GETTING TO THE RIGHT PLACE: LIFE SAFETY STANDARDS AND THE SPEECH TRANSMISSION INDEX AS A DRIVER OF INTERDISCIPLINARY DESIGN.

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1 INTRODUCTION

A Voice Alarm system, or any sound system intended for emergency purposes, provides a range of beneficial functions. The most critical, of course, is its use as an effective tool in evacuating and informing the occupants, in the event of an emergency.

Perhaps the most commonly conceived emergency scenario is the risk of a fire spread, where occupants of the building need to be evacuated quickly, and in an orderly fashion. The prompt given to evacuate can be given by a simple and clear signal, such as from sounders or bells, or it may be given by verbal instructions.

Research in the 1980s showed that a verbal instruction over a Voice Alarm provides invaluable benefits over simple bells, and, most critically, can typically illicit a much swifter response. As most fires escalate dangerously within minutes of detection, especially with regards to smoke build-up and the compromise of escape routes, those first seconds and minutes before initiating movement have a real effect on life safety.

With large crowds in a contained environment, such as at a sports stadium, there are also significant risks associated with the management of the movements and behavioral responses of groups and densities of people. While good voice communications are essential in an emergency, they also have a role in de-escalating emerging situations that may have otherwise turned hazardous or harmful. Thus, in large crowds, the critical safety aspects served by the loudspeaker system span across both emergency and routine usage.

Despite the awful memories of disasters such as the Bradford fire of May 1985, design codes and practices have significantly reduced the risks of fire in places of mass assembly by; applying controls on the intrinsic non-flammability of materials; attention to routes and signage; and restrictions on smoking and other hazardous activities. While fire risk has been reduced, there has been an unfortunate evolution of the threats from terrorism, 'active shooters', vehicle attacks and similar. Criminal activities aimed at crowded spaces now present a more complex set of possibilities to plan for in the modern stadium or place of assembly.

The unpredictable complexity of such attacks and threats, coupled with the detail of 'live' information available through CCTV and coordinated manual surveillance, calls for 'real-time' information systems to provide detailed, clear and authoritative instructions and information. Thus, the initial role of a Voice Alarm, to provide as a vocal prompt to evacuate due to a fire, has evolved into a critical information system that saves lives. The VA now has a role as part of offering an effective, directed and coordinated response.

This paper recognises the evolution of loudspeaker systems as effective tools in evacuation and emergency management, and the improvement of the skills and understanding available in the design and commissioning of these systems into challenging acoustic environments. It is acknowledged that the concept of Speech intelligibility has provided a significant force towards establishing these skills and products. In particular, it is proposed that the adoption of the Speech Transmission Index metric has been a positive driver towards lower risk and harm.

2 HISTORY

2.1 A History of Disaster

Any planning to minimize risk of harm must take full historic note of known disasters. Fire Engineers have legislated in ways that have learned from major fires through history, from the Great Fire of London onwards.

In 1971, 66 people died at Ibrox Stadium in Glasgow, Scotland, UK when early leavers from the game heard a last-minute goal score and attempted to return to the stands. The contra-flow of pedestrians created unresolvable crowding that quickly escalated and resulted in deaths from compressive asphyxiation.

Two years later, the seminal and often sited "Green Guide" was published by the UK government Dept of Culture media and Sport, as a Guide to Safety at Sports Grounds (Green Guide" SGSG, 1973. 1986, 1990, 1997, 2008). Written by the Football Licencing Authority (FLA, now the Sports Ground Safety Authority), the document itself had no legislative authority, but its recommendations were often given a force of law at individual grounds by their inclusion in General Safety Certificates issued under the Safety of Sports Grounds Act 1975 or the Fire Safety and Safety of Places of Sports Act 1987.

In 1985, 56 people were killed in a swiftly spreading fire at Bradford City Stadium. In the following year, The FLA issued the 2nd Edition of the Green Guide.

In 1989, 94 died at Hillsborough due to crowd crushes as latecomers were admitted to an already full stand. In 1990, the 3rd Edition of the Green Guide was provided.

In December 1991, the Football Stadia Advisory Design Council published "Stadium Public Address Systems" (FSADC, 1991), focussing, of course, on the role of the loudspeaker system. The very next month, the Sound and Communications Industries Federation (SCIF) responded on behalf of the industry by publishing the "Code of practice for the assessment, specification, maintenance and operation of sound systems for emergency purposes at Sports Grounds and stadia in pursuit of approval by Licencing Authorities" (Sound and Communications Industries Federation, 1991). This was adapted and developed into BS7827:1996 "Code of practice for designing, specifying, maintaining and operating emergency sound systems at sports venues" (BS7827, 1996, 2011, 2019) which was revised in 2011 and is currently under development for a new edition.

An edition of the Green Guide in 1997 addressed accessibility and the hosting of spectators with Disabilities and in 2008, the 5th Edition added in task management, counter terrorism, guidance on training and qualifications of stewards.

Looking beyond stadiums, at King's Cross Underground Station London, on Wednesday 18 November 1987, around 19:30, a discarded lit match likely fell between the treads of a wooden escalator leading up from the Piccadilly Line, to land in a dusty oil store. Debris that had been gathering in the rarely visited oil store provided the tinder, and the escalator shaft provided the draft needed to start a fire that caused a flashover at 19:45, that claimed 31 lives and injured 100. As a result of this horrific incident, London Underground immediately overhauled their policies on fire prevention and response. Within 5 days of the event, the London Underground smoking ban become rigidly enforced and applied to *anywhere* on the underground; it had been banned already in 1985 but generally ignored by passengers on the escalators. The Fennell Report (Fennell OBE QC, 1988) noted that:

Public Address Systems

10. The public address system at King's Cross ordinarily reaches each of the eight platforms, concourses and both ticket halls. It can be operated from three points: locally on each platform, the temporary station operations room in the tube lines ticket hall, and the line controllers' offices. There are facilities in the temporary station operations room to override local platform announcements, and the line controllers and information assistants can override them all. Recorded messages from information assistants may be automatically repeated.

13. It is remarkable that no use whatever was made of the public address system at King's Cross throughout the fire and evacuation. I include in my recommendations improvements to the existing equipment and its coverage of station areas and more training and practice for staff in the use of the public address system.

Recommendations included:

Chapter 16: Communications systems

*Most Important*****

(110) The quality and scope of public address equipment must be improved. It shall cover a wider area of stations.

London Underground, naturally, took this very seriously, and quickly began research into the use, effectiveness and resilience of its Public Address systems throughout their stations and maintenance sheds. Some changes were made almost immediately, such as the decision to move from loudspeakers spaced around 15m along platforms to a standard 5m centres, as well as to make the on-platform microphone able to over-ride messages being broadcast from centralised and off-site information services. LUL was also receptive to understanding the reasons why speech was notoriously so often unintelligible on the platforms and circulation, and to proposals how to raise standards through their contracting and maintenance relationships. This work would go on to form a major driving force in establishing Speech Intelligibility as a defined requirement in voice-alarm and emergency sound systems, and the spaces they served.

2.2 Voice Alarm Standards, Guides and Codes of Practice – the Response

The sound industry recognised its role in responding to the Kings Cross Fire, Bradford City Fire and the Hillsborough Stadium disaster. In the years that immediately followed, the industry, at least in the UK, was forced to rely on BS5839-1 (BS 5839 Part 1, 1988) and BS5839-4 (BS 5839 Part 4, 1998). These guides had been written in previous decades, to cover the general case of fire detection and alarm systems, and the sound industry found itself interpreting these, as best it could, for the installation of effective sound systems for emergency purposes.

The first British Standard written specifically to cover Voice Alarm was BS7443 (BS 7443, 1991) and was published in June 1991. By this time, various organisations had begun publishing other guides and codes of practice:

- *The Green Guide* was first published in 1973 (in response to the 1971 Ibrox disaster, as set out in the sections above) and was then subsequently updated (1986, 1990) in response to

Bradford City and Hillsborough respectively. It has also been revised since in 1997 and 2008.

- In 1991, the Football Stadia Advisory Design Council published *Stadium Public Address Systems.*
- In 1992, the Sound and Communications Industries Federation (SCIF, a predecessor both to the Institute of Sound and Communication Engineers, ISCE, and the Professional Light and Sound Association, PLASA) published the *SCIF Code of Practice for the assessment, specification, maintenance and operation of sound systems for emergency purposes at sports grounds & stadia in pursuit of approval by Licensing Authorities*
- In 1994, the British Fire Protection Systems Association Limited (BFPSA) published Code of practice for the design, installation and servicing of voice alarm systems associated with fire detection systems. (BFPSA, 1994)

Further developments in standards followed on, including those listed below, relating to the resilience and performance of the designed and installed system:

- In 1996 (in Spanish) and 1999 (in English), the National Fire Protection Association in the United States published NFPA 72 *National Fire Alarm Code* (later *National Fire Alarm and Signalling Code*). This has been revised in 2002, 2007, 2010 (where Speech Intelligibility was added as a clear requirement), 2013 and 2016, with a revision due in 2019. (NFPA 72, 1996, 1999, 2002, 2007, 2010, 2013, 2016, 2019)
- In 1998, BS5839-8 Fire detection and fire alarm systems for buildings. Code of practice for the design, installation, commissioning, and maintenance of voice alarm systems was published (BS5839 Part 8, 1998), providing a similar set of Speech Intelligibility requirements to BS7443, but with an important recognition of the conditions in which the proposed standard may not be practicable or achievable. Importantly, the responsibilities for identifying this and agreeing alternative standards were made clear, forcing the subject onto the table at the right part of the design process. BS 5839-8 has since been extensively revised in 2008 and 2013.
- In the same month in 1998, IEC 60849 *Sound Systems for Emergency Purposes* (IEC 60849, 1998) was published, replacing BS 7443:1991. This covered the case of when a system NOT connected to an automatic instruction from a Fire Alarm system but still had similar requirements for resilience and performance. This IEC became adopted as a Euronorm (EN) and hence a British Standard (BS), as well as equivalent local adoptions across the EU.
- In 2007, ISO 7240-16 Fire detection and alarm systems — Part 16: Sound system control and indicating equipment was published with Part 19 (below) (ISO 7240-16, 2007)
- In 2007, ISO 7240-19 Fire detection and alarm systems — Part 19: Design, installation, commissioning and service of sound systems for emergency purposes was published (ISO 7240-19, 2007), cancelling and replacing, at an international level of applicability (and in conjunction with Part 16), IEC 60849:1998.
- Applicable across the EU from 2017, BS EN 50849 has also replaced the original IEC 60849. This sits independent of the ISO 7240 components above. This document does not apply to emergency sound systems for use in the case of fire emergency, and the reader is directed to CEN/TS 54-32 (systems), EN 54-16 (control and indicating equipment product conformity), EN54-24 (loudspeaker product conformity) and national, regional and local regulations.

- Though other parts of the EN54 series are concerned with the compliance of components and equipment for sale within the EU for use in voice alarms system, CEN/TS 54-32 Fire detection and fire alarm systems - Part 32: *Planning, design, installation, commissioning, use and maintenance of voice alarm systems* (CEN/TS 54-32, 2015), also provides Technical Specifications for voice alarm systems, as well as systems for emergency purposes other than fire.
- Not directly related to voice alarm or sound systems for emergencies, BS EN IEC 60268-16 *Sound system equipment - Part 16: Objective rating of speech intelligibility by speech transmission index* (BS EN IEC 60268-16, 1988, 1998, 2003, 2011) has been through a regular series of highly informed revisions. Originally covering a number of speech intelligibility related metrics, it now concentrates on Speech Transmission Index, and variants and measurement methods thereof.

3 CHANGING TIMES

3.1 Reliability and Resilience

In a fire, the time it takes for the initial motivation is critical to minimising casualties. The idea that spoken commands to evacuate would carry greater authority than anonymous bells, and hence illicit a swifter response, was comprehendible, and it was a 1980s BBC Equinox documentary that illustrated this so well. In it, subjects had been invited to what they thought was a job interview process and gathered together and left in a basement meeting room. Left alone, but monitored on camera, for one group, a fire bell was played in, and it took 8 minutes before the first person left the room and 11 minutes before the room was cleared. With a different group under the same conditions, and an evacuate instruction given over the loudspeakers, elicited an immediate response and cleared the room in under 1 minute. It was clear how this would potentially save many lives and injury.

So, the concept of Voice Alarm became a firm proposition, with initial concerns turning to the reliability of the audio equipment that it would depend on. At the time, most people were familiar with audio through cassette players (that would often mis-spool and 'chew up' the valuable tape containing the audio), home hi-fi and, perhaps, electric guitar amplifiers, both of which were vulnerable to damage and wear through excessive gain amplification, as well as poor quality control in the manufacture of popular amplifiers, loudspeaker and microphones So the common perception of audio was that it was not robust enough to be left in charge of critical evacuations.

Perceivable failure risks included:

- *amplifiers and loudspeakers were felt to be vulnerable and unreliable (perhaps based on domestic experience of overdriven/underpowered amplifiers)*
- *easily damaged loudspeaker cones/windings (at least with non-audiophile products),*
- *unreliable production processes (eg solder joints, internal wiring etc),*
- *constant hot operation of large components (eg capacitors) etc*

Failure resilience measured began emerging in specifications and then in the published standards, including:

- *No moving parts – eg avoiding tape decks as sources and pushing the use of steady-state storage of digital audio*
- *Dual loudspeaker circuits in any space, so that the failure of any single amplifier or the severing of any single loudspeaker line could not result in silence in any broadcast area*

- *Line & loudspeaker monitoring – generally using pilot tones to confirm continuity through the critical signal path*
- *End of Line devices that detected and confirmed the presence of the pilot tone at after the furthest device in the circuit.*
- *Loudspeaker line impedance monitoring, to raise clues as to when individual loudspeakers may have failed*
- *Open circuit, Short circuit, Short to earth of any loudspeaker line*

When early systems based on microprocessors appeared, the checks called for were to use watchdog' circuits to monitor a parity check on the compiled code being run by the processor.

Failure details were set out and reported by illumination displays at the main racks, with common fault indications being displayed on critical user equipment (eg the Fire Microphone) and via a simple link back to the Fire Alarm system, usually to be printed out on an automated paper log.

3.2 Requirements to be Intelligible

The initial development in standards and guidance were a response to the need for reliability and resilience in the systems that give warnings and instructions in the event of an emergency. Based on research as early as the 1980s, the industry had recognised the need to provide reliable speech-based instructions in an emergency, both in order to elicit swift responses as well as to provide situation-specific instructions. However, the available standard guidance made little reference to the capability of the system to provide *intelligible* speech, let alone making any requirement of the environment that the speech system was designed to work into.

3.3 The Speech Transmission Index - a Metric

Before 1998, only BS7443 made any specific requirement for speech intelligibility, applying the Speech Transmission Index (STI) metric. STI had been developed by researchers at The Netherlands Organisation (TNO) for Applied Scientific Research, taking inspiration from methods of evaluating optical systems. Herman Steeneken and Tammo Houtgast lead research in the 1970's, initially into ways of rating electronic communication channels in military applications, and then quickly opening up the applicability to include acoustic noise, reverberation and echoes.

The STI method is well documented elsewhere, including the highly informative and developed standard IEC 60268-16. In measurement terms, it comprises a series of amplitude modulated, octave band-limited, pink noise signals. These stimuli are inputted into a system with a 100% modulation depth, and the output of the system is tested for the remnant modulation depth after being affected both by background noise and by reverberation and other temporal effects, ie the characteristics of the system under test that would similarly affect the acoustic articulations of a typical speech signal. This ratio of modulation depths between the output and input is measured for each of a series of modulation frequencies and octave bands, to build up the Modulation Transfer Function. See an example in Figure 1.

F(Hz)	63	125	250	500	1000	2000	4000	8000	16000
SNR(dB)	20.7	43.7	47.1	53.4	49.3	49.9	47.4	45.4	44.0
MTF									
0.63 Hz		0.918	0.908	0.890	0.875	0.909	0.938	0.975	
0.80 Hz		0.889	0.872	0.847	0.827	0.874	0.911	0.963	
1.00 Hz		0.857	0.831	0.798	0.771	0.832	0.877	0.946	
1.25 Hz		0.824	0.786	0.743	0.709	0.785	0.837	0.922	
1.60 Hz		0.783	0.731	0.676	0.632	0.729	0.785	0.885	
2.00 Hz		0.738	0.670	0.610	0.555	0.677	0.734	0.842	
2.50 Hz		0.678	0.588	0.531	0.467	0.623	0.676	0.786	
3.15 Hz		0.603	0.486	0.430	0.367	0.567	0.605	0.716	
4.00 Hz		0.527	0.368	0.306	0.244	0.505	0.529	0.630	
5.00 Hz		0.510	0.272	0.253	0.150	0.455	0.477	0.544	
6.30 Hz		0.508	0.274	0.261	0.182	0.442	0.449	0.449	
8.00 Hz		0.486	0.322	0.269	0.171	0.424	0.440	0.334	
10.0 Hz		0.357	0.321	0.213	0.093	0.372	0.394	0.210	
12.5 Hz		0.353	0.242	0.074	0.098	0.319	0.334	0.170	
r(m)	21.8								

Figure 1: Example array of modulation transfer ratios for each octave band and modulation frequency, making up the Modulation Transfer Function (example courtesy of the WinMLS manual)

The matrix of Modulation Transfer Function values is then combined into a single value, with a weighting system that accounts for the different relative importance of each of the octaves in their contribution to speech intelligibility.

This method was originally developed to test communication channels, but because of its thorough approach to both intensity and temporal interferers, it became clear that it could be equally used for assessing the broadcast of speech into acoustic spaces, ie talking into a room, or perhaps, vocal messages played through Voice Alarm loudspeakers.

At that time, the only practical field measurement technique was by use of the RaSTI method, which was eventually discredited for reliable use in amplified speech systems, after considerable research by Peter Barnett, Peter Mapp and others through the 90s. It remains as valid for testing 'natural' speech channels, ie modelling of the path from a human talker to a listener in the presence of an acoustic environment. Unfortunately, Houtgast & Steeneken's 'full' STI measurement by the modulated signal method requires a considerable measurement period to work through the full set of octaves and modulation frequencies, which are not orthogonal, meaning that not all values can be measured simultaneously. Impulse response methods, ie where the system complex transfer function is measured by auto-correlation methods and analysed for a host of metrics, were shown to be able to generate 'full' STI measures in the post-processing. In 2002, the STIPA metric was introduced, using a modulated signal method by use of a reduced set of modulation frequencies and over the 250Hz to 8kHz octave bands. This provided the direct measurement portability of the discredited RaSTI method but in a way that had been scientifically researched to show a high correlation with a 'full' STI method.

3.4 The Force of Standards

While BS7443 called for an STI of 0.5 minimum, the standard seemed to lack enough threat of any consequence through non-compliance, and so was often side-lined in the very situations where its purpose was most critical. Many shopping malls, office atriums and, initially, railway stations appeared to shrug at this seemingly impossible requirement.

Not surprisingly, it was London Underground Ltd (LUL) who seemed to take most seriously the need for assured speech intelligibility levels, along with their counterparts in the Hong Kong Mass Transit Rail Corporation (MTRC). Both organisations were planning significant expansion of service, with the Jubilee Line Extension in London and the Lantau and Airport Line in Hong Kong, out to the island of Lantau where Chek Lap Kok airport was being constructed on a massive man-made island. Around the mid-1990s, both organisations invested in Consultants to advise on the strategies needed to meet compliant levels of speech intelligibility, as well as on just what level (and metric) of speech intelligibility should be required. The critical developments to come out of this process included:

- Speech intelligibility was critical, and needed to have a metric attached to it – mere sound level requirements, such as in BS5839-1, would not be sufficient
- Speech intelligibility performance relied as much on the architecture of the space (ie its acoustic response, or reverberation) as it did on the choice or quality of audio equipment used. Poor speech intelligibility could not be continued to be 'thrown back' at the audio installer's contract to be fixed. The rooms had to be fixed too. This was an inter-disciplinary issue and had to be tackled in that way.
- Practicable methods of measuring metrics corelated with speech intelligibility were available, such as the now widely adopted Speech Transmission Index. Some doubt was being sown over the use of the RaSTI field method. It remained, however, the main factor to drive good decisions across the design process, including setting essential requirements on acoustic finishes by way of architectural factors.
- Methods of predicting speech intelligibility metrics, as well as the physical acoustic parameters that factored into them, were available and were being tested in use. These were the tools used to drive the design decisions, to shift expectations and to overcome the incredulity that the control of ceiling finishes and loudspeaker spans were absolutely necessary for the safety of life.

It was not until 1998 that, in the UK and the EU, standards appeared that could no longer be so easily ignored, making clear requirements on speech intelligibility. Both BS5839-8 and BS EN IEC 60849 arrived in February that year, and both requiring equivalent to STI 0.5, just as BS7443 had done 7 years previously. Importantly, both recognised that practical situations often dictated that this standard could not be met, opening the door to reasoned alternative performance standards.

Essentially, where an STI 0.5 standard could not practicably be expected, such as in a noisy and/or voluminous space, a lower value could be proposed. This proposal was subject to agreement by all interested parties. As this would include the Operator of the Building (and their insurance liabilities), the appropriate Licencing Authority and the Design Consultants (Acoustics, Audio and Architectural), this usefully forced a conversation on the issue. My experience was that, in spaces that might otherwise have been treated as unachievable for STI 0.5 and left to fall unchecked, often as low as STI 0.3, a moderated standard could be developed to be significantly more achievable, proposed, hopefully agreed and then written into the contract. Along the way, inevitabilities would be established over a minimum amount of acoustic absorption and density of loudspeakers, as well as valuable constraints on the technical scope of loudspeaker products and locations. Effective speech intelligibility in life safety systems was gaining traction against conflicting aesthetic aspirations and perceived cost issue. In the best projects, the aesthetic agendas shifted to accommodate the right loudspeaker schemes into a new visual agenda.

Alongside developments in LUL and MTRC, as well as Network Rail on major overground rail stations, the stadium industry also took notice. Perhaps because it is a more fractured client base than LUL, NR or MTRC, but even to this day, many small, medium and even large stadiums seem to find the concept of speech intelligibility new and the need to comply on it, still somewhat unexpected. Only the highest profile venues, ie those of the very top clubs, international stadiums and stadiums being built for international tournaments appear to come ready to commit to this issue.

Similarly, shopping mall projects still appear to be surprised by the need to address the acoustics, or do so in a very minimal way. Meanwhile, in airports, despite them being predominantly shopping centres with a captive market, the commitment to speech intelligibility and compatible acoustic conditions seemed to come early, such as at Stansted in 1990, Manchester in 1993, Bristol in 1996 and JFK Terminal 4 in 1999 and Dublin T2 in 2005 among others.

(In addition, speech intelligibility was being championed by good designers in applications such as courtrooms, parliament buildings, lecture halls and places of worship. This paper limits itself to the life safety applications.)

4 BEGINNING TO DESIGN WITH STI

4.1 The Drive to Tools

In the disasters described in earlier sections, the loudspeaker systems were of course only one part of the issue, and clearly many other factors conspired to the loss of life, injury and damage. However, the positive role of an effective form of speech broadcast in handling or de-escalating a serious situation was becoming clear.

At the same time, the effectiveness of loudspeaker systems in public spaces was of poor reputation, and expectations were low that speech intelligibility could reach effective levels in train stations, shopping centres, sports grounds and other similar spaces.

In a renewed drive to improve this, audio systems took the blame. They were the clear target of disrepute, and many systems were aging, seemed to be poorly installed or maintained, with sparse and poorly balanced coverage. Consultants, installers and suppliers were set to 'coming down hard' on the sound system contracts and deliverables, but it was clear to some that room acoustics were at least part of the issue.

The STI metric allowed the speech intelligibility of a loudspeaker system in an acoustic space to be evaluated, not only by measurement but by calculation. Practical calculation methods were being built into modelling software. JBL's Central Array Design Program (CADP, 1983) could calculate the %ALCons metric. AFMG's EASE provided STI calculations, initially via an empirical conversion from %ALCons to RASTI (EASE 1.0, 1990), and then directly as STI based on Reverberation Times and Signal-to-Noise ratios using statistical 'Standard Mapping' techniques (EASE 2.0, 1994). This was followed in EASE 4 (2002) with the AURA impulse response method, taking away the need to rely on the limitations of assuming a linear reverberation tail and homogenous reverberant level at all points in the room, but at the expense of extended calculation times that are best saved for checking the final design iteration. Then EASE 4.3 (2009) added a derivation of the STI from the MTF matrix derived by the swift Standard Mapping statistical method.

Meanwhile, CATT-Acoustic came from the other direction and developed IR methods that ran quick enough to allow some design iterations, while embracing the definition of loudspeakers through the Common Loudspeaker Format (CLF) filetype, as well as, from 1999, proprietary Dynamic Link Libraries (DLL) for more bespoke clustered and electronically controlled product packages, such as the Duran Intellivox series and L-Acoustics concert arrays. EASE followed suit with DLL support with EASE 4 (2001 Beta versions), and then the Generic Loudspeaker Library (GLL) format that provides users with a software package to create their own DLL-equivalent product file definitions.

Like CATT, Odeon has come from the Impulse Response (IR) synthesis method, with its origins in concert hall modelling, and has also embraced loudspeakers as sources, through CLF definitions.

The time of change in attitudes towards speech intelligibility standards, and the understanding of where to place the 'blame' between the system and the room, was in the 1990s and into the early 2000s. At that time, EASE was the obvious platform, as it delivered (relatively) quick results, quick enough to make practical a generous number of design iterations and investigations. It also had access to a seemingly unlimited range of manufacturers and product ranges, as having your data in EASE became a basic requirement for any manufacturer wanting to be seen as 'serious' about their products being used in critical situations. This was an essential draw as a designer consultant, knowing that I could develop the advice needed at the stage in the job where it could have its most effective influence, without tying the project in to one particular manufacturer of what would mostly be large-volume distributed products. This brand-agnostic design tool, with (relatively) quick calculation methods, attending to the combined effect of loudspeaker scheme and room acoustics, seemed to be the only viable tool to use. This is not to say that EASE did not provide some frustrations to its users, or some initial issues with transparency over the calculation algorithm, but it did provide a platform with which to start driving electro acoustic designs down the right paths.

Crucially with EASE, performance questions could be investigated not just in the auditorium, or on the stadium stands, but also in concourses and corridors, and train sheds, platforms, escalators, malls, ticket halls, atriums and offices. As well as the high power 'public address' products for the theatre and the sports arena, the manufacturers of large volume, low cost units from Philips, DNH, Bouyer, Penton etc became at our disposal.

4.2 Deriving the Essentials

Around this time, Hong Kong's MTRC and London's LUL were asking, just what speaker types and spacings did we need to get an STI of, say, 0.5. Just 10 years earlier, the industry was struggling with loudspeaker polar patterns printed onto clear plastic sheets that the designer would use to 'view' the loudspeaker footprint by holding that at an angle to the page. But by the early and mid-90s, we were creating geometric wire-frame models inside our computers, assigning third-octave absorption coefficients to each surface, picking our loudspeaker products from a database of 1000s, and setting them to work in distributed and centralised arrays in our virtual spaces.

From this test bed, a number of scenarios, myths, accepted practice and better ideas could be played out and compared. Common question in numerical modelling, not least in modelling for acoustic and electroacoustic performance is, how close is the calculated value to the measured one. This seems a fair question on the face of it, and of course no model is valuable if it misleads us with incorrect results. It is important to keep a clear eye on what the 'result' a model is intended to deliver. Perhaps it is to show that Proposal A, an idea identifiable as unsuitable electro-acoustically, however attractive in other terms, would fall short when tested in the correct conditions. And perhaps another version, based on Proposal B, is made to show how the proposed solution based entirely on performance would indeed meet the requirements. Then, having accepted the inevitability of Proposal A being unsuitable, while admitting how Proposal B could be improved on for cost, practicality, size or downright ugliness, perhaps that inter-disciplinary journey can begin to create Proposal C, the solution that finds the right common currency between the conflicting requirements that make up any design challenge.

In these scenarios, the measure of 'accuracy' of the model method would be whether it provided for the Designer to make the right decision, or helped the Designer convince a fellow designer of the wisdom of the decision that should be made. Of course, accuracy in practice goes beyond this and should also indicate:

- Areas where the performance requirements are satisfied with low risk
- Areas where the risk of failure is high and need to be mitigated through further design iterations
- Areas where a lower performance is anticipated, where the increased risk of compliance failure is understood but managed, in the context of the fuller design.

4.3 Case: Overhead Loudspeakers

For examples, a model can be used to track the achievable STI rating for a range of ceiling speaker spacings, to identify the relative benefits of:

- Reducing the speaker spacing (ie increasing the speaker density), vs
- Introducing acoustic absorption (hence reducing the Reverberation Time).:

The usual experimental controls would be needed, ie making sure that the overall sound level in the room, as would be judged in commissioning settings, is equal between the cases, as well as the background noise spectrum. The loudspeakers would need to be checked for operating within their linear range, accounting for the dynamic range of speech versus the pink noise test conditions used to define the device performance in the model database.

Take an example room, 4m tall, by an extended area in both other dimensions. Imagine this room with a Reverberation Time (T_{MF}) of 2.0s, as might result from a basic fitout and moderate absorption from open face blocks, and a limited area of acoustic materials. This may be an underpass concourse to a metro network, or a retail concourse in a stadium. In this space we can start with ceiling or soffit-mounted loudspeakers on centres of 8-12m, and we find that the rated STI value falls in at 0.45, which fails the usual STI 0.50 requirement. See Figure 2.

The response might be to suggest that we add more loudspeakers until we get the required STI values. Another might be to address the minimal acoustic absorption in the space, but for many PAVA designers, this part may not be conveniently available to scope. So, the model can be used to investigate loudspeaker centres of 6m, 4m, and even 3m and 2m in the extreme. See Figure 3 and Figure 4.

Note that the calculation model used here is EASE Evac, which is based on a statistical linear consideration of the reverberant tail and reverberant field. For any effects of specific reflection behaviours, such as including the floor or close to the side walls, an impulse-response synthesis method (eg EASE Aura, Odeon, Catt) would need to be employed. As this only realistically offers data at identified sample positions without considerably extended calculation times, the trend-spotting approach here would not be as clear to conclude from.

Looking at the compiled data from these experiments in Table 1, we can see that, once the unfeasible extremes of 12m and 2m spacings are discounted, there advantages of even halving the spacing, and quadrupling the amount of product and installation, returns little advantage and an arguably insignificant benefit, given the general precision of the method.

However, if instead we consider a room where the 2.0s RT is reduced to 1.6s, such as from adding a basic acoustic finish (eg Class C) over 30%-50% of wall space or 50-70% of ceiling (or more, if the base case shows a higher RT), we show the data in Table 2. Instantly, the compliant STI values become achievable with practicable spacings.

Given that rooms of these dimensions without any significant identifiable acoustic absorption could typically exhibit RT values of 2s-4s, while any form of full acoustic ceiling could drop this to close to 1s, this demonstrates well the relative importance of where to put the investment, and how moving from acoustically untreated to acoustically controlled quickly flips the STI problem from being impossible or impracticable to, basically, a trivial design issue.

Table 1: Predicted STI values for 4m high room with RT (T_{MF}) 2.0s. Compare with requirement STI 0.50

Room Height	Acoustic Conditions	Loudspeakers	Rated STI (Mean – SD)
4m	RT = 2.0s (Tmf) L_N = 68dBA L_T = 83dbA (mean + SD)	12m on centres Ceiling C (70 x 70)	0.45
		8m on centres Ceiling C (70 x 70)	0.45
		6m on centres Ceiling C (70 x 70)	0.46
		4m on centres Ceiling C (70 x 70)	0.46
		3m on centres Ceiling C (70 x 70)	0.47
		2m on centres Ceiling C (70 x 70)	0.47

Table 2: Predicted STI values for 4m high room with RT (T_{MF}) 1.6s. Compare with requirement STI 0.50

Room Height	Acoustic Conditions	Loudspeakers	Rated STI (Mean – SD)
4m	RT = 1.5s (Tmf) L_N = 68dBA L_T = 83dbA (mean + SD)	12m on centres Ceiling C (70 x 70)	0.49
		8m on centres Ceiling C (70 x 70)	0.51
		6m on centres Ceiling C (70 x 70)	0.51
		4m on centres Ceiling C (70 x 70)	0.52
		3m on centres Ceiling C (70 x 70)	0.52
		2m on centres Ceiling C (70 x 70)	0.53

So, in an extended reverberant room, such as shopping mall, metro station etc, the excessive reverberation due to the lack of acoustic absorption is not practically or reliably overcome by supplying a denser coverage of loudspeakers. Neither would the significant subjective sound quality, frequency range of dynamic headroom differences observed between the various products available make anything like as much an effect on the STI compliance as the change in Reverberation Time shown here.

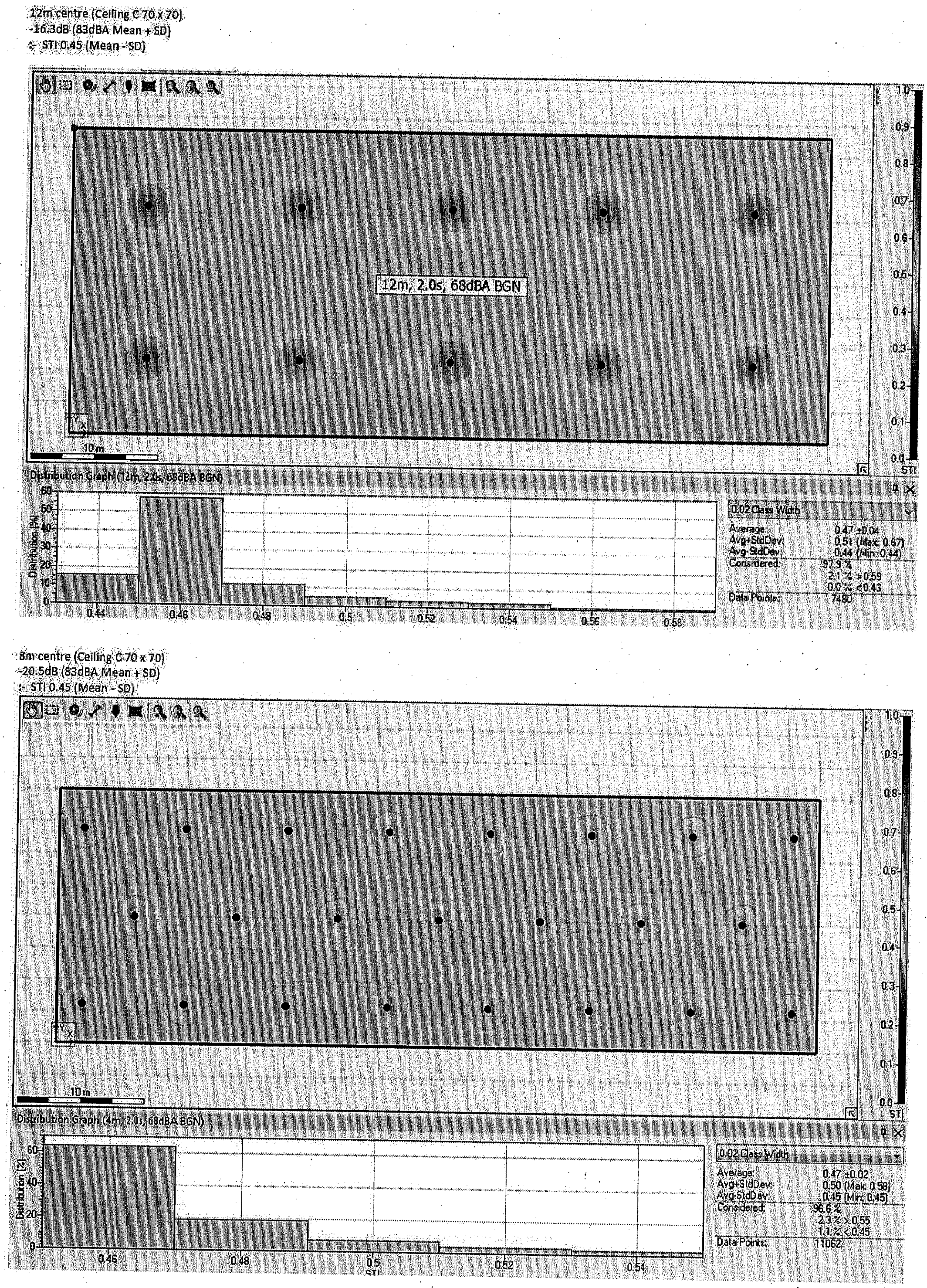
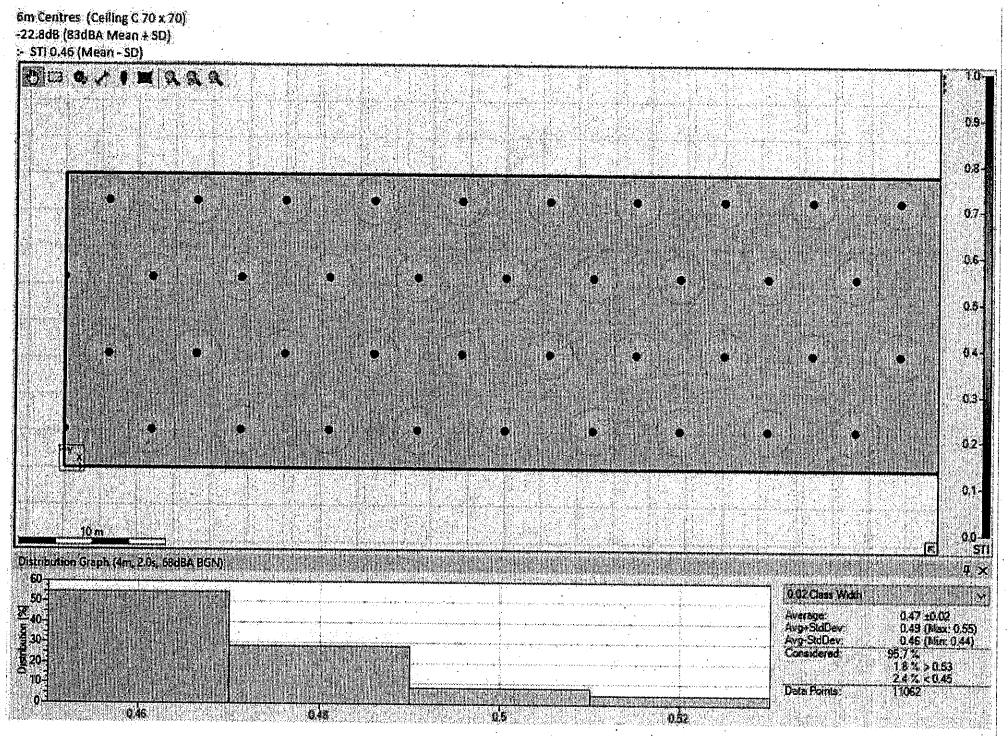


Figure 2: 4m room with 2.0s RT - ceiling loudspeakers at 12m and 8m centres, 83dBA L_T vs 68dB L_N



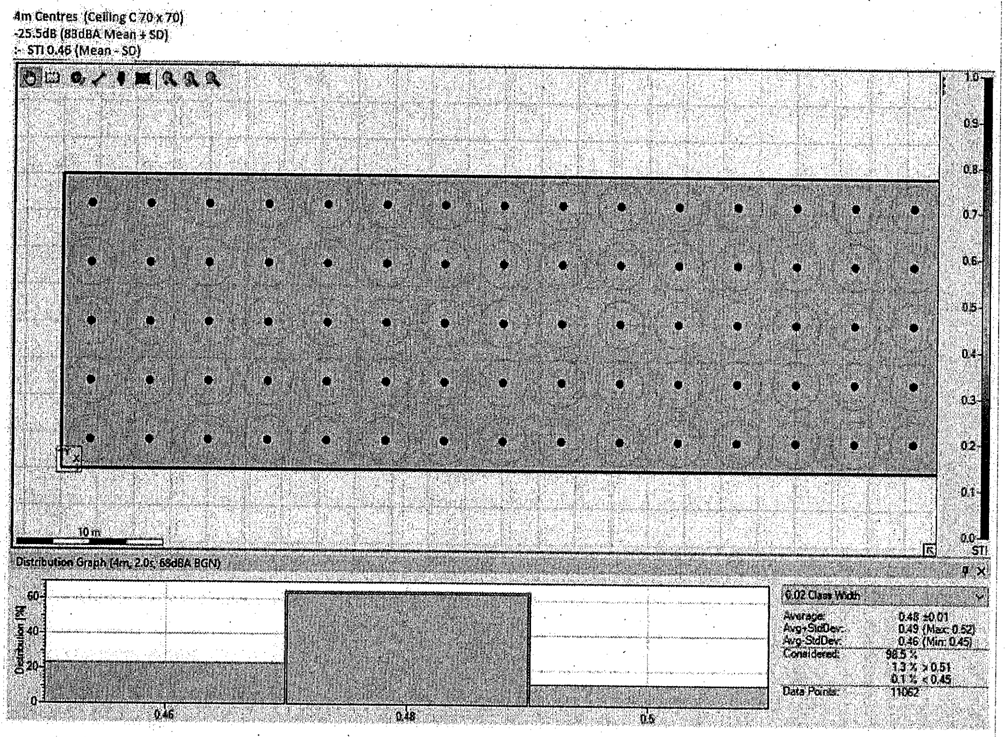


Figure 3: 4m room with 2.0s RT - ceiling loudspeakers at 6m and 4m centres, 83dBA L_T vs 68dB L_N

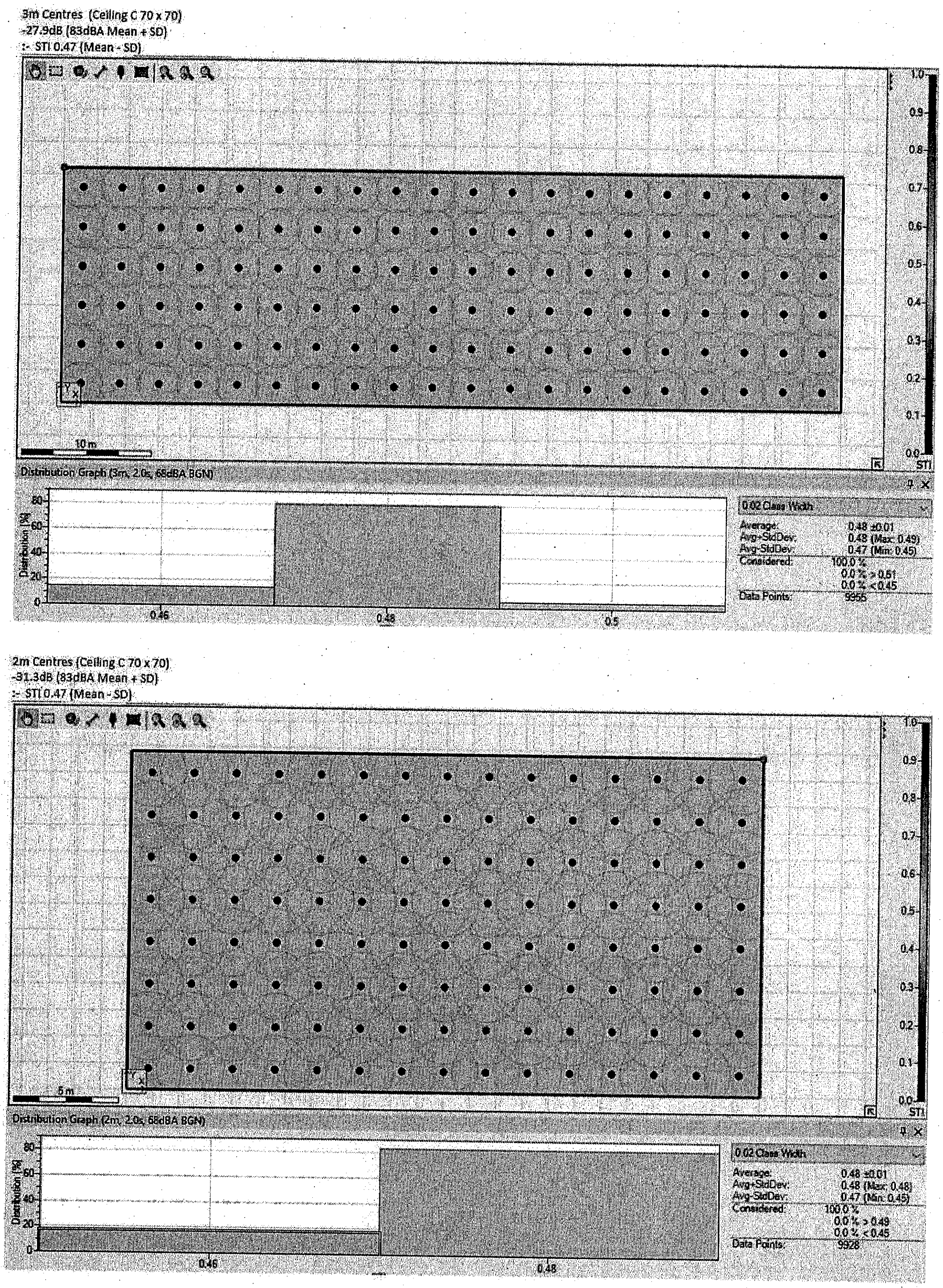


Figure 4: 4m room with 2.0s RT - ceiling loudspeakers at 3m and 2m centres, 83dBA L_T vs 68dB L_N

4.4 Case: Lateral Coverage

Similar tests can be done on other configurations, such as the mounting of column or other loudspeakers, aiming laterally into a space from a height above heads (eg 2.5-3m) and in clusters of 2 to 4 on centres. In this case, reverberation is controlled (1.6s in a 15m tall space), but background noise is similar when heavily occupied (eg 68dBA), and as low as 50dBA when sparsely occupied.

Figure 5 shows the calculated STI meeting STI 0.5 in the furthest locations from the widely spaced loudspeakers (clusters on 36m centres), and total sound pressure level (SPL, dBA) needed to achieve this. Against the busy noise case of 68dBA, levels of around 82dBA and above are required, resulting in levels of 91dBA (and potentially up to 94dBA) close to the loudspeakers! As this level would be at risk of inducing stressful responses and so unhelpful behaviour patterns, in the event of an evacuation, it may be desirable to reduce the output level accordingly. This would also apply to general PA announcements outside of an evacuation, which may also be of value in managing the public safely.

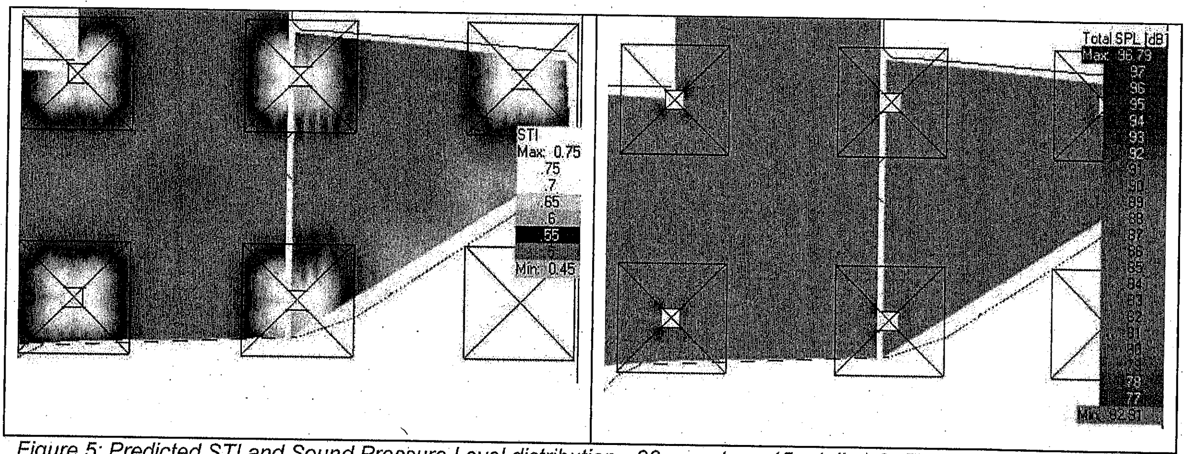


Figure 5: Predicted STI and Sound Pressure Level distribution - 36m centres, 15m tall, 1.6s T_{MF}, L_N 68dBA, PA Levels 82-91dBA

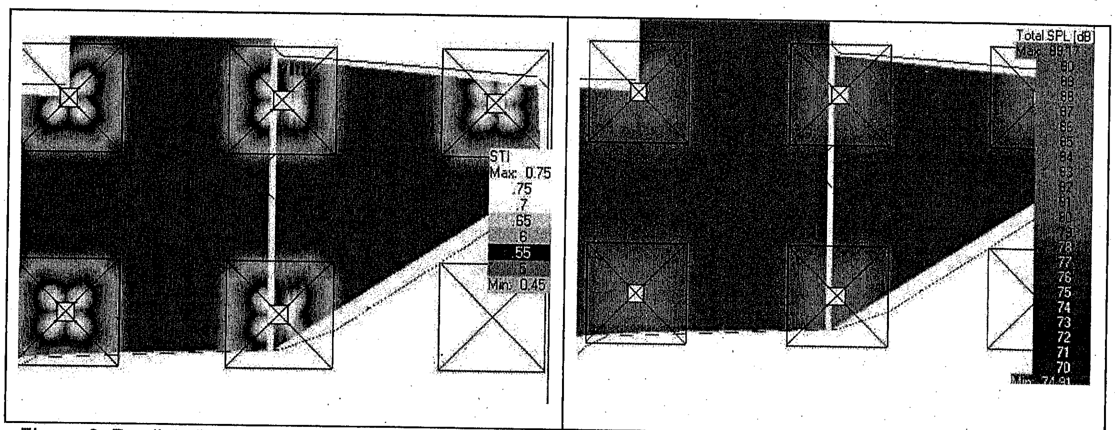


Figure 6: Predicted STI and Sound Pressure Level distribution - 36m centres, 15m tall, 1.6s T_{MF}, L_N 68dBA, PA Levels 74-83dBA

Figure 6 then illustrates that when the output levels are reduced to something manageable, STI drops to around 0.34 to 0.42 (Figure 7). The outcome of this study may be to identify the need for spacings considerably lower than 36m, to look for long-throw solutions and/or higher mounting positions, or to accept the risk of high speech levels in critical use.

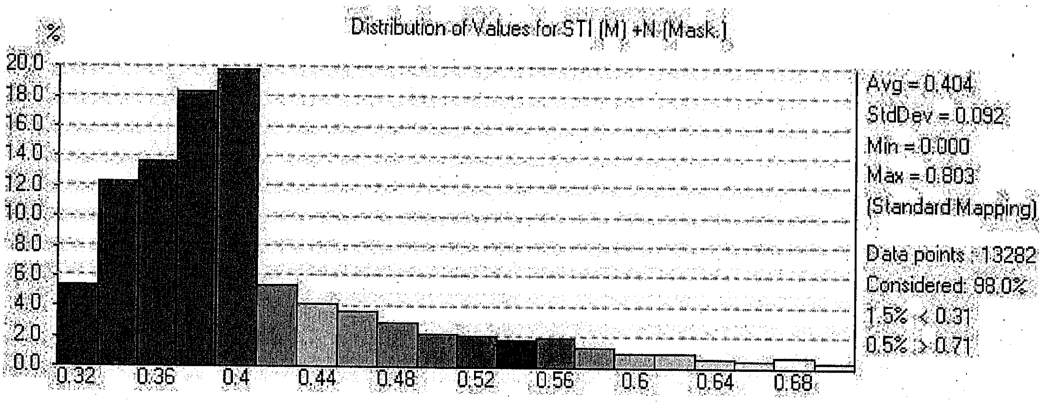


Figure 7: STI Distribution calculated with controlled sound pressure level

4.5 The Steerable Array

The principle of arranging multiple loudspeaker drivers into a linear array is not new. The (notionally) narrowed vertical coverage beam created is easy to imagine having an advantage in directing sound onto areas of audience or congregation while minimising how much sound output is directed at the ceiling and other areas where coverage is not required. The potential was quickly identified for this approach to improve speech intelligibility ratings in rooms with live acoustic responses (such as churches, railway stations), by minimising the reverberant acoustic field for a given 'direct' useful coverage. Medium and long column loudspeakers, such from Philips, Penton and others, have been a regular feature of speech-critical distributed audio systems since the early 1980s. Early experimentation with EASE in the 1990s identified an advantage to be gained from column loudspeakers, in allowing compliant speech intelligibility in higher Reverberation Time cases.

However, this advantage had been well known and had been developed further using progressive delay and filtering functions to form and aim the output 'beam'. Early examples, using analogue technologies, were the AIRO columns that were installed in Westminster Abbey in the early 1970s, involving research by Peter Parkin and a young Peter Barnett.

The renewed interest in speech intelligibility, partly driven by the availability of the STI metric, raised interest in the 1990s in delay and filtering functions to allow beamforming to meet precise coverage areas. The Dutch Acoustic Consultant, Johan Van der Werff of Peutz, specified an array of Bose 102 units in a vertical array (Wal, Start, & Vries, 1996), with logarithmic spacing, each driven by a discrete amplifier channel, each with dedicated micro-second delay and equalisation (Wal, Start, & Vries, 1996).

This was installed at Schipol Airport (Werff, 1994) by the established audio manufacturer, Duran Audio, which lead Duran into developing its own series of DSP controlled packaged line array loudspeakers (Van Beuningen G. d., 1994) and then on to important research by Evert Start and others (Van Beuningen & de Vries, 2000).

Acoustic consultants charged with fixing the seemingly impossible problem of achieving compliant speech intelligibility in voluminous spaces from limited mounting opportunities leapt on this technology and quickly started to learn how to apply it in real architectural designs (Katz, Malpas, & Wise, 1999).

It was initially unclear how to use this technology in the computer models we were developing to predict STI coverage. These were not only to demonstrate the likely compliance of a solution, but more to compare novel and expensive approaches with more traditional ones, or in this case to help answer if we really could cover a 45m wide international airport check-in hall from a single line of units along one side.

All the acoustic modelling packages available at the time, including ODEON, EASE, CATT and Ulysses, defined the rooms by planar geometry, and the loudspeakers as point sources with 'far field' balloon plot radiation patterns. A line array is not the usual point source acoustic entity, with a directivity pattern 'balloon' that scales at any practical distance from the device. In fact, their advantage came in their use of the transition between near and far-field to 'cheat' the coverage requirement. So, the modelling software introduced the concept of a library definition of packaged, multiple loudspeaker products, with each acoustic source modelled separately and the control of the relationships between the sources available to the user through a manufacturer's prescribed user interface. CATT, EASE and others introduced Dynamic Link Library (DLL) techniques as a way of encapsulating this.

Designing for Speech Intelligibility using long-throw linear array sound systems throws up a number of particular challenges to practical modelling for STI values:

- To model the array correctly, each audio source needs to be calculated for individually and their combined effect derived in the complex domain, to account for the interference patterns that define their coverage effects. This extends calculation times dramatically, especially for calculation methods using impulse-response approaches.
- The near/medium/far field approach of the products invalidates any attempt to calculate using far-field balloon plots, and further frustrates standard attempts to calculate STI by statistical means. Moreover, the reverberant field is no longer uniform.
- Long-throw coverage where more than one device is used to span a very large area introduced the importance of optimal time alignment, and a 3D conundrum to solve.

In addition, the actual coverage patterns when you array many loudspeakers together is not necessarily the pattern you would imagine from inspecting the component boxes visually. Often the result is counter-intuitive, even to experienced designers, and highly dependent on frequency/wavelength. IN parallel with the development of packaged line array loudspeakers for speech, large scale component systems for concert touring and sports venues were also emerging from L-Acoustic, Duran Audio's Target system, Nexo Geo, Outline Butterfly, JBL, Meyer, d&b, Turbosound, Martin Audio and others. With these products came the manufacturers' own loudspeaker coverage prediction software, alongside the DLL interfaces for CATT and EASE. Aimed more at the live sound market and at venues where the room acoustics were not going to change as part of the project, these applications limited themselves to predicting the direct field coverage only, on the basis that if that was designed to be even, the effect of the room acoustics on speech intelligibility had been minimised.

The more advanced array systems, such as Duran Target, Martin Audio, Tannoy, ActiveAudio and others, invoked DSP control and individual FIR filters to form the beam shaping to best match the audience areas intended, as well as avoiding areas where sound was undesirable (such as curved backwalls). Some of the softwares provided offered the user the option to identify audience and 'avoid' surfaces, at least on a section through the room.

Amongst all this, Duran Audio took the extensive investment to develop their extensive acoustic modelling package Digital Directivity Analysis (DDA). Cleverley, the acoustic response, and hence the STI values expected, were derived from a modified form of statistical analysis, allowing both direct and reverberant energy to be derived relatively quickly while remaining reliable. Most impressively, the software allowed a full 3D model of the whole room, in a way we were more used to in EASE, CATT and Odeon, with every surface potentially identified as audience, as 'avoid' or as neutral. The algorithms would optimise the FIR filters applied to each part of each array to best match these user-priorities and would even use regression analysis to map the optimum field of delay time needed to maximise speech intelligibility.

4.6 Tailored Designs and High-Power Loudspeaker Systems

Stadiums present the imperative to meet speech intelligibility requirements (refence the crowd disasters that have occurred in stadiums), with the need to provide very high speech levels to get over crowd noise typically ranging from 85dBA to over 102dBA when goals are scored. The stadiums often offer very few practical options for loudspeaker mounting, typically on the leading edge of the roof at distances from 12-28m from spectators.

A special solution is clearly required in a stadium, and all of the loudspeaker and analysis tools described so far have been applied. In order to achieve the very high sound levels everywhere without unnecessary excesses, evenness of coverage is paramount. This also contributes to good speech intelligibility by maximising the direct and minimising the reverberant component of the acoustic response. Despite being semi-open spaces, stadium stands can exhibit a response that acts much like a reverberant tail similar to an RT of 2-3 seconds.

So, one approach is to adopt well-chosen and critically located point sources, and loudspeakers and amplifiers with very high headroom to maintain articulation at speech levels of 95-115dBA.

In stands needing to target upper and lower tiers, multiple sources can be co-located with definitive aiming, and analysed for any unintended arraying effect.

For stands above, say, 20m throw and speech levels above 100dBA, single box approaches become more risky and tailored line arrays become more necessary. Genuine array behaviour needs to be analysed by suitable means. Often this is done by using the 'direct only' approach of the manufacturers' aiming software, with the optimised angles, levels shading, and product choices then fed into a fuller acoustic model such as EASE, AURA, CATT etc.

A biproduct of this is that sports grounds are expecting to install a highly designed system to meet safety standards, only to find it offers dividends in musical quality and matchday entertainment. In fact, in grounds where a new system has not been implemented recently, it is common now for the Club to hire in ground-stacked supplemental systems to bring the kind of spectator experience that has come to be expected.

5 A MODERN STORY

5.1 Terrorist Threats

It has become clear in the last 10-20 years that the risk of a fire or over-crowding is being joined by the risk of terrorist attacks. While fires and crowding are relatively unpredictable, their mechanics have been extensively researched, and this has fed into ever more sophisticated fire planning and evacuation scenario-building.

A terrorist attack, while still extremely rare, is unpredictable by nature. This means that the instructions and directions that may need to be given at any one moment as an indecent unfolds may well need to be highly specific and barely anticipated by the public they serve to protect. This indicates a need or a trend go beyond the basic intelligibility standards derived for fire and crowds, and to call for a level of clarity and authority that can convince spectators to, for example, evacuate a ground that they have travelled to from 100s or 100s of miles, perhaps spend many £100s on tickets and have been looking forward to for many weeks or months. Moreover, you may ask other spectators to remain in their place while other parts of the ground are evacuated, in order to minimise overcrowding risks. You may need to ask spectators in specific areas to move away from the threat, or to track an adjust a response to a mobile threat, such as an 'active shooter'. You may need to address spectators not yet in the ground and advise them not to enter.

These responsive crowd management steps will require sound systems that are:

- Highly intelligible, beyond minimum requirements
- Intelligently zones
- Easy to use in a crisis

5.2 More Than Intelligible

Audibility is a prerequisite for intelligibility. If you cannot hear the speech over the noise, it cannot be intelligible to any essential standard.

Of course, audibility may not be sufficient on its own, and more must be done to reach that essential level of speech intelligibility that would be regarded safe for an evacuation.

Speech intelligibility is a prerequisite for the message to fully engage with the listener's attention, and then for it to be informative of actions to be taken that are not obvious. Higher speech intelligibility levels open the opportunity for the messages to carry a strong authority, needed to motivate people on mass to act in ways they be unready to comply with. See Figure 8 as an illustration. Higher up this Maslow's pyramid we push, the more important other factors become, such as the choice of words, the announcers delivery skills, the use of familiar or trusted announcers and the ability to reference actions and routes clearly.

So, it is possible that higher STI requirements than STI 0.5 are going to become essential in areas of mass gatherings vulnerable to unpredictable risks and complex responses. The Annex to IEC 60268-16 (see Figure 9) offers some qualitative categories to different ranges of STI values, and this may be a useful reference to establishing what alternative, higher standards may become necessary.

6 CONCLUSIONS

When loudspeaker speech systems (Voice Alarms) were identified as potentially superior to anonymous bells and sounders at efficiently evacuating the public, concerns and attentions turned to the need to make the message sufficiently intelligible.

The Speech Transmission Index metric provided a measurable way of demonstrating, and therefore specifying levels of speech intelligibility. Calculation methods and modelling software provided the forum with which to progress and mature the industry, recognising that the problem was not simply to be solved by insistence and contract penalties on loudspeaker system suppliers. The acoustics of the spaces needed to be made compatible also and has in fact been shown to be more critical in the risks of failing to meet speech intelligibility requirements.

The imperatives placed on Voice Alarms to meet STI requirements, combined with the maturity of the market and the design expertise in delivering against this, has driven up the quality of sound supplied in critical situations, such as for the travelling public and spectators at sports and other events. This has offered venue owners and operators a secondary dividend in the quality of musical and verbal entertainment that can be provided during events. At the highest level of venue, this has in turn driven up the quality of the sound systems at delivering precise and authoritative information, and in motivating the public to respond in safe ways.

The modern threats beyond fire and evacuation now include terrorist and 'live shooters'. The higher standard of speech intelligibility now expected in some markets offers real safety advantages in handling these complex situations safely.

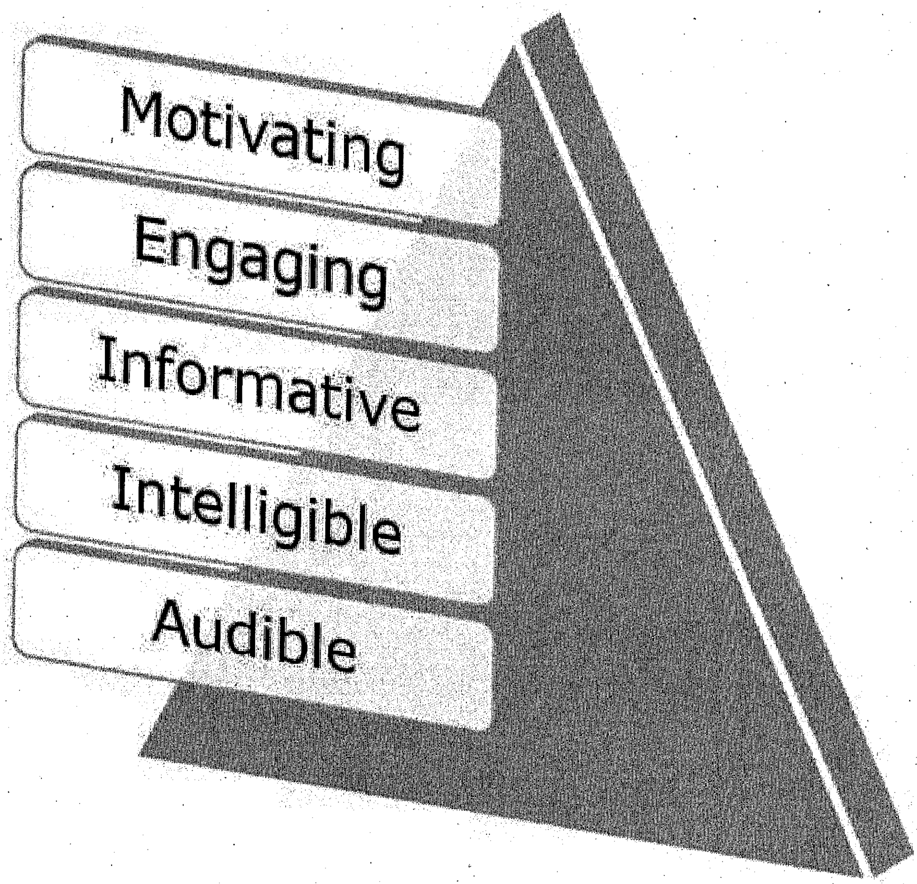


Figure 8: Maslow's pyramid of needs, applied to speech instructions and their ability to affect behaviours

Category	Nominal STI value	Type of message information	Examples of typical uses (for natural or reproduced voice)	Comment
A+	>0,76		Recording studios	Excellent intelligibility but rarely achievable in most environments
A	0,74	Complex messages, unfamiliar words	Theatres, speech auditoria, parliaments, courts, Assistive Hearing Systems (AHS)	High speech intelligibility
B	0,7	Complex messages, unfamiliar words		
C	0,66	Complex messages, unfamiliar words	Theatres, speech auditoria, teleconferencing, parliaments, courts	High speech intelligibility
D	0,62	Complex messages, familiar words	Lecture theatres, classrooms, concert halls	Good speech intelligibility
E	0,58	Complex messages, familiar context	Concert halls, modern churches	High quality PA systems
F	0,54	Complex messages, familiar context	PA systems in shopping malls, public buildings offices, VA systems, cathedrals	Good quality PA systems
G	0,5	Complex messages, familiar context	Shopping malls, public buildings offices, VA systems	Target value for VA systems
H	0,46	Simple messages, familiar words	VA and PA systems in difficult acoustic environments	Normal lower limit for VA systems
I	0,42	Simple messages, familiar context	VA and PA systems in very difficult spaces	
J	0,38		Not suitable for PA systems	
U	<0,36		Not suitable for PA systems	

Figure 9: Excerpt from IEC 60268-16 Appendix

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