Proceedings of the Institute of Acoustics

THE DESIGN AND COMMISSIONING OF INTEGRATED PRODUCTION AUDIO / VOICE ALARM SYSTEMS AT THE MILLENNIUM DOME.

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1. INTRODUCTION

This paper presents an overview of the design work completed by Symonds Group to facilitate the integration and augmentation of production audio and dedicated voice alarm systems to achieve the specified system/s intelligibility performance for the site life safety systems through the latter part of 1999 through to the project completion.

The paper discusses the design constraints associated with the project and describes the design process and commissioning methodology used to predict and verify the intelligibility of the system and system elements within different areas on the site.

The paper compares and contrasts the practicality, efficacy and accuracy of the predictive techniques employed, with reference to objective and subjective assessments completed prior to and during commissioning.

2. SYSTEMS CONCEPT AND DESCRIPTION

2.1 General

The Millennium Dome has been the subject of much publicity over the past few years. What is perhaps not widely appreciated even within the audio industry is the scale and complexity of the audio systems and the fact that the vast majority of the audio systems are networked to provide a site-wide integrated voice evacuation system. Both production audio systems and dedicated voice evacuation systems provide intelligible coverage of the site in accordance with the Standards [1,2,3]. The magnitude of the installation is worthy of note and includes:

- Over 50 miles of fibre optic cable
- Over 40 miles of fire rated loudspeaker cable
- Over 30 miles of CAT-5 cable
- Over 1000 power amplifiers
- Over 5000 loudspeakers

The Dome has been a very high profile project from its inception and has always been considered a likely target for terrorist groups. The provision of these systems to assist the Operational staff safeguard the public was considered essential. The Dome has had to call upon these systems on at least one occasion to facilitate a phased and orderly evacuation of the main structure and areas contained therein.

2.2 Network and Site Topography

The voice alarm system on the site consists of three basic types of audio systems:

- Building Systems
- Integrated Production Audio Systems
- Dedicated Systems

In addition to these three types of systems, there are also hybrid systems, containing areas covered respectively by both production audio systems and building systems.

2.3 Building Systems

The building systems are conventional industry standard systems, installed by a sub-contractor to the site fire alarm and detection contractor. These systems provide local coverage of staff areas, catering areas, the six 'Core Buildings' within the Dome and four of the fourteen exhibits.

Included within the shell and core installation was the provision of a network providing distribution of audio and also control information. This network provides distribution of priority audio messages, either from emergency microphones or from message stores located in distributed 'nodes' and returns 'common fault' information, indicating the presence of an audio equipment fault within any individual Management Area.

The site is divided into individual Management Areas, in accordance with the strategy of phased evacuation. (See Figures 1 and 2). To provide operational flexibility, the building systems are linked together to enable messages or announcements to be routed to individual areas e.g. exhibits and individual / multiple management areas. Zone or area selection is carried out via a 'mimic panel' (See Figure 1) which approximates a topographical layout of the site

The primary control position and emergency microphone is located at 'Bronze Control', which is where the Operations staff are based. Additional emergency microphones and message stores are located at distributed nodes within each Management Area, which are located adjacent to Fire Panels.

2.4 Integrated Systems

Wherever production audio systems were proposed on the site, the design strategy was to use these systems to provide voice alarm coverage. This required that the systems were designed to achieve compliance with the Standards, including augmenting or extending the coverage if required. Although beyond the scope of this paper, the augmentation of the production audio systems required:

- Monitoring of system integrity
- Interleaving of loudspeaker circuits
- Provision of secondary power supply
- Appropriate fire-resistant cable specification
- Priority audio override and muting of production audio / AV / games etc.
- Intelligible coverage [1].

The integrated approach was adopted in the Central Arena, Skyscape and ten of the fourteen Exhibits, avoiding the duplication and cost of having two separate sound systems within any given area. In the Central Arena, this cost saving was estimated to be in the region of £1 million.

2.5 Dedicated Systems

For various reasons, in some areas it was decided not to integrate production audio systems with voice alarm function and dedicated systems were designed. This approach was adopted in Skyscape and five of the Exhibits. Skyscape and the one of the Exhibits were production audio based dedicated systems, four of the Exhibits were Building Systems as described above.

3. DESIGN FOR INTELLIGIBILITY

3.1 General

The design parameters which must be considered when designing an intelligible sound system within a given space have been widely documented.

The following points are presented as an overview of areas of design focus, which were integral parts of the electroacoustic design process:

- Reverberation Time and Direct to Reverberant Ratio

Predictions of reverberation time were carried out for individual areas. This information was provided to the rest of the design team for each area. The electroacoustic design was (and typically is) a function of negotiations on two fronts, architecture (aesthetics) and cost. Hence when asked to consider a design using aesthetically approved loudspeakers lacking directivity in a reverberant space, then absorbent finishes and treatments were suggested to reduce the reverberation time (and hence to improve the intelligibility of the voice evacuation system). This dialogue was generally effective. In some instances, designers wished to maximise the impact of production audio or the ambience within an area and areas were thoroughly treated with absorbent material. Electroacoustic design in these areas was greatly simplified with exceptionally intelligible results. Alternatively, architectural design in some areas required the use of hard finishes. In these instances designs were progressed using more directive loudspeakers and loudspeakers with controlled dispersion at lower speech frequencies (500Hz octave band and above). Some areas have very low ceiling heights and in these areas for example, designs were progressed using loudspeakers with wider dispersion characteristics to minimise quantities.

The client has a beneficial arrangement with a large manufacturer of audio equipment and a significant amount of the production audio equipment was free-issued to contractors. It was a requirement that if possible, equipment such as loudspeakers were sourced from this manufacturers 'approved' product line. This generally did not preclude intelligible design, However, where an appropriate loudspeaker was not available from this range, the design team had to argue the case for the use of non 'approved' loudspeaker products. (This was generally a function of a loudspeakers exhibiting minimal pattern control being proposed for use in a particularly reverberant or long throw situation). This was generally although not always possible and there are certain areas where intelligibility of coverage is reduced accordingly.

- Signal level (Gain) and Signal to Noise Ratio

The occupancy noise design criteria determined to be appropriate were based on the analysis of several different factors. The strategy for phased evacuation of different areas precluded the muting of the central show system in the event that address of an an adjacent management area was required. Based on an analysis of the central show sound system and programme material, a noise level of approximately 75 - 80dB(A) was considered likely throughout the circulatory areas and open exhibits. The accuracy of the original criteria, based on previous measurements conducted in similar environments were vindicated by measured data recorded during Preview events and during the operational year. (See Figure 3). An appropriate design target signal level for speech input was considered to be approximately 90dB(A) with 6dB of electrical headroom.

- Bandwidth and frequency response

All Production audio equipment utilises a 24-bit DSP based system with a 20Hz – 20kHz bandwidth. Distribution and routing of audio is predominantly via fibre-optic cable or CAT-5 via a proprietary protocal. As described elsewhere, the core audio distribution network for priority audio has a bandwidth of approximately 125Hz to 8kHz. Selection of loudspeakers therefore included a consideration of the linearity of the frequency response only within this bandwidth. Provision of separate parametric equalisation for every loudspeaker output was specified within the production audio DSP to facilitate requisite equalisation. (See Appendix A).

3.2 Exhibit Systems

With many of the exhibit structures still being revised and content / fit-out in a constant state of flux almost until completion, consultation with architects and designers in all areas was required to progress integrated electro-acoustic designs. The speech intelligibility of each design proposal was modelled using the Raynoise package prior to installation. This approach enabled computer modelling to be used to confirm designs were likely to meet the required performance and enabled the condensed nature of the design stage of the project to meet construction deadlines.

Typical RASTI predictions output from Raynoise for some of the exhibits are attached. (See Figures 4-8). The predictions offered were found to be fairly consistent with the measured results. Generally, the intelligibility predictions were slightly optimistic. A comparison of predicted versus measured STIs as a function of measurement locations is attached (See Figure 9). Further research is being undertaken to substantiate the differences between predicted results and measurements. It is considered likely that the margins of error are associated firstly within the model, i.e:

1. Accuracy of source definitions - a/symmetry, directivity and sound power level.
2. Accuracy of propagation methods and constraints – number of rays, reflection order, dynamic range.
3. Accuracy of surface absorption and diffusion characteristics.

Secondly within the measurement process, i.e:

1. Errors arising as a function of non-linearity in the measurement process. (Time variant noise).
2. Errors arising as a function of system non-linearities (See Section 5.3).

Some of the original production audio system designs in the exhibits required little or no augmentation in terms of coverage. Indeed, the re-appraisal of the original design proposals focussed around the careful selection and judicious location / orientation of the smallest quantity of production loudspeakers required to provide intelligible voice alarm coverage. The Faith Zone (see Figure 5) was a good example of this, having a highly distributed production audio system.

3.3 Central Arena

The production audio system for the Central Arena was designed by Spencer Hey Associates. The system consists of a central loudspeaker array with centralised and distributed effects loudspeakers. Following consultation with SHA, it was decided to integrate the high level central effects array with the voice alarm system. These devices, mounted on the central 'Circ 0' trusswork consist of twelve Funktion One mid/high horn-loaded loudspeakers, equispaced on a radius of 12m from the centre of the Dome and at a height of 48m. Although far from ideally located, this array comprises the only element of the system that is static and therefore permanently correctly configured . All other loudspeakers are only in their correct configuration during a show and hence cannot provide life safety coverage except during show time.

In order to ascertain whether or not the high level array would provide intelligible voice alarm coverage of the central seating areas and surrounding promenade, anechoic measurements of the loudspeakers sensitivity and directivity parameters were carried out prior to definition in the Raynoise model of the Dome interior. (See Figures 10, 11). Subsequent computer predictions suggested that the design would be effective. (See Figure 12).

Intelligibility measurements carried out during commissioning confirm that the predictions of intelligibility were somewhat optimistic. However, operational constraints precluded effective alignment during commissioning. Further equalisation and alignment was subsequently permitted. This system is frequently used prior to each performance in the Central Arena and the intelligibility performance is subjectively perceived to be fair. A comparison of predicted and measured results is included with the exhibit results in Figure 9. The subjective appraisal of system intelligibility is more in accordance with the measured values than the modelled output.

3.4 Circulatory Areas

The Central Arena is surrounded by the main circulatory concourse and associated radial access roads which interweave the exhibits and six Core buildings. Computer-modelling of a variety of designs utilising different loudspeaker devices at various positions using both EASE and Raynoise were commenced early in 1999. Various proposals were considered but all were ruled out on aesthetic grounds.

In June of 1999 a design was proposed utilising 'Intellivox' loudspeaker arrays. However, it was not possible to define the arrays using any of the (by now well advanced) existing computer models. Symonds liased with the manufacturer of the speakers (Duran Audio) and third party software houses, to enable the sources to be either included within our existing computer models or to transfer the existing model to a different software package (CATT). However, the amount of time required to complete the conversion was considered to be unfeasible due to time and financial constraints.

For the reasons described above, Symonds arranged for a series of subjective and objective assessments to be carried out on site, in order to confirm the design for these areas without the benefit of computer modelling as a design tool. With the co-operation of the manufacturers and also the UK distributors (Autograph), objective measurements and subjective assessments of intelligibility were carried out.

Initially, tests were carried out using the '6c' line-array model. It was originally proposed to deploy a variety of line-array models around the central promenade in each Management Area. The largest '6c' model being used to extend coverage out to the perimeter wall, with the smaller '4c' and '2c' models selected to provide coverage, of relatively near-field areas. The proposal was to orientate all outwards in a radial configuration, enabling time alignment of these speakers with the Circ. 0 high level array. This proposal was however also deemed aesthetically unacceptable.

Further to the positions indicated on Figure 2 being offered up as architecturally acceptable (rather than acoustically preferable), further tests were undertaken using four of the '2c' line-array models in Management Area 5 and two of the Circ 0 loudspeakers covering the adjacent section of the Promenade. The positions are not ideal. Cross firing this type of array over long distances should be avoided. The distance between the front of Core positions is approximately 100metres, with sound arriving at a listener close to either Core from the opposite Core around 290ms later than the first arrivals. The design therefore minimised the strength of these late arrivals by selecting the smallest models possible to provide adequate coverage of each area.

At no measurement position was an STI of less than 0.5 recorded using the methodology described in Section 5.3 with the line arrays only in operation. The subjective assessment of the intelligibility of the assessment was also good and the decision was made to progress the design.

However, with the simultaneous use of the appropriate two elements of the Circ. 0 array, the objective STI intelligibility measurement immediately fell to 0.46 – below the minimum intelligibility requirements of BS 7443.

The adoption of these positions then effectively ruled out time alignment with the Circ. 0 array, precluding intelligible coverage of any of the circulatory areas in the event of an all-calls scenario or the simultaneous address of the Central Arena and any of the surrounding Management Areas. This was subsequently enshrined in the evacuation strategy and the provision of mutually exclusive zone selection buttons on the mimic panel operator interface.

3.5 Review of Building Systems

Building systems design was generally a function of distributed overhead loudspeaker layouts using 'preferred' loudspeakers. Symonds role was to advise the building systems designers of appropriate criteria and design requirements and to amend or approve designs as required. With minimal technical data previously available, the technical parameters of the loudspeakers were measured in an anechoic facility. Such a restrictive design approach based on unsuitable products being considered 'approved', undoubtedly increased the quantity of loudspeakers required to achieve intelligible coverage in these areas. Some of the loudspeakers were considered appropriate for design in certain areas. The benefits and suitability of DML loudspeakers has been widely documented now [8] and this type of product was used in several of the exhibits with the resultant audio quality of the integrated systems being both clear and intelligible. In some areas, various building systems contractors were nominated to install production based audio elements and were therefore free to utilise more effective loudspeakers.

4. PRE-COMMISSIONING

Further to guidance provided throughout the duration of the project, a 50 point pre-commissioning checklist was provided to all systems contractors to assist them with their works prior to commissioning. (See Appendix A).

5. COMMISSIONING

5.1 General

In mid-December 1999, Symonds was faced with the arduous task of aligning and commissioning all voice alarm systems by December 30th. Some of the exhibits were still in the construction phase. Many of the audio installations were still incomplete. The 'Jupiter' network linking the primary control position 'Bronze Control' with the rest of the site was still not functional. Many of the required interfaces between the production audio systems and the network were also still not functional. This posed problems in terms of being able to consistently and objectively quantify the intelligibility of all systems as specified, prior to December 31st 1999.

5.2 Specification

The Buro Happold Specifications required system speech intelligibility to be in accordance with BS7443:1991 'Specification for Sound Systems for Emergency Purposes'. This Standard specifies that objective measurements of intelligibility be carried out using the RASTI method as detailed and in accordance with the guidance detailed in IEC 60268-16:1998.

IEC60268 recommends however that the RASTI method is not used where various conditions (notably the two conditions detailed below) cannot be met:

'Overall system frequency response between the octave bands centred on 125Hz and 8kHz is uniform, i.e. the difference in sound pressure level between any two adjacent octave bands should not exceed 5dB.'

This condition is never likely to be achieved with any of these systems. All the emergency microphones (Shure 521B) have an approximate bandwidth of only 200 Hz to 4kHz. The limiting factor is that the frequency response of this microphone in the 125Hz and 8kHz octave bands is 10–20dB down relative to adjacent usable octave bands. (See Figure 13).

'Reverberation time is not strongly frequency dependent. Over the range of centre frequencies 125Hz to 8kHz...'

IEC60268 recommends that the use of the STI method may be considered when the first condition cannot be met and recommends that the STI method should be used when the second condition cannot be met. For these reasons the STI method has been used by Symonds whilst carrying out objective measurements of speech intelligibility.

5.3 Method of Assessment

All non-linear amplitude signal processing (compressors, limiters, duckers etc) were removed from the signal chain or bypassed prior to carrying out STI measurements. An MLS analyser was used to generate the maximum length sequence (band limited pseudo random white noise) test signal into the sound system under test, using one of the two methods detailed below. A CEL 593 Type 1 Sound Level Meter was used as a microphone to receive the system output. The analyser then derives an impulse response from the maximum length sequence (MLS) test signal. From this impulse response the STI (Speech Transmission Index,), RASTI (Rapid Speech Transmission Index) and several other acoustic quantities may be derived.

5.3.1 Method of Measurement Using an Acoustic Excitation Signal.

The signal was input to the system via a close talking microphone, further to the guidance given in IEC 60268 and ITU-T Recommendation P.51:1996. Where possible, the test signal input was applied from a B&K 4227 mouth simulator. The artificial mouth was positioned on the axis of the microphone at 25mm distance. The Sound Level Meter was calibrated and then the amplifier adjusted to set the acoustic test signal at the microphone position to be equal to a sound pressure level of 68dB(A).

5.3.2 Method of Measurement Using Direct (Electrical) Injection of the Test Signal.

Where the above method was not possible the test signal was injected electrically as close as possible to the microphone input to quantify as much of the system response as possible. Where the site audio distribution network was not functional, the test signal was input either at the local network 'node' or prior to the local equipment rack.

5.3.3 Simulation of Occupancy Noise.

Further to the guidance contained in the Standards [3], previous research [4] and the requirement to make a large number of measurements in a very short space of time. It was decided to make measurements in the presence of simulated occupancy noise levels. Whilst increasing the amount of time required to make the measurements, (due to the time taken to ensure octave band noise levels at the receiver were correct) post-processing time was reduced.

A series of 'Dome Preview' events were staged prior to completion. This enabled octave band occupancy noise levels to be measured for most zones / areas. Appropriately shaped pink noise with the same spectral distribution and level as the expected noise from occupancy was then mixed with the MLS signal within the system DSP to give an approximation of the anticipated expected octave band signal to noise ratio at each measurement position within each area. Received levels and spectral content were checked at the measurement microphone prior to each measurement. Equalisation was adjusted at each measurement position.

5.3.4 Repetition of Measurements.

Repeated measurements using this method do not result in identical results. Although the test signal is pseudo random, the shaped pink noise used to simulate occupancy fluctuates slightly in level and cannot be considered constant. It is also important to quantify the uniformity of coverage in any area / zone. For these reasons, the procedure described above was repeated several times, at each location and at several locations in each area. The mean was recorded with the standard deviation also derived and included with the results. A summary is attached (See Figure 14).

5.3.5 Validation

The STI method of measuring system intelligibility is by no means infallible [5, 6,]. As described in 5.3, great care was taken prior to and during the measurements to ensure that system non-linear processing was removed. During measurements and subsequent analysis of the modulation reduction matrices, particular attention was paid to the presence of late reflections and potentially optimistic results. (See Figure 15). Given that all measurements were made in the presence of noise, (whether or not such measurements were essentially noiseless), a significant amount of time was required to ensure that at each receiver position, the octave band noise levels were in accordance with the levels measured during the Preview events.

6. SYSTEM ALIGNMENT

All signal processing was completed in the digital domain. The provision of gain, compression and equalisation adjustment was specified for all inputs, with gain, compression, limiting and delay adjustment specified for all loudspeaker outputs. Hence the requisite alignment tools were available to complete the alignment of the systems. As a minimum, the provision of equalisation and compression was specified for all emergency microphone inputs.

All amplifiers were set to deliver full rated output power. Limiters were set to limit the level of the audio input both to prevent the onset of amplifier clipping and to prevent loudspeaker damage.

Prior to measurements of intelligibility being undertaken, the frequency response of the system was equalised to optimise both the octave band signal to noise ratio and the uniformity of coverage. The input signal was high passed at 100Hz. Further adjustments were made to compensate for the response of the emergency microphones. Adjustments to output equalisation were made to optimise the frequency response of the loudspeakers.

Further to previous research [9], after making measurements of intelligibility, compressors in the signal chain were set to provide a substantial amount of amplitude compression. The subjective result of this was dramatic with a significant improvement perceived in the quality and intelligibility of the system response. The STI method of objective assessment is unable to account for this effect and results presented do not account for this improvement in intelligibility performance.

7. CONCLUSIONS

7.1 Audibility versus Intelligibility

Hostility within the various design teams was expressed towards the cost of the systems and quantities of loudspeakers being used to provide coverage of areas on the site. In the authors opinion this is due to a lack of awareness of the fundamental difference between design for audibility and design for intelligibility. In several exhibits, Symonds was asked to review ('sign off') totally inappropriate designs, which were obviously based on an audibility criterion more correctly applied to fire alarm sounders. (BS 5839 Pt 1 1988). The relevant Standards need to be more carefully co-ordinated in this and many other respects.

All areas and zones on the Millennium Dome site have systems that provide intelligible and by default audible coverage.

7.2 Specification and Method of Assessment

It was proposed at one stage in the project by various parties within the design team that as the Standard against which the systems were required to be designed [1] precludes subjective assessments of intelligibility, but that [2] does not, then the specification should be amended to require compliance with the latter. It was erroneously perceived that a subjective assessment would be less exacting than an assessment carried out using the STI method and that this would enable a less costly design.

Symonds recommendation to the client was that IEC 60849 [1] would be a more appropriate specification, not because it is less onerous, but because it allows for subjective assessment of a subjective perception, namely the intelligibility of reproduced speech. The constraints and limitations of objective assessments of intelligibility using the STI method are recognised and the codification and standardisation of a unified, easily implemented and reliable method for the subjective assessment of speech intelligibility would be welcomed.

7.3 Under-specification

Estimations of occupancy noise level, as a function of distributed AV and show systems as well as noise from the public have a big impact on the cost of a voice evacuation system. It has been noted [6] that when unrealistically low noise level criteria are specified, this results in reduced system specification, reduced costs (although not necessarily) and reduced intelligibility. This was not permitted to constrain voice evacuation design at the Millennium Dome.

7.4 Room for Improvement

Finally, it is surely worthy of note that the intelligibility of the integrated voice alarm systems costing several million pounds, was largely dependent on the quality of the emergency microphones. Despite recommendations made to utilise alternative microphone products, they remain as an effective system constraint. These microphones are predominantly hand held push to talk 'fist' microphones, which retail for approximately £50. Whereas handling noise may not be particularly apparent on conventional voice evacuation systems with typically low sensitivity loudspeakers on constant voltage lines, this noise is disturbingly apparent when reproduced over highly sensitive, high-powered constant directivity loudspeakers. The frequency response of the microphone is nominally from 300Hz to 5kHz. This prevents the reproduction of speech frequency information in the higher octave bands. This is more likely to effect the intelligibility of announcements made by female talkers given the more significant contribution of higher frequencies to the typical female speech spectrum. The effective bandwidth of this microphone does not allow the full bandwidth of the audio distribution network to be utilised at the Millennium Dome. This is clearly illustrated in the subjective quality of the digitally recorded messages, which is superior to that of announcements made using the emergency microphones.

8. REFERENCES

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