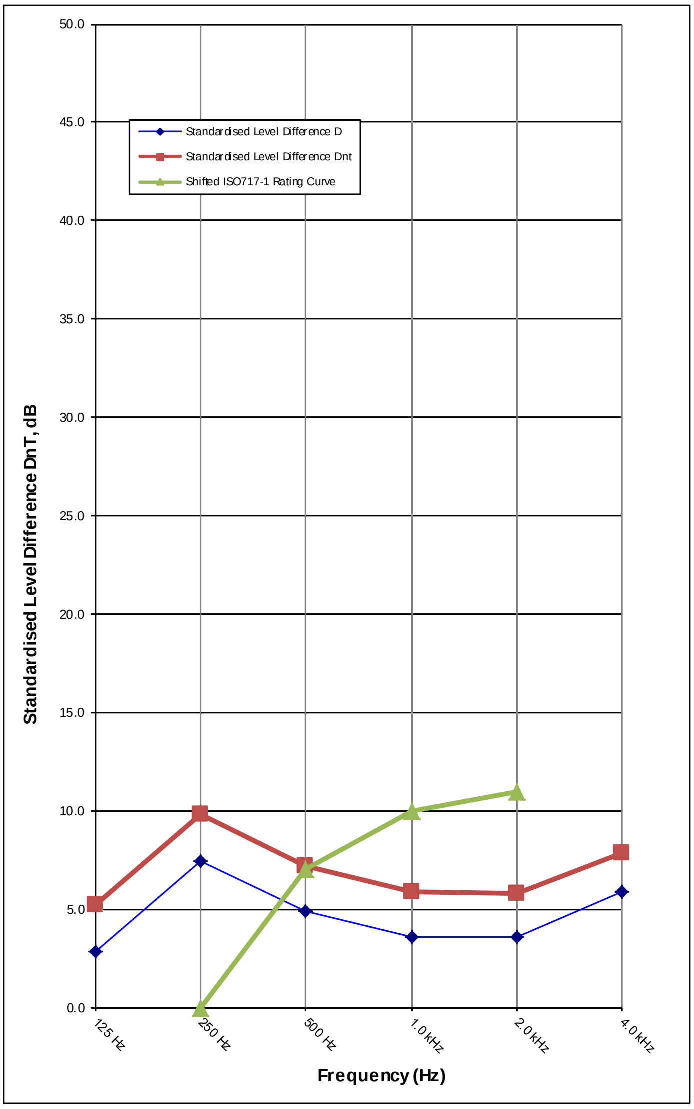
Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 8**
Site: Building A, London

Source room : S1_Level 4_Environment_181 Receiver room : S1_Level 4_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-3.4	-1.7
125	2.8	5.2
250	7.4	9.8
500	4.9	7.2
1k	3.6	5.9
2k	3.6	5.8
4k	5.9	7.8



Rating according to ISO 717-1

$D_{nT,w}$ = 7 dB **$D_{w=}$** **5 dB** N/A

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

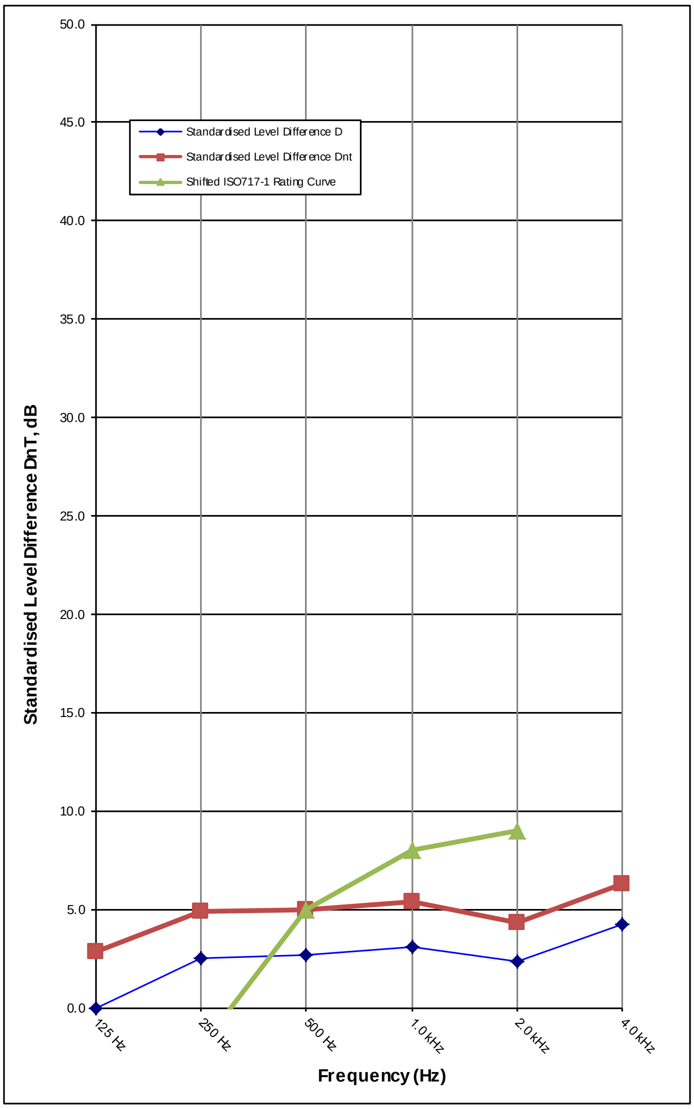
Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 9**

Site: Building A, London

Source room : E1_Level 5_Environment_181 Receiver room : E1_Level 5_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-4.3	-2.3
125	0.0	2.8
250	2.5	4.9
500	2.7	5.0
1k	3.1	5.4
2k	2.3	4.3
4k	4.2	6.3



Rating according to ISO 717-1

$D_{nT,w}$ = 5 dB **D_{w}=** **3 dB**

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

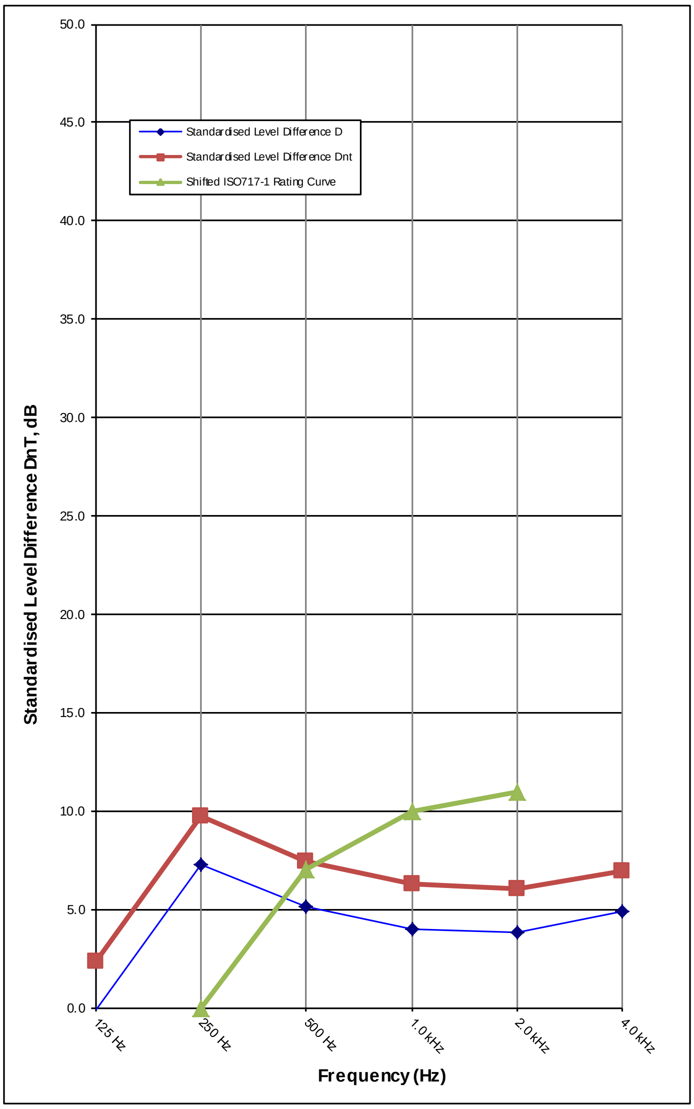
Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 10**
Site: Building A, London

Source room : S1_Level 5_Environment_181 Receiver room : S1_Level 5_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-4.7	-2.9
125	-0.1	2.3
250	7.3	9.7
500	5.1	7.4
1k	4.0	6.3
2k	3.8	6.0
4k	4.9	6.9



Rating according to ISO 717-1

$D_{nT,w}$ = 7 dB **$D_{w=}$** **5 dB**

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

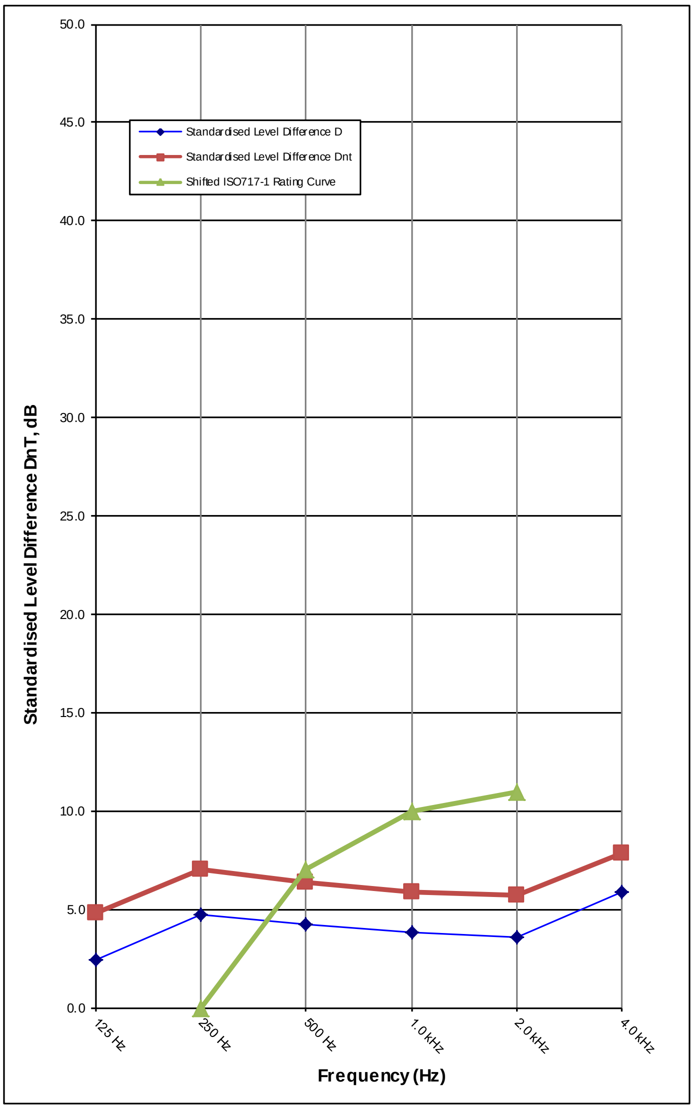
Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 11**
Site: Building A, London

Source room : E1_Level 6_Environment_181 Receiver room : E1_Level 6_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-3.1	-1.3
125	2.4	4.8
250	4.7	7.0
500	4.2	6.4
1k	3.8	5.9
2k	3.6	5.7
4k	5.9	7.8



Rating according to ISO 717-1

$D_{nT,w}$ = 7 dB **D_{w}=** **4 dB**

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

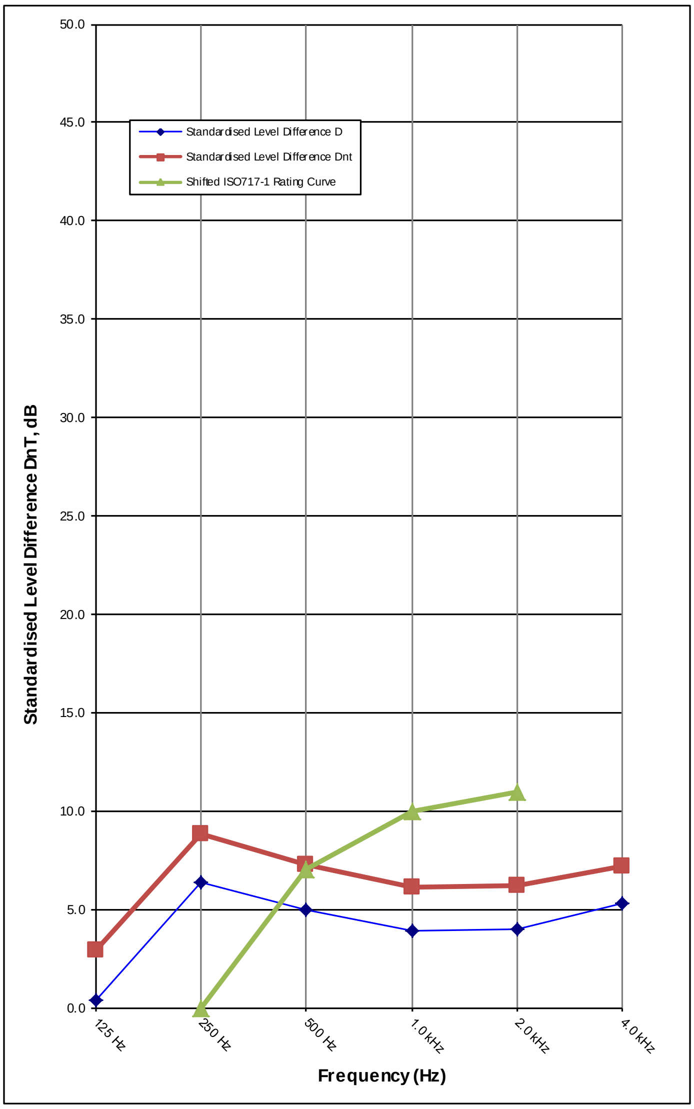
Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 -12**
Site: Building A, London

Source room : S1_Level 6_Environment_181 Receiver room : S1_Level 6_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-4.0	-2.2
125	0.4	2.9
250	6.4	8.8
500	5.0	7.3
1k	3.9	6.1
2k	4.0	6.2
4k	5.3	7.2



Rating according to ISO 717-1

$D_{nT,w}$ = 7 dB **D_{w}=** **5 dB**

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

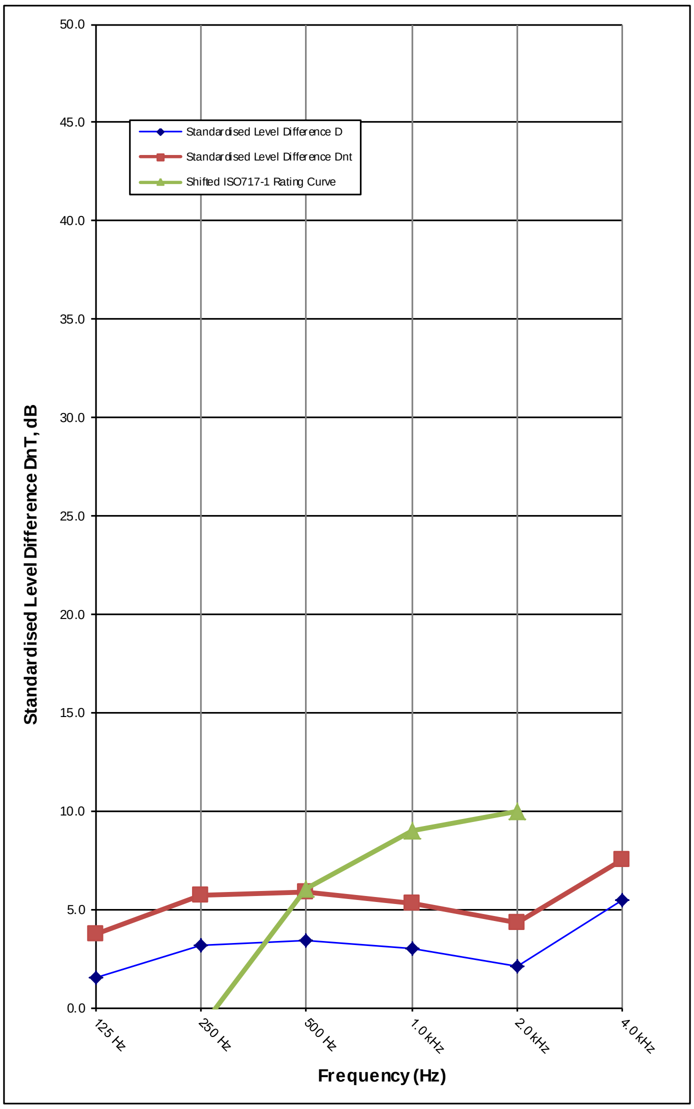
Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 13**
Site: Building A, London

Source room : E1_Level 7_Environment_181 Receiver room : E1_Level 7_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-3.2	-1.4
125	1.5	3.7
250	3.2	5.7
500	3.4	5.9
1k	3.0	5.3
2k	2.1	4.3
4k	5.5	7.5



Rating according to ISO 717-1

$D_{nT,w}$ = 6 dB **$D_{w=}$** **3 dB**

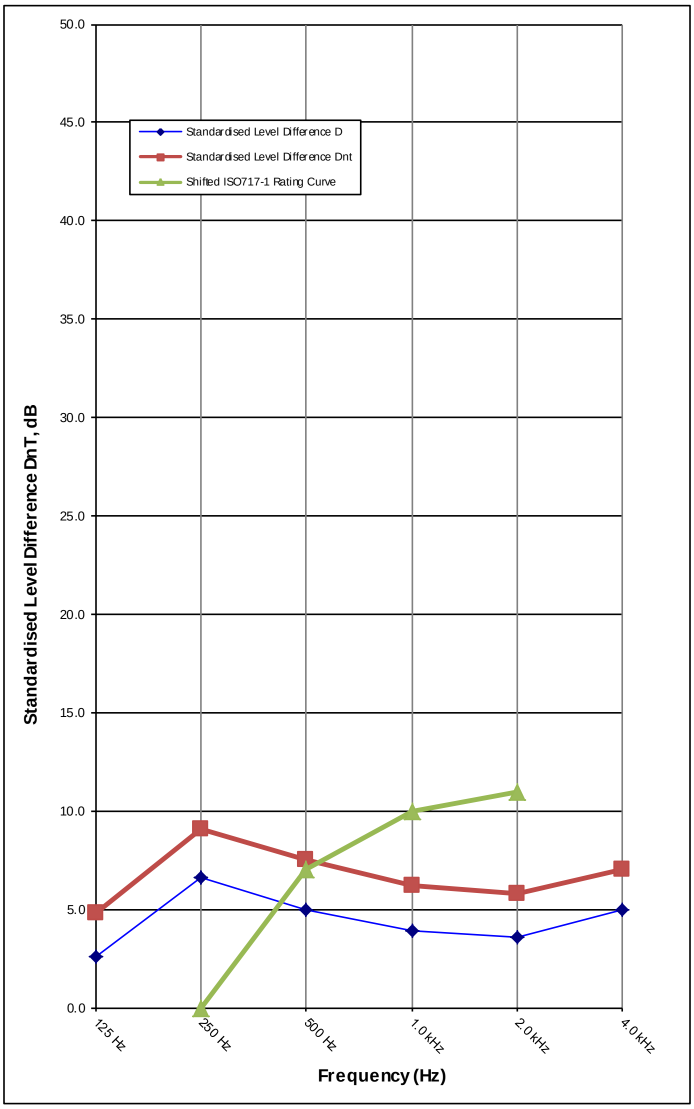
Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 14**
Site: Building A, London

Source room : S1_Level 7_Environment_181 Receiver room : S1_Level 7_In Cavity_131

Frequency (Hz)	D, dB	DnT, dB
63	-4.7	-2.9
125	2.6	4.8
250	6.6	9.1
500	5.0	7.5
1k	3.9	6.2
2k	3.6	5.8
4k	5.0	7.0



Rating according to ISO 717-1

$D_{nT,w}$ = 7 dB **D_{w}=** **5 dB**

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

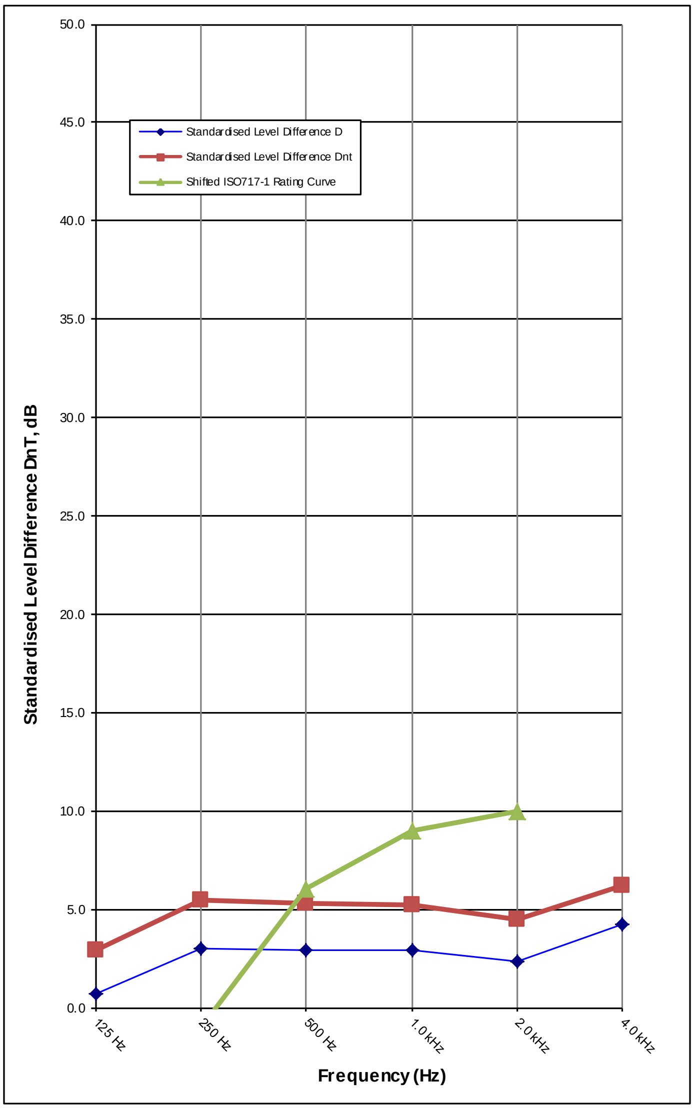
Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 15**
Site: Building A, London

Source room : E1_Level 8_Environment_181 Receiver room : E1_Level 8_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-5.2	-2.7
125	0.7	2.9
250	3.0	5.5
500	2.9	5.3
1k	2.9	5.2
2k	2.3	4.5
4k	4.2	6.2



Rating according to ISO 717-1

$D_{nT,w}$ = 6 dB **D_{w}=** **3 dB**

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

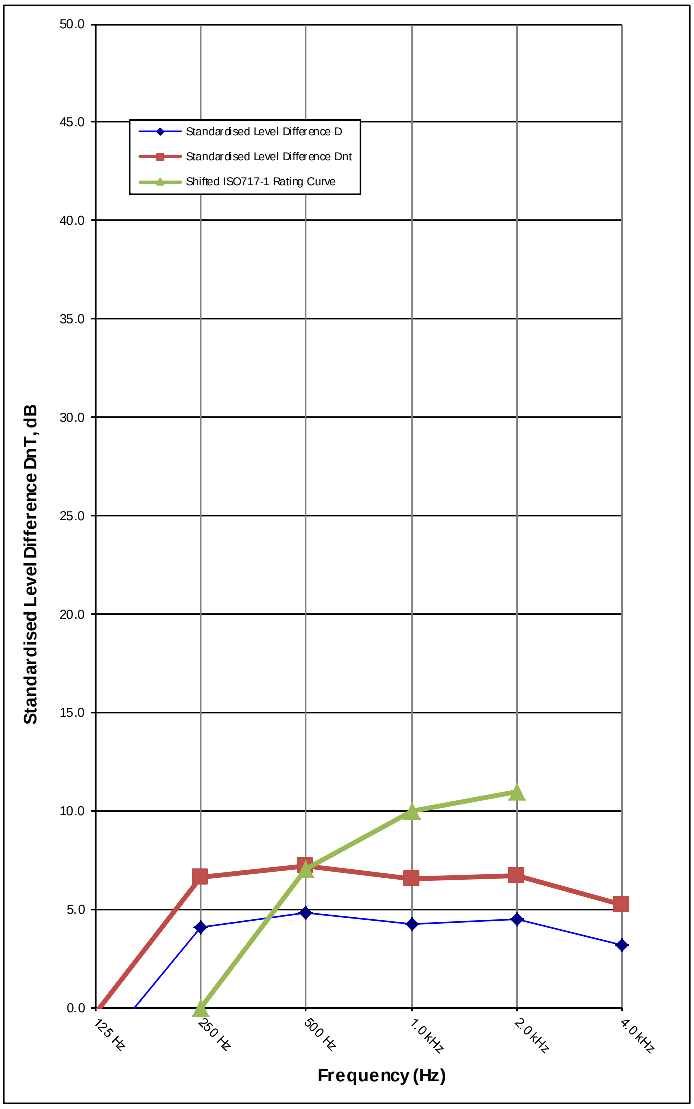
Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 16**
Site: Building A, London

Source room : S1_Level 8_Environment_181 Receiver room : S1_Level 8_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-5.4	-2.9
125	-2.4	-0.3
250	4.1	6.6
500	4.8	7.2
1k	4.2	6.5
2k	4.5	6.7
4k	3.2	5.2



Rating according to ISO 717-1

$D_{nT,w}$ = 7 dB **$D_{w=}$** **5 dB**

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

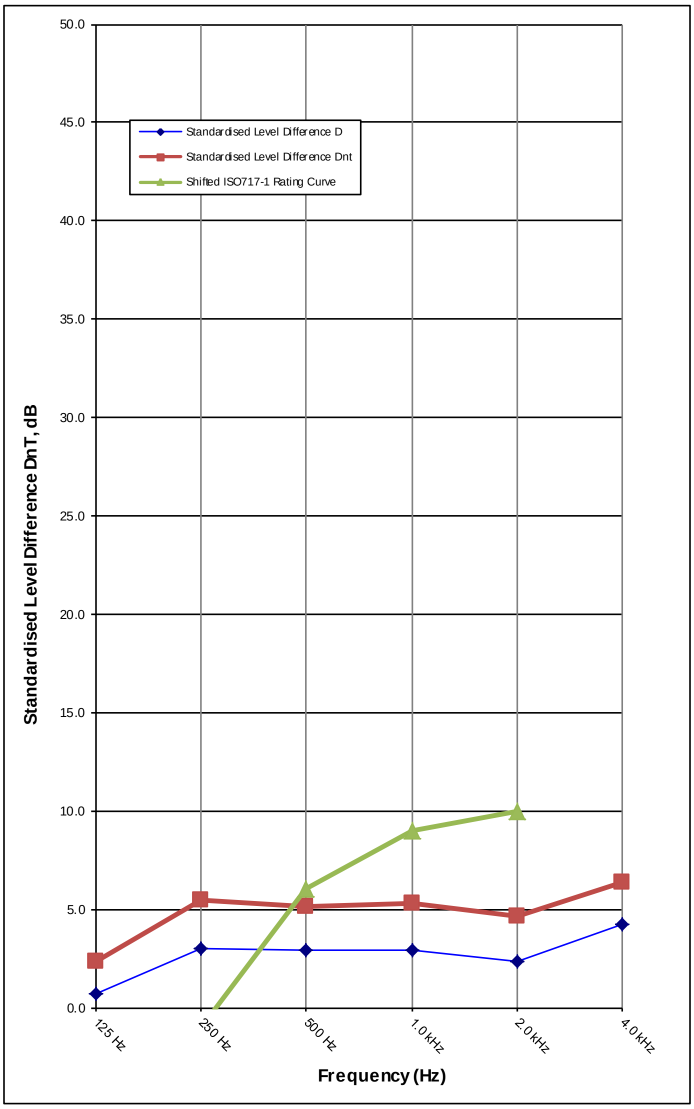
Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 17**
Site: Building A, London

Source room : E1_Level 9_Environment_181 Receiver room : E1_Level 9_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-5.2	-2.0
125	0.7	2.3
250	3.0	5.5
500	2.9	5.1
1k	2.9	5.3
2k	2.3	4.6
4k	4.2	6.4



Rating according to ISO 717-1

$D_{nT,w}$ = 6 dB **D_{w}=** **3 dB**

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

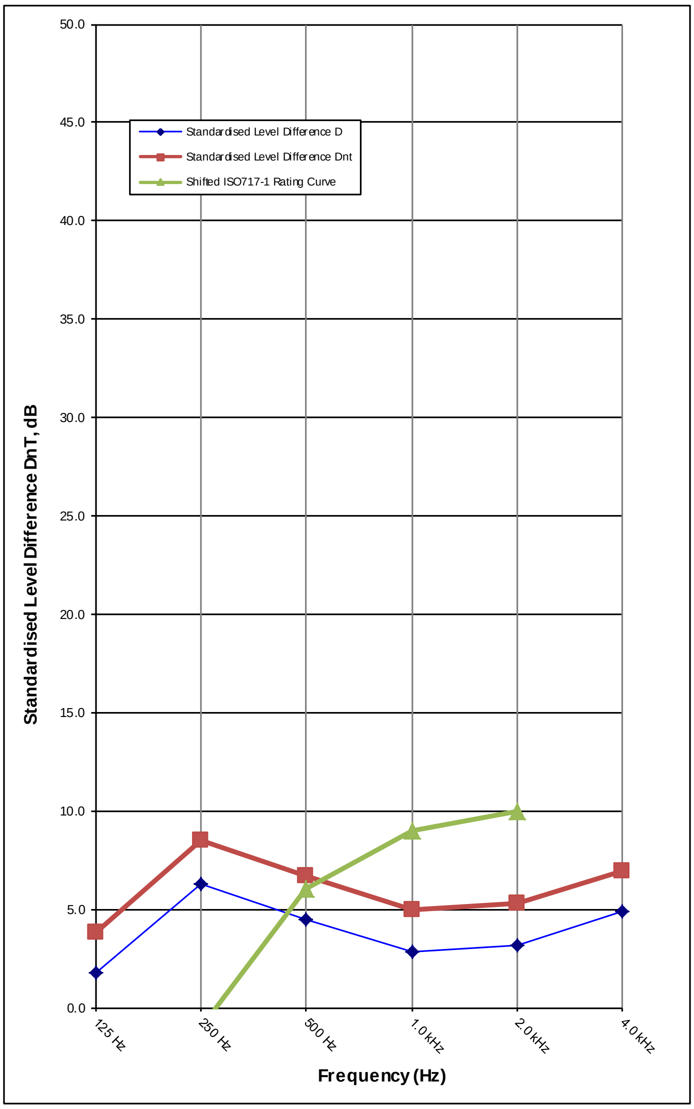
Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 18**

Site: Building A, London

Source room : S1_Level 9_Environment_181 Receiver room : S1_Level 9_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-0.7	2.2
125	1.8	3.8
250	6.3	8.5
500	4.5	6.7
1k	2.8	5.0
2k	3.2	5.3
4k	4.9	6.9



Rating according to ISO 717-1

$D_{nT,w}$ = 6 dB **$D_{w=}$** **4 dB**

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

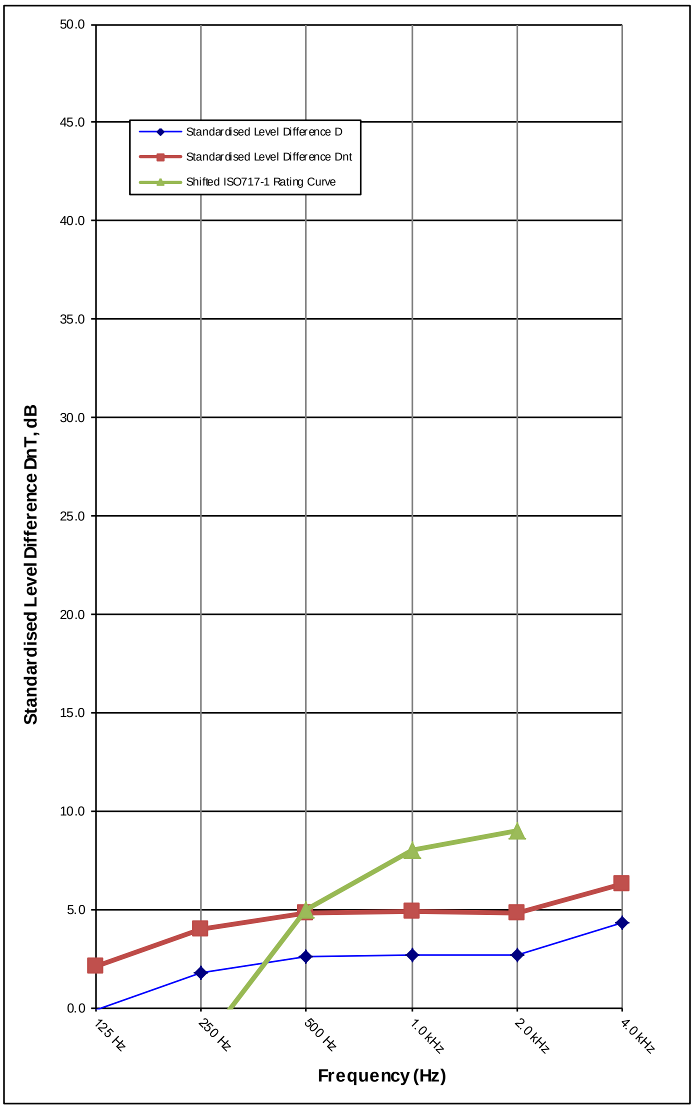
Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 19**
Site: Building A, London

Source room : E1_Level 10_Environment_181 Receiver room : E1_Level 10_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-2.1	0.9
125	-0.1	2.1
250	1.8	4.0
500	2.6	4.8
1k	2.7	4.9
2k	2.7	4.8
4k	4.3	6.3



Rating according to ISO 717-1

$D_{nT,w}$ = 5 dB **D_{w}=** **3 dB**

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

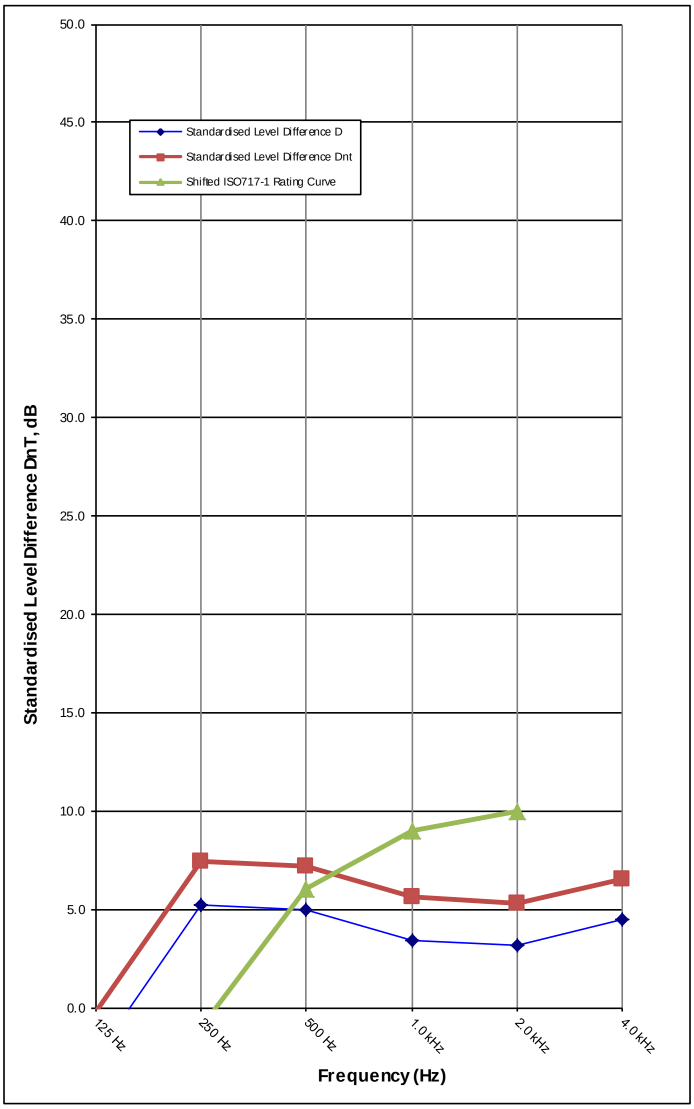
Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 20**
Site: Building A, London

Source room : S1_Level 10_Environment_181 Receiver room : S1_Level 10_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-4.9	-1.7
125	-2.5	-0.2
250	5.2	7.4
500	5.0	7.2
1k	3.4	5.6
2k	3.2	5.3
4k	4.5	6.5



Rating according to ISO 717-1

$D_{nT,w}$ = 6 dB **D_{w}=** **4 dB**

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

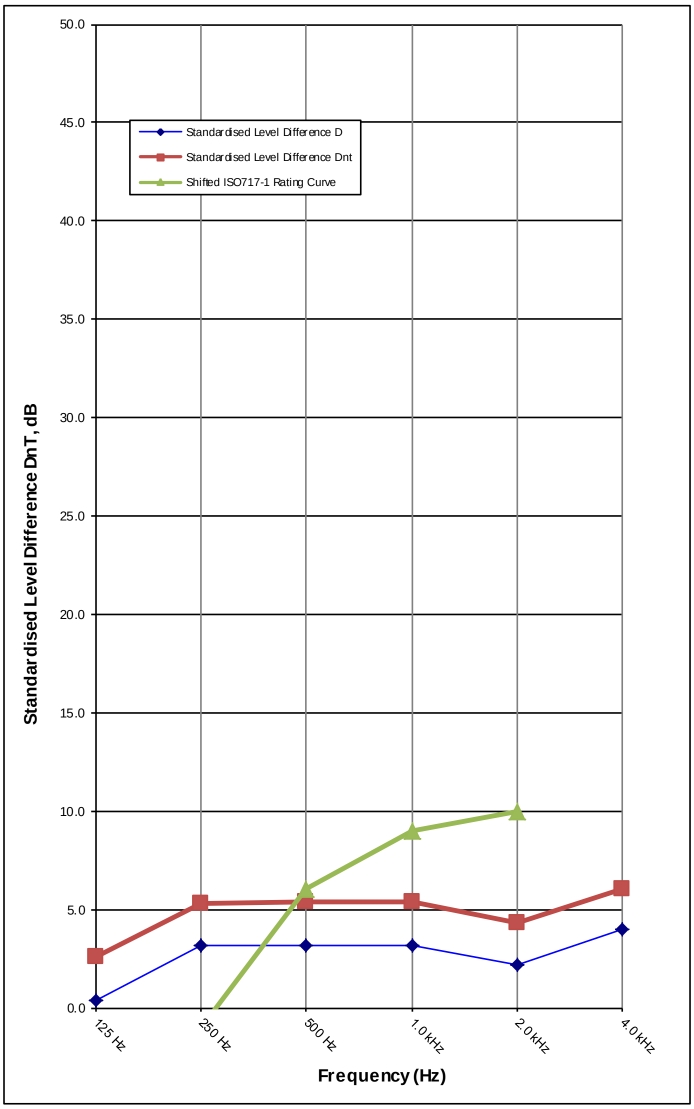
Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 21**
Site: Building A, London

Source room : E1_Level 11_Environment_181 Receiver room : E1_Level 11_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-4.6	-1.5
125	0.4	2.6
250	3.2	5.3
500	3.2	5.4
1k	3.2	5.4
2k	2.2	4.3
4k	4.0	6.0



Rating according to ISO 717-1

$D_{nT,w}$ = 6 dB **$D_{w=}$** **3 dB**

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

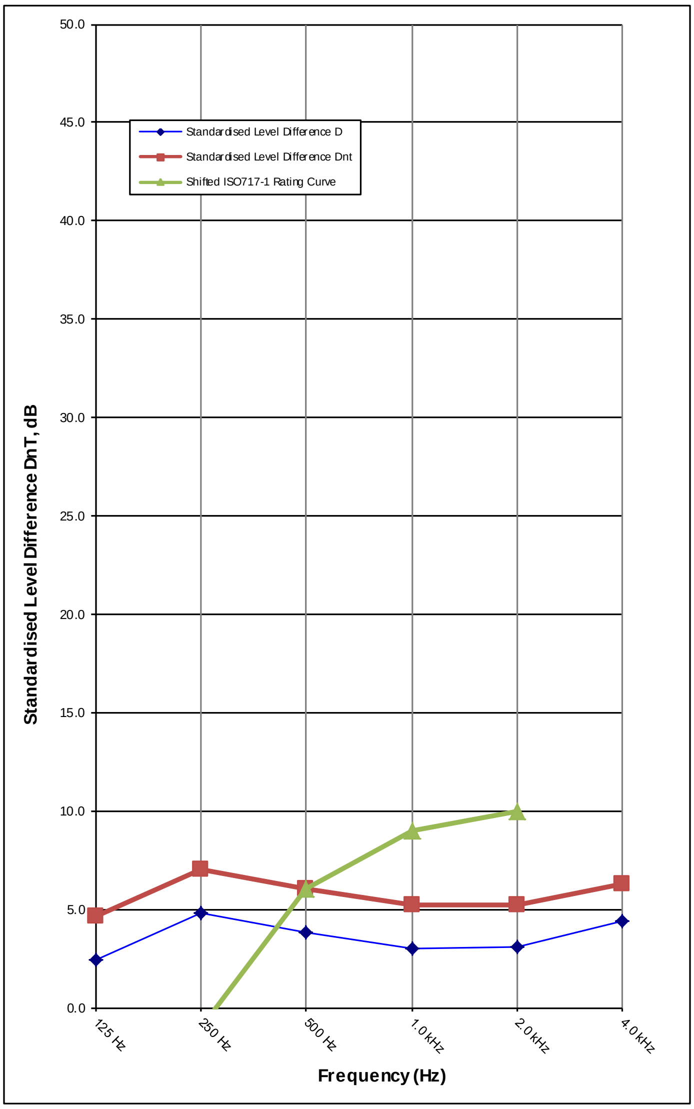
Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 22**

Site: Building A, London

Source room : S1_Level 11_Environment_181 Receiver room : S1_Level 11_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-2.0	1.1
125	2.4	4.6
250	4.8	7.0
500	3.8	6.0
1k	3.0	5.2
2k	3.1	5.2
4k	4.4	6.3



Rating according to ISO 717-1

$D_{nT,w}$ = 6 dB **D_{w}=** **4 dB**

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

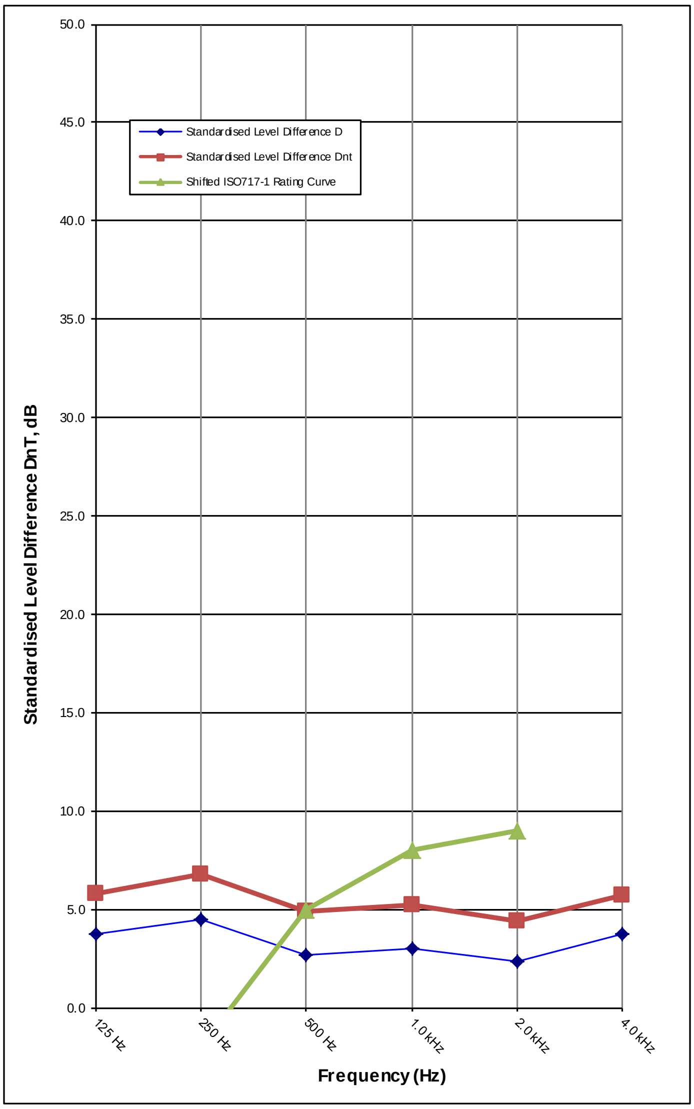
Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 23**

Site: Building A, London

Source room : E1_Level 12_Environment_181 Receiver room : E1_Level 12_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-3.6	-0.6
125	3.7	5.8
250	4.5	6.8
500	2.7	4.9
1k	3.0	5.2
2k	2.3	4.4
4k	3.7	5.7



Rating according to ISO 717-1

$D_{nT,w}$ = 5 dB **D_{w}=** **3 dB**

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

Standardised level difference according to ISO 140
Field measurements of airborne sound insulation between rooms

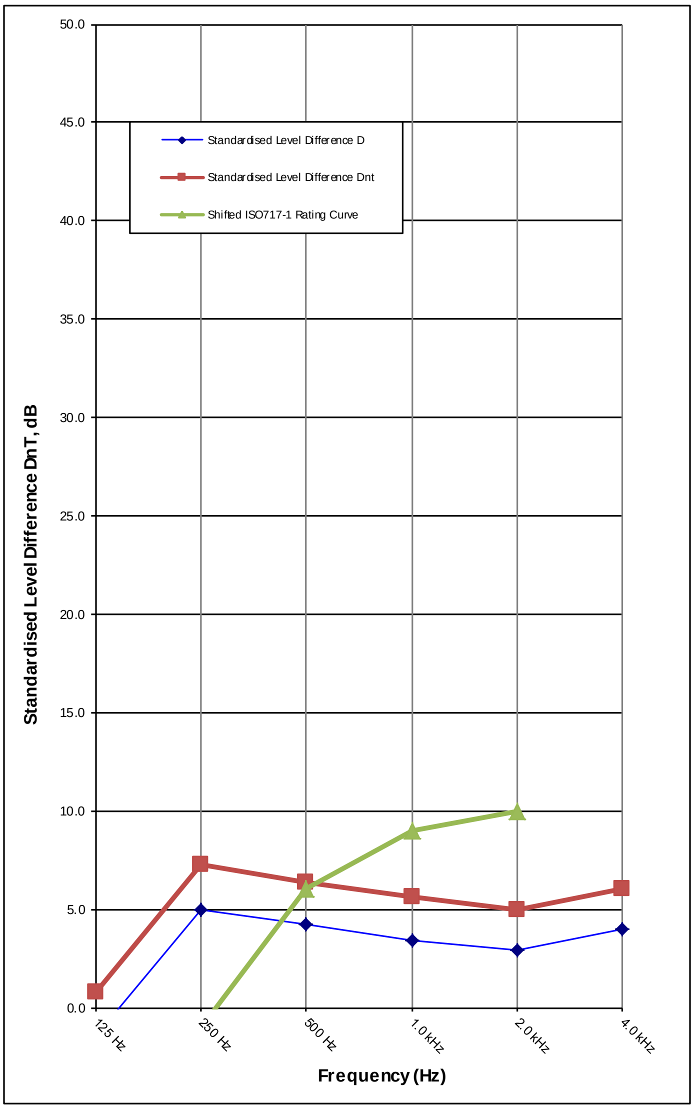
Client: John Downes, MSc Façade Eng. Test date: 20/06/13 Test No: **1 - 24**

Site: Building A, London

Source room : S1_Level 12_Environment_181 Receiver room : S1_Level 12_In Cavity_131

:

Frequency (Hz)	D, dB	DnT, dB
63	-5.3	-2.2
125	-1.4	0.8
250	5.0	7.3
500	4.2	6.4
1k	3.4	5.6
2k	2.9	5.0
4k	4.0	6.0



Rating according to ISO 717-1

$D_{nT,w}$ = 6 dB **$D_{w=}$** **4 dB**

Evaluation based on field measurement results obtained in one-third octave bands by an engineering method

Appendix 12 Test 2 E3, E2, E1, S1, W3, W3, W2, W1, Level 4 Full Results

Ref	Level	Dw	LAeq	dBA	63 Hz	125 Hz	250 Hz	500 Hz	1.0 kHz	2.0 kHz	4.0 kHz	8.0 kHz
E3	L4	57	62.2	59	66.1	58.9	59.2	58	59.6	53.3	43.5	30.4
E3	L4	59	64.1	60.9	65.3	60.4	62	60	61.4	54.9	47.3	36.3
E2	L4	61	65.9	62.6	67.2	63.3	61.9	61.3	63.8	55.8	47.6	36.4
E1	L4	68	72.8	69.5	76.1	71.1	71	68.6	70.1	63.2	56	47
S1	L4	72	76.8	73.6	76.1	74.4	73	72.3	74.8	66.7	57.8	48.6
S1	L4	72	77.1	73.9	73.3	69.9	72	72.3	75.3	66.9	57.5	46.2
S1	L4	72	77.3	74.1	76	72.1	72.8	72.8	75.2	67.6	59.3	50.5
W1	L4	69	73.6	70.4	71.8	69.4	69.7	69.4	71.5	63.7	55.4	44.5
W1	L4	65	69.9	66.6	67.9	64	64.9	65.3	67.9	59.7	49.5	37.7
W2	L4	62	67.3	64	68.9	62.8	64.1	63	64.9	58	46.9	34.9
W3	L4	58	63.3	60.1	62.2	59.7	58.8	57.6	61.5	53.6	42.3	29.7
W4	L4	54	61.8	57.7	72.8	65.8	60.9	61	57.2	49.4	44.7	38.4

Appendix 13 Test 3-6, W1, W2, W3, S1, Loudspeaker Test -Full Results

	Ref	Level	Dw	LAeq	dBA	63 Hz	125 Hz	250 Hz	500 Hz	1.0 kHz	2.0 kHz	4.0 kHz	8.0 kHz
Test 3	W3	Level 2	95	103.3	98.8	87.1	91.6	91.8	92.9	93.9	97.8	98.1	92.7
	W3	Level 3	88	94.9	89.4	75.1	85.5	86.2	88.8	88.6	86.2	89.9	82.2
	W3	Level 4	87	93.3	89	74.7	82.8	84.5	87.1	87	86.7	86.8	81.4
	Ref	Level	Dw	LAeq	dBA	63 Hz	125 Hz	250 Hz	500 Hz	1.0 kHz	2.0 kHz	4.0 kHz	8.0 kHz
Test 4	W2	Level 1	95	103.1	98	88	91.6	90.6	94.1	92.2	97.1	98.5	92.6
	W2	Level 2	89	96	90.6	80.6	84.6	86.1	87	88.6	88.6	91.1	86.2
	W2	Level 3	87	95.1	90.3	79.3	82.8	84.2	86	85.7	89.2	90.3	83.6
	W2	Level 4	87	94.4	88.6	78.8	81.2	83.9	86.5	85.1	87	90.4	82.8
	Ref	Level	Dw	LAeq	dBA	63 Hz	125 Hz	250 Hz	500 Hz	1.0 kHz	2.0 kHz	4.0 kHz	8.0 kHz
Test 5	W1	Level 1	96	103.8	98.5	86.9	91.7	91.6	95.7	92.1	97.6	99.3	94.1
	W1	Level 2	88	95.8	89.2	77.9	83.0	84.7	86.9	89.4	85.3	91.9	83.7
	W1	Level 3	87	93.0	89.3	76.0	80.3	81.5	84.7	85.9	87.9	86.1	81.5
	W1	Level 4	84	90.4	85.5	74.6	77.7	80.7	84.0	82.9	83.5	85.1	77.6
	W1	Level 5	82	87.7	83.1	72.9	76.7	79.2	81.4	81.8	80.5	81.6	74.8
	W1	Level 6	82	87.7	83.3	72.6	77.1	80.1	83.0	80.9	80.9	81.2	74.6
	W1	Level 7	81	87.2	82.8	71.8	74.9	78.3	82.4	80.3	80.5	80.6	73.9
	Ref	Level	Dw	LAeq	dBA	63 Hz	125 Hz	250 Hz	500 Hz	1.0 kHz	2.0 kHz	4.0 kHz	8.0 kHz
Test 6	S1	Level 1 (1)	100	109.8	105.7	94.0	97.7	99.2	97.0	103.3	104.1	103.7	99.3
		Level 1 (2)	99	109.1	102.7	92.4	95.8	98.0	101.4	97.1	101.5	105.1	100.4
		Log Average	102	109.5	104.4	93.3	96.9	98.6	99.7	101.2	103.0	104.5	99.9
	S1	Level 2 (1)	93	104.1	96.7	83.6	88.5	90.6	93.0	94.6	94.8	100.9	94.5
		Level 2 (2)	93	102.6	95.9	85.0	88.3	90.1	94.0	94.8	93.2	98.5	94.3
		Log Average	93	103.4	96.3	84.4	88.4	90.4	93.5	94.7	94.1	99.9	94.4
	S1	Level 3 (1)	90	97.3	93.8	83.8	83.7	86.9	90.3	90.3	92.3	90.2	83.6
		Level 3 (2)	90	97.3	93.8	83.8	83.7	86.9	90.3	90.3	92.3	90.2	83.6
		Log Average	90	97.3	93.8	83.8	83.7	86.9	90.3	90.3	92.3	90.2	83.6
	S1	Level 4 (1)	88	97.3	91.0	80.3	83.7	86.2	88.7	88.8	88.9	93.4	87.6
		Level 4 (2)	88	96.9	90.7	79.9	83.4	86.0	88.6	88.1	88.8	92.9	87.1
		Log Average	88	97.1	90.8	80.1	83.6	86.1	88.7	88.5	88.9	93.2	87.4
	S1	Level 5 (1)	86	96.3	89.4	77.6	81.4	83.7	86.6	86.9	87.6	93.0	85.7
		Level 5 (2)	90	99.0	93.8	83.9	84.3	86.9	90.3	90.3	92.3	94.4	89.2
		Log Average	88	96.0	92.1	81.8	83.1	85.6	88.8	88.9	90.6	93.8	87.8
	S1	Level 6 (1)	86	95.1	89.3	76.1	78.9	83.3	86.8	85.9	87.7	91.1	82.9
		Level 6 (2)	85	94.6	88.2	75.8	79.1	83.2	86.1	85.4	86.4	90.9	83.2
		Log Average	86	94.9	88.8	76.0	79.0	83.3	86.5	85.7	87.1	91.0	83.1
	S1	Level 7 (1)	84	91.5	87.3	78.8	78.1	81.9	84.1	84.6	85.6	85.6	78.2
		Level 7 (2)	86	94.1	88.0	79.5	81.6	83.3	86.7	86.3	85.6	89.8	83.8
		Log Average	85	93.0	87.7	79.2	80.2	82.7	85.6	85.5	85.6	88.2	81.8
	S1	Level 8 (1)	83	91.9	85.8	78.0	77.6	81.1	83.5	82.6	84.2	88.0	80.6
		Level 8 (2)	85	95.8	90.0	76.8	79.6	83.3	85.7	85.6	88.8	92.2	83.2
		Log Average	84	92.0	88.4	77.4	78.7	82.3	84.7	84.4	87.1	90.6	82.1
	S1	Level 9 (1)	83	91.0	85.0	79.1	76.0	80.5	83.6	83.7	82.2	86.6	79.9
		Level 9 (2)	84	91.7	87.5	75.2	78.1	81.0	85.4	85.5	85.4	85.1	78.1
		Log Average	84	91.4	86.4	77.6	77.2	80.8	84.6	84.7	84.1	85.9	79.1
	S1	Level 10 (1)	82	89.1	84.8	81.2	75.7	79.4	82.7	82.2	82.9	83.0	74.7
		Level 10 (2)	84	91.0	86.7	75.8	76.3	80.4	85.2	84.5	84.5	84.6	77.1
		Log Average	83	90.2	85.8	79.3	76.0	79.9	84.1	83.5	83.8	83.9	76.1
	S1	Level 11 (1)	81	88.3	83.6	74.7	73.4	79.4	81.5	81.8	81.3	82.8	75.3
		Level 11 (2)	83	89.8	85.6	77.1	76.3	80.7	82.9	83.6	83.5	83.3	74.9
		Log Average	82	89.1	84.7	76.1	75.1	80.1	82.3	82.8	82.5	83.1	75.1
	S1	Level 12 (1)	80	87.0	83.3	79.2	73.0	77.6	80.0	80.5	81.6	80.0	71.7
		Level 12 (2)	82	89.2	85.1	75.0	73.5	80.0	82.5	82.8	83.1	83.1	74.5
		Log Average	81	88.2	84.3	77.6	73.3	79.0	81.4	81.8	82.4	81.8	73.3

Appendix 14 Test 7 Reverberation Time, Full results

Reference	63 Hz T20 (sec)	125 Hz T20 (sec)	250 Hz T20 (sec)	500 Hz T20 (sec)	1 kHz T20 (sec)	2 kHz T20 (sec)	4 kHz T20 (sec)	8 kHz T20 (sec)	T20 Av
W3_1_floor	3.63	0.7	0.9	1.17	0.89	0.91	0.83	0.55	0.88
W3_1_floor	0.76	0.49	0.58	0.85	1.03	0.69	0.76	0.55	0.93
W3_1_floor	4.44	0.69	0.89	1.05	1.03	1.02	0.79	0.58	0.98
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av
W2_1_floor	0.14	0.28	1	0.79	0.82	0.79	0.77	0.62	0.79
W2_1_floor	0.3	0.36	0.66	0.65	0.81	0.84	0.77	0.62	0.81
W2_1_floor	0.22	0.33	0.93	0.83	0.9	0.85	0.79	0.62	0.83
W2_1_floor	0.25	0.29	0.75	0.71	0.8	0.82	0.81	0.62	0.81
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av
S1_1_floor	2.28	0.16	0.69	0.86	0.92	0.86	0.73	0.44	0.82
S1_1_floor	0.17	0.24	0.95	0.57	0.73	0.82	0.64	0.5	0.75
S1_1_floor	3.75	0.68	0.83	0.74	0.81	0.87	0.65	0.49	0.8
S1_1_floor	3.23	0.25	0.79	0.47	0.68	0.67	0.65	0.51	0.66
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av
W1_2_floor	0.28	0.25	0.8	0.74	0.64	0.63	0.65	0.52	0.64
W1_2_floor	2.78	0.79	0.79	0.63	0.62	0.63	0.66	0.55	0.64
W1_2_floor	1.78	0.79	0.6	0.63	0.61	0.63	0.66	0.58	0.63
W1_2_floor	3.84	0.83	0.61	0.64	0.64	0.65	0.69	0.58	0.66
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av
W3_3_floor	0.19	0.38	0.9	0.9	0.84	0.9	0.84	0.68	0.86
W3_3_floor	0.99	0.57	0.91	0.92	0.84	0.98	0.89	0.7	0.91
W3_3_floor	4.24	0.94	0.94	0.96	0.85	1.02	0.87	0.69	0.92
W3_3_floor	3.09	0.57	1.01	0.96	0.87	1.01	0.86	0.71	0.94
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av
W2_4_floor	0.86	0.61	0.88	0.7	0.67	0.7	0.72	0.57	0.7
W2_4_floor	0.5	0.48	0.71	0.72	0.68	0.76	0.7	0.57	0.7
W2_4_floor	0.16	0.4	1.05	0.83	0.69	0.73	0.71	0.61	0.72
W2_4_floor	3.67	0.94	1.01	0.74	0.66	0.72	0.69	0.58	0.69
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av
W1_4_floor	0.51	0.42	0.58	0.65	0.61	0.59	0.58	0.52	0.6
W1_4_floor	1.7	0.55	0.82	0.65	0.69	0.71	0.63	0.55	0.68
W1_4_floor	0.16	0.75	0.7	0.68	0.6	0.7	0.69	0.57	0.67

	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av
S1_4_floor	3.92	0.83	0.98	1.12	1	0.86	0.78	0.6	0.88
S1_4_floor	4.18	0.73	1.25	1.06	0.96	1.04	0.92	0.59	0.99
S1_4_floor	1.42	0.35	1.11	1.12	0.97	1.04	0.86	0.62	0.97
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av
W3_7_floor	0.16	0.39	1.1	0.85	0.78	0.92	0.79	0.66	0.84
W3_7_floor	0.14	0.27	0.65	0.83	0.8	0.9	0.86	0.64	0.85
W3_7_floor	0.16	0.44	0.69	0.76	0.76	0.87	0.78	0.65	0.83
W3_7_floor	1.16	0.48	0.71	0.78	0.74	0.86	0.82	0.64	0.8
W3_7_floor	0.15	0.41	0.96	0.78	0.79	0.92	0.87	0.65	0.86
W3_7_floor	0.19	0.94	1.04	1.04	0.89	0.96	0.93	0.71	0.96
W3_7_floor	0.13	0.13	0.73	0.82	0.85	0.9	0.92	0.66	0.88
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av
S1_8_floor	3.1	0.52	1.22	1.12	0.96	0.9	0.87	0.63	0.91
S1_8_floor	3.14	0.48	0.93	1.17	1.2	0.99	0.91	0.74	1.03
S1_8_floor	2.54	1.23	0.82	1.17	1.08	0.97	0.94	0.74	0.99
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av
S1/E1_corner_8	4.47	0.76	0.69	0.85	0.82	0.95	0.87	0.68	0.89
S1/E1_corner_8	3.73	0.97	0.9	0.88	1.02	0.95	0.89	0.69	0.95
S1/E1_corner_8	2.4	0.16	0.53	0.86	0.97	0.97	0.88	0.66	0.94
S1/E1_corner_8	0.24	0.09	0.66	0.9	0.93	0.92	0.84	0.65	0.9
S1/E1_corner_8	2.92	2.22	1.11	0.92	0.9	0.91	0.87	0.69	0.9
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av
S1_12_floor	1.88	2.28	0.76	1.05	0.87	0.96	0.86	0.68	0.93
S1_12_floor	1.99	2.6	0.71	0.91	0.9	0.88	0.83	0.68	0.87
S1_12_floor	3.94	2.12	0.95	0.95	0.91	0.91	0.87	0.63	0.9
S1_12_floor	3.54	1.87	0.96	0.92	0.86	0.87	0.83	0.64	0.86
S1_12_floor	0.88	0.37	1.05	1.01	0.94	0.91	0.81	0.67	0.9
S1_12_floor	3.83	1.57	0.68	0.9	0.85	0.91	0.85	0.65	0.88
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av
S1/E1_corner_1	2.25	0.25	0.38	0.74	0.73	0.79	0.8	0.62	0.77
S1/E1_corner_1	4.15	3.07	0.56	0.65	0.72	0.72	0.79	0.63	0.73
S1/E1_corner_1	3.8	0.87	0.51	0.9	0.77	0.79	0.84	0.62	0.79
S1/E1_corner_1	1.66	1.07	0.74	0.76	0.74	0.8	0.85	0.64	0.79

Appendix 15 Simulation 7Reverberation Time, Full results

Model Data									
Reference	125Hz T20 (sec)	250Hz T20 (sec)	500Hz T20 (sec)	1kHz T20 (sec)	2kHz T20 (sec)	4kHz T20 (sec)	8kHz T20 (sec)	16kHz T20 (sec)	T20 Av
W2_1_floor	0.62	0.65	0.86	1.18	0.55	0.68	0.41	0.29	0.77
W2_1_floor	0.83	0.81	0.81	0.85	0.65	0.7	0.52	0.27	
W2_1_floor									
	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz	16kHz	T20 Av
W3_1_floor	0.32	0.33	0.28	0.31	0.33	0.3	0.23	0.26	0.72
W3_1_floor	4.66	0.38	0.34	0.36	0.34	0.71	0.26	0.19	
W3_1_floor									
W3_1_floor									
	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz	16kHz	T20 Av
S1_1_floor	1.42	1.3	0.78	0.79	0.78	0.92	0.05	0.03	0.84
S1_1_floor	0.63	0.61	0.6	0.75	0.78	0.66	0.06	0.03	
S1_1_floor									
S1_1_floor									
	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz	16kHz	T20 Av
W4_2_floor	0.18	0.17	0.16	0.18	0.17	0.17	0.24	0.19	0.19
W4_2_floor	0.2	0.18	0.18	0.19	0.19	0.18	0.21	0.18	
W4_2_floor									
W4_2_floor									
	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz	16kHz	T20 Av
W2_3_floor	0.25	0.23	1.03	1.8	0.32	0.24	0.33	0.26	0.74
W2_3_floor	0.44	0.5	0.47	2.2	0.52	0.3	0.37	0.26	
W2_3_floor									
W2_3_floor									
	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz	16kHz	T20 Av
W3_4_floor	7.73	7.42	7.82	7.02	8.77	6.43	0.2	0.13	10.03
W3_4_floor	10.83	10.75	11.64	10.28	10.24	6.45	0.024	0.13	
W3_4_floor									
W3_4_floor									
	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz	16kHz	T20 Av
W4_4_floor	0.09	0.1	0.09	0.12	0.11	0.97	0.1	0.1	1.22
W4_4_floor	1.18	1.22	1.22	1.32	1.25	1.11	0.12	0.09	
W4_4_floor									
	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz	16kHz	T20 Av
S1_4_floor	3.6	3.38	2.34	6.4	7	2.89	0.71	4.73	4.39
S1_4_floor	4.82	5.21	2.81	5.51	4.96	3.01	0.76	2.66	
S1_4_floor									
	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz	16kHz	T20 Av
W2_7_floor	0.32	0.26	0.24	0.22	0.32	0.45	0.3	0.21	0.53
W2_7_floor	0.59	0.62	0.49	0.48	0.53	0.47	0.37	0.24	
W2_7_floor									
W2_7_floor									
W2_7_floor									
W2_7_floor									
W2_7_floor									
	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz	8kHz	16kHz	T20 Av
S1_8_floor	1.56	1.35	0.85	0.89	0.9	0.95	0.23	0.2	0.93
S1_8_floor	0.65	0.66	0.62	0.93	0.97	0.88	0.83	0.32	
S1_8_floor									

Test Data

Reference	63 Hz T20 (sec)	125 Hz T20 (sec)	250 Hz T20 (sec)	500 Hz T20 (sec)	1 kHz T20 (sec)	2 kHz T20 (sec)	4 kHz T20 (sec)	8 kHz T20 (sec)	T20 Av	T20 Av
W2_1_floor	3.63	0.7	0.9	1.17	0.89	0.91	0.83	0.55	0.88	
W2_1_floor	0.76	0.49	0.58	0.85	1.03	0.69	0.76	0.55	0.93	0.93
W2_1_floor	4.44	0.69	0.89	1.05	1.03	1.02	0.79	0.58	0.98	
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av	
W3_1_floor	0.14	0.28	1	0.79	0.82	0.79	0.77	0.62	0.79	
W3_1_floor	0.3	0.36	0.66	0.65	0.81	0.84	0.77	0.62	0.81	0.81
W3_1_floor	0.22	0.33	0.93	0.83	0.9	0.85	0.79	0.62	0.83	
W3_1_floor	0.25	0.29	0.75	0.71	0.8	0.82	0.81	0.62	0.81	
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av	
S1_1_floor	2.28	0.16	0.69	0.86	0.92	0.86	0.73	0.44	0.82	
S1_1_floor	0.17	0.24	0.95	0.57	0.73	0.82	0.64	0.5	0.75	0.76
S1_1_floor	3.75	0.68	0.83	0.74	0.81	0.87	0.65	0.49	0.8	
S1_1_floor	3.23	0.25	0.79	0.47	0.68	0.67	0.65	0.51	0.66	
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av	
W4_2_floor	0.28	0.25	0.8	0.74	0.64	0.63	0.65	0.52	0.64	
W4_2_floor	2.78	0.79	0.79	0.63	0.62	0.63	0.66	0.55	0.64	0.64
W4_2_floor	1.78	0.79	0.6	0.63	0.61	0.63	0.66	0.58	0.63	
W4_2_floor	3.84	0.83	0.61	0.64	0.64	0.65	0.69	0.58	0.66	
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av	
W2_3_floor	0.19	0.38	0.9	0.9	0.84	0.9	0.84	0.68	0.86	
W2_3_floor	0.99	0.57	0.91	0.92	0.84	0.98	0.89	0.7	0.91	0.91
W2_3_floor	4.24	0.94	0.94	0.96	0.85	1.02	0.87	0.69	0.92	
W2_3_floor	3.09	0.57	1.01	0.96	0.87	1.01	0.86	0.71	0.94	
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av	
W3_4_floor	0.86	0.61	0.88	0.7	0.67	0.7	0.72	0.57	0.7	
W3_4_floor	0.5	0.48	0.71	0.72	0.68	0.76	0.7	0.57	0.7	0.70
W3_4_floor	0.16	0.4	1.05	0.83	0.69	0.73	0.71	0.61	0.72	
W3_4_floor	3.67	0.94	1.01	0.74	0.66	0.72	0.69	0.58	0.69	
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av	
W4_4_floor	0.51	0.42	0.58	0.65	0.61	0.59	0.58	0.52	0.6	
W4_4_floor	1.7	0.55	0.82	0.65	0.69	0.71	0.63	0.55	0.68	0.65
W4_4_floor	0.16	0.75	0.7	0.68	0.6	0.7	0.69	0.57	0.67	
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av	
S1_4_floor	3.92	0.83	0.98	1.12	1	0.86	0.78	0.6	0.88	
S1_4_floor	4.18	0.73	1.25	1.06	0.96	1.04	0.92	0.59	0.99	0.95
S1_4_floor	1.42	0.35	1.11	1.12	0.97	1.04	0.86	0.62	0.97	
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av	
W2_7_floor	0.16	0.39	1.1	0.85	0.78	0.92	0.79	0.66	0.84	
W2_7_floor	0.14	0.27	0.65	0.83	0.8	0.9	0.86	0.64	0.85	
W2_7_floor	0.16	0.44	0.69	0.76	0.76	0.87	0.78	0.65	0.83	
W2_7_floor	1.16	0.48	0.71	0.78	0.74	0.86	0.82	0.64	0.8	0.86
W2_7_floor	0.15	0.41	0.96	0.78	0.79	0.92	0.87	0.65	0.86	
W2_7_floor	0.19	0.94	1.04	1.04	0.89	0.96	0.93	0.71	0.96	
W2_7_floor	0.13	0.13	0.73	0.82	0.85	0.9	0.92	0.66	0.88	
	63 Hz	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	T20 Av	
S1_8_floor	3.1	0.52	1.22	1.12	0.96	0.9	0.87	0.63	0.91	
S1_8_floor	3.14	0.48	0.93	1.17	1.2	0.99	0.91	0.74	1.03	0.98
S1_8_floor	2.54	1.23	0.82	1.17	1.08	0.97	0.94	0.74	0.99	

Appendix 16 Simulation, Component 3, 25mm opening

Component 3 - Open Window Simuation for 25mm opening									
Receiver:	1	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	95.60	96.40	98.40	103.00	103.80	103.60	104.50	110.60	101.63
E (Red)	91.20	93.90	97.00	101.40	102.70	105.50	108.00	110.50	
Receiver:	2	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	93.80	94.20	95.40	98.80	103.40	103.30	101.00	105.50	99.17
E (Red)	88.70	93.30	94.50	96.90	102.10	103.20	105.20	107.40	
Receiver:	3	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	93.60	93.40	97.20	100.50	102.80	103.50	101.00	105.70	99.66
E (Red)	90.80	93.70	96.40	98.50	101.90	103.40	105.30	106.90	
Receiver:	4	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	89.70	87.50	92.80	94.90	98.40	100.50	102.00	99.60	95.16
E (Red)	84.70	87.70	90.60	93.50	96.40	99.00	101.70	103.60	
Receiver:	5	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	78.00	79.10	82.80	85.20	86.90	87.50	87.40	85.60	83.83
E (Red)	76.50	79.70	82.00	85.10	86.60	86.90	86.10	85.80	
Receiver:	6	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	77.00	77.30	79.30	82.60	85.50	87.80	89.70	89.90	83.78
E (Red)	74.60	77.50	80.60	83.30	86.00	88.20	90.00	91.20	
Receiver:	7	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	75.70	76.00	77.80	81.30	84.20	86.60	88.40	88.50	82.46
E (Red)	73.30	76.30	79.10	82.10	84.70	86.90	88.70	89.80	
Receiver:	8	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	73.50	73.80	75.60	79.00	82.00	84.30	86.10	86.00	80.19
E (Red)	71.10	74.10	76.90	79.80	82.50	84.70	86.40	87.20	
Receiver:	9	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	71.70	71.90	73.80	77.20	80.20	82.50	84.10	83.90	78.31
E (Red)	69.30	72.20	75.00	78.00	80.70	82.80	84.50	85.10	
Receiver:	10	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	70.20	70.50	72.30	75.70	78.60	80.90	82.50	82.00	76.73
E (Red)	67.80	70.80	73.50	76.50	79.10	81.20	82.90	83.20	
Receiver:	11	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	68.90	69.20	71.00	74.40	77.30	79.60	81.00	80.40	75.31
E (Red)	66.50	69.50	72.20	75.20	77.80	79.90	80.50	81.50	
Receiver:	12	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	67.80	68.10	69.90	73.30	76.20	78.40	79.70	78.90	74.19
E (Red)	65.40	68.40	71.20	74.10	76.70	78.70	80.20	80.00	

Component 3 - Open Window Simuation for 50mm opening									
Receiver:	1	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	96.60	94.10	95.80	100.90	104.40	106.90	109.70	111.00	102.63
E (Red)	92.80	95.70	98.70	101.60	104.50	107.10	109.80	112.40	
Receiver:	2	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	93.90	91.70	91.80	98.60	100.80	103.30	105.90	107.00	99.29
E (Red)	89.90	92.70	95.40	98.40	101.20	103.70	106.00	108.30	
Receiver:	3	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	93.10	91.30	92.60	95.70	99.60	102.30	104.40	105.70	98.16
E (Red)	88.70	91.60	94.50	97.20	100.10	102.30	104.60	106.80	
Receiver:	4	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	92.60	91.20	91.30	92.90	98.60	100.40	102.50	103.20	96.66
E (Red)	87.60	90.60	93.20	96.00	98.70	100.60	102.70	104.40	
Receiver:	5	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	84.20	84.20	86.50	89.80	93.20	95.90	98.60	99.80	91.63
E (Red)	81.70	84.60	87.50	90.60	93.40	96.10	98.80	101.10	
Receiver:	6	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	77.20	77.40	79.30	83.00	85.60	87.90	89.70	89.90	83.92
E (Red)	74.80	77.80	80.50	83.90	86.20	88.20	90.10	91.20	
Receiver:	7	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	75.90	76.00	77.90	81.20	84.20	86.60	88.40	88.50	82.49
E (Red)	73.40	76.30	79.20	82.00	84.80	86.90	88.70	89.80	
Receiver:	8	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	73.60	73.80	75.60	79.00	82.00	84.30	86.10	86.00	80.20
E (Red)	71.10	74.20	76.90	79.80	82.50	84.70	86.40	87.20	
Receiver:	9	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	71.70	71.90	73.80	77.20	80.20	82.50	84.10	83.90	78.31
E (Red)	69.30	72.20	75.00	78.00	80.70	82.80	84.50	85.10	
Receiver:	10	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	70.20	70.40	72.30	75.70	78.60	81.10	82.50	82.00	76.74
E (Red)	67.80	70.70	73.50	76.50	79.10	81.30	82.90	83.20	
Receiver:	11	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	68.90	69.10	71.00	74.40	77.30	79.60	81.00	80.40	75.36
E (Red)	66.50	69.40	72.20	75.20	77.80	79.90	81.50	81.50	
Receiver:	12	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	67.80	68.00	69.90	73.30	76.20	78.40	79.70	78.90	74.18
E (Red)	65.40	68.30	71.10	74.10	76.70	78.80	80.20	80.00	

Component 3 - Open Window Simuation for 100mm opening									
Receiver:	1	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	95.70	97.00	97.70	99.40	97.90	107.00	107.60	109.70	101.54
E (Red)	91.70	94.80	97.50	100.20	103.20	105.90	108.40	110.90	
Receiver:	2	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	94.40	93.50	95.40	98.40	98.40	102.00	105.40	106.90	99.20
E (Red)	89.70	92.40	95.10	98.20	101.00	103.00	105.80	107.60	
Receiver:	3	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	93.00	91.60	94.60	98.10	98.20	100.00	104.50	104.90	98.03
E (Red)	88.10	91.70	94.00	96.90	100.00	102.10	104.40	106.40	
Receiver:	4	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	89.90	87.40	94.00	96.10	96.80	96.20	103.00	102.80	95.78
E (Red)	86.80	89.10	91.80	95.20	97.60	99.60	102.10	104.00	
Receiver:	5	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	84.70	84.30	86.50	89.80	92.90	96.10	98.50	99.80	91.66
E (Red)	81.60	84.70	87.90	90.50	93.30	96.10	98.70	101.10	
Receiver:	6	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	77.80	77.50	79.70	82.70	85.70	87.90	89.70	90.00	84.03
E (Red)	75.00	77.80	80.90	83.70	86.40	88.20	90.10	91.30	
Receiver:	7	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	75.70	76.10	77.90	81.30	84.20	86.60	88.40	88.50	82.49
E (Red)	73.40	76.30	79.30	82.00	84.80	86.90	88.70	89.80	
Receiver:	8	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	73.50	73.80	75.60	79.00	82.00	84.30	86.10	86.00	80.20
E (Red)	71.20	74.10	76.90	79.80	82.50	84.70	86.50	87.20	
Receiver:	9	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	71.70	72.00	73.80	77.20	80.20	82.50	84.10	83.90	78.32
E (Red)	69.30	72.20	75.10	78.00	80.70	82.80	84.50	85.10	
Receiver:	10	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	70.20	70.40	72.30	75.70	78.60	80.90	82.50	82.00	76.73
E (Red)	67.80	70.70	73.50	76.40	79.20	81.30	82.90	83.20	
Receiver:	11	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	68.90	69.10	71.00	74.40	77.30	79.60	81.00	80.40	75.36
E (Red)	66.50	69.50	72.20	75.20	77.80	79.90	81.50	81.50	
Receiver:	12	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	67.80	68.10	69.90	73.30	76.20	78.40	79.70	78.90	74.18
E (Red)	65.40	68.30	71.20	74.10	76.70	78.70	80.20	80.00	

Component 3 - Open Window Simuation for 150mm opening									
Receiver:	1	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	95.90	97.00	97.00	96.60	103.50	105.60	108.30	109.60	101.74
E (Red)	92.10	94.90	97.70	100.80	103.40	105.90	108.50	111.00	
Receiver:	2	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	93.90	94.20	95.10	96.90	97.60	103.90	104.80	106.60	99.17
E (Red)	89.50	92.60	95.60	98.30	101.00	103.40	105.50	107.80	
Receiver:	3	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	92.20	92.00	94.60	96.60	98.10	103.20	103.90	105.10	98.17
E (Red)	88.70	91.70	94.20	97.30	100.10	102.20	104.30	106.50	
Receiver:	4	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	91.10	90.70	94.60	95.00	96.70	99.00	101.70	103.50	96.34
E (Red)	87.20	89.60	92.60	94.90	98.20	100.10	102.40	104.10	
Receiver:	5	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	84.60	84.40	86.30	89.50	92.90	95.80	98.50	99.80	91.59
E (Red)	81.60	84.70	87.50	90.40	93.36	96.10	98.80	101.10	
Receiver:	6	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	77.70	77.60	79.30	82.70	85.70	88.00	89.80	90.00	84.03
E (Red)	75.20	78.40	80.60	83.50	86.30	88.30	90.10	91.30	
Receiver:	7	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	75.80	76.10	78.00	81.30	84.30	86.70	88.40	88.50	82.55
E (Red)	73.50	76.40	79.30	82.10	84.80	87.00	88.80	89.80	
Receiver:	8	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	73.50	73.80	75.70	79.10	82.00	84.30	86.10	86.00	80.21
E (Red)	71.20	74.10	76.90	79.80	82.50	84.70	86.40	87.20	
Receiver:	9	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	71.70	72.00	73.80	77.20	80.20	82.50	84.10	83.90	78.33
E (Red)	69.40	72.30	75.10	78.00	80.70	82.80	84.50	85.10	
Receiver:	10	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	70.20	70.50	72.30	75.70	78.60	80.90	82.50	82.00	76.73
E (Red)	67.80	70.70	73.50	76.50	79.10	81.30	82.90	83.20	
Receiver:	11	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	68.90	69.20	71.00	74.40	77.30	79.60	81.00	80.40	75.37
E (Red)	66.50	69.50	72.20	75.20	77.80	79.90	81.50	81.50	
Receiver:	12	Rays:	Auto	172000 approx					
	125	250	500	1k	2k	4k	8k	16k	SPL
h (Blue)	67.80	68.00	69.90	73.30	76.20	78.40	79.70	78.90	74.16
E (Red)	65.40	68.30	71.10	74.00	76.70	78.70	80.20	80.00	