Achieving Speech Intelligibility

at

Paddington Station,

London, U.K.

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Paddington Station was built as part of the Great Western Railway project in 1852. It is a living testament to the architecture and engineering design of Isambard Kingdom Brunel (1806 – 1859). It has achieved Grade 1 listed status with English Heritage which has offered this magnificent building protection and which puts all modernisation proposals under close scrutiny.

After WWII it had been decided to demolish the structure in favour of a more functional modern station. These plans were shelved and time has shown that with due diligence cherished sites can be integrated sympathetically with the demands of the modern age.

The Brunel train shed comprises three spans and two transepts. Brunel's train shed at Paddington Station is an impressive structure from both an engineering and architectural viewpoint. It is a steel structure with a vaulted glass roof comprising three spans. At the concourse end there is a full height glass screen with a decorative steel tracery. The other end is open at the bottom until the over-bridge takes over; above which there is again glass. Spans 1 to 3 houses a large concourse some 75m by 55m and eight long platforms, 160m of which are enclosed within the shed. Within the concourse area are a number of kiosks that act to visually separate the concourse from the platform areas. During its time the basic structure has remained although it has been re-roofed and the train tracks have been reconfigured. Originally there were only five passenger platforms and the Customer Information required was only the time of the train departure which was orally conveyed. As the demand grew, the station followed suit. A fourth span was added and a lawn area for passenger congregation. As the volume of traffic increased so did the complexity of the train management and the need for more detailed customer information was born.

The three span shed has the effect of creating imposing arches and is a feat of Victorian engineering. It was extremely avant-garde in its day and reflects the architecture of its ground breaking predecessor, the Crystal Palace was built for the Great Exhibition of 1851. This enormous greenhouse like structure was constructed from iron girders and tonnes of glass and it is noted that during it's design phase one of the engineering concerns was resonance. However the Victorian concern was for vibration resonance caused by moving people which would cause the structure to vibrate to destruction. There is no record of the acoustic performance of the Crystal Palace but if we wish to have some sense of it, Paddington Station is a similar environment. From the overbridge at the far end of the train shed an appreciation of the size of the structure is gained more easily than when walking around at ground floor level.

The structure itself is 213m long, with irregular span widths of 20.7m, 31.2m and 20.7m. The maximum height of the cast iron roof structure is 10.5m.

Acoustics of the Brunel Shed

Given the cast iron and glass structure and the sheer dimensions involved we would all expect to have a reverberation dominated environment. Due to the inherent constraints of the fire regulations and the practicalities of its' function, there are no soft or fibrous materials. The harshness of the environment on any structure is not to be underestimated since diesel fumes released in the shed, coat every surface.

In order to measure the reverberation time it is necessary to fully excite the space. Some large building may never have enough sound power released into them during the course of their normal functions. Paddington Station is an exception. Again with the idling and revving of diesel trains the reverberant field of the Brunel Shed is excited constantly throughout the working day.

To excite the shed fully during engineering hours required the use of a large source which would be easily controllable. The following measurements were made using the existing high density distributed system. Octave band noise bursts were injected into the system for 5 seconds and stopped. The tones and the decay were recorded onto the DAT medium and analysed using the traditional paper tracing method. Many positions were measured and the following average reverberation time determined.

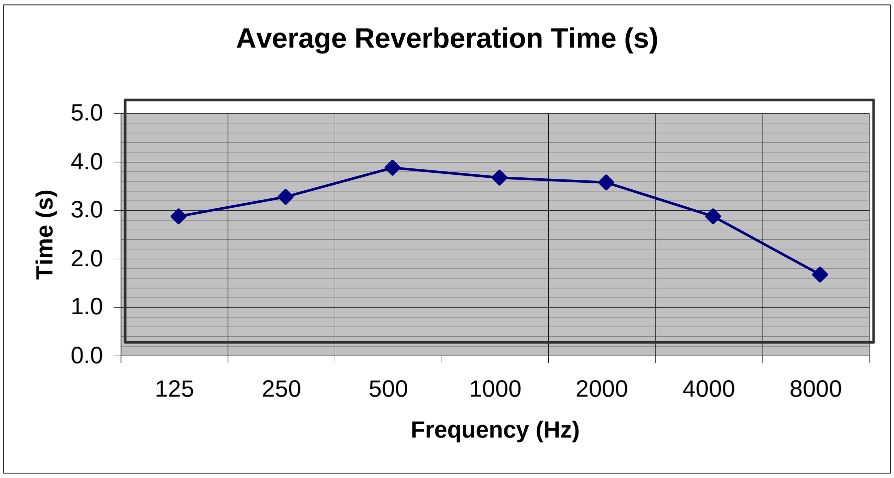

Fig 1

There was little difference in the reverberation times measured which shows that the reverberant field is dominant and that the space itself is truly diffuse. We had expected to encounter strong reflections from the solid wall along platform 1 and the glass wall of the lawn.

A Brief History of PA at Paddington Station.

Documentation has been scarcely available for the current 6 year old system at Paddington and so previous PA system information is not available. However, from photographs it appears that the first PA system was installed in the early 1930's. These loudspeakers were of a re-entrant horn type. From 1960-1980 the PA comprised individual loudspeakers suspended from the iron roof ribs on 10m centres along the length of each platform. The suspension length is not discernable.

In the mid 1980's a directional arrangement of column loudspeakers was installed around the large train information flapper board. This provided intelligible information to the congregated waiting public. The system was in operation until 1996, and is still hailed as the best to date. It was removed due to the introduction of the Voice Alarm requirements of BS7443 and BS5839 PART8 which declared that any public area would have a Voice Alarm System which would achieve a minimum of 0.5 RASTI always and everywhere. The column arrangement did not cover the entire area and so was replaced by a distributed system.

The current system comprises a typical analogue head end system that interfaces with the fire alarm panel. The concourse is covered by 30 horn loaded cabinet loudspeakers mounted along the beams at the top of the supporting columns 6m from finished floor level. The platforms are covered by 5 driver column loudspeaker mounted in the top of the roof span at 10m to 15m from finished floor level. These loudspeakers are not visible with the naked eye and are clearly too far from the passenger ears.

Design Criteria

Upon the presentation of the measurement survey which also detailed other equipment dilapidations, Railtrack decided to seek a solution. From a technical perspective the primary limiting factors were and remain the acoustics and the inherent noise within the space.

It is widely accepted that in order to achieve intelligible speech, a reverberation time of 1.5s at mid-frequency is the maximum time that will allow success. With a mid frequency RT of 3.5s Paddington Station is way off the mark. The issue of bringing the acoustics under control was discussed and quickly dismissed on the grounds of the fire regulations and aesthetics. Given the esteemed Grade 1 listed status. The aesthetics of the Brunel shed cannot be materially altered. The available acoustic absorption would compromise the visual aesthetic given the vast amount required since the obvious treatment area would be the expansive vaulted glass roof. Further, the treatment available would not only obscure the ceiling and reduce the natural light levels but would degrade quickly in the corrosive fumes spewing from the HST diesel engines. Any PA/VA design is limited by the reverberation time which is also the primary function of the direct to reverberant ratio, which is extremely negative at Paddington. In order to improve the direct to reverberant ratio any loudspeakers chosen would need to have carefully chosen characteristics in terms of directivity.

The inherent noise levels at Paddington Station are high, with the diesel engines idling at 85dBA. It is understood that ideally a signal to noise ratio of 15dB and above is conducive to good speech intelligibility. In this instance, this would put the operation level of the PA/VA system at between 100 & 105 dBA. This level is not allowed due to Health & Safety Executives Noise at Work regulations that protect the hearing of employees. If the PA were to operate at these levels all staff members, in the vicinity of the concourse for most of their working day, would be required to wear hearing protection which would affect their duties. The operational system sound pressure level was compromised to be 90dBA which only gives a 5dB signal to noise ratio in the presence of an idling train.

From an operational perspective the new system should be a high quality audio customer information tool and a fully compliant Voice Alarm System.

The subjective perception of Public Address & Voice Alarm Systems by the public is that they are poor quality. This is mainly due to the increased expectations that they have. Sound reproduction has progressed significantly since the days of the first Paddington PA system. Today the public are used to having high fidelity audio in the controlled acoustics of their homes and expect to have the same quality, clarity and intelligibility anywhere they go.

A fully compliant Voice Alarm System is outlined in the British Standard BS5839 which is a fire alarm code of practice. Given the heritage of the standard its primary concern is safety ie: reliability, availability and integrity. All component parts must be able to resist heat, which means that loudspeaker construction is limited to metal enclosures, with ceramic blocks and thermal fuses. Generally this means using industrial loudspeakers which have reduced bandwidth or uneven frequency response in order to maximise their sensitivity. This conflicts with the design criteria of a high quality audio signal.

A Voice Alarm System has to interface with the Fire Alarm Panel and broadcast recorded emergency messages when triggered. It also has to have a fireman's microphone so that the fire brigade can take control during an evacuation and broadcast live directions. It must also function in the event of mains power failure which is set out as 24 hours in a standby state followed by 30 minutes of continuous usage.

It has to be fully monitored through a series of internal watchdog circuits and line checks. Any faults detected are to be reported to the Fire Alarm Panel so that the station's operational staff are aware of the situation and can take a decision as to the implications. Traditionally Voice Alarms Systems are 100V line systems, with all central equipment and powering components housed in lockable racks.

From an installation perspective any equipment to be mounted within the Brunel train shed has to receive English Heritage Approval and Local Authority planning consent. Any proposal would have to be accepted by the Railtrack Architects who would then make the necessary representations to English Heritage and the Local Authority.

The Electro-Acoustic Options

Initially three electro-acoustic options were considered:

1. Re-using the current loudspeakers.
2. Using small column loudspeakers.
3. Introducing intelligent line array loudspeakers.

Each option was designed using acoustic modelling programs and room acoustic mathematics.

The current loudspeakers are mounted in the roof space and need to be brought closer to the travelling public in order to improve the direct-to reverberant ratio. This is easily achieved in an acoustic model but the reality of the installation meant that the loudspeakers were all moved to replicate a dense overhead system. This could only be realised by having the loudspeakers and associated cables suspended on chains or drop rods from the roof. The optimum height was 4m from the finished floor level which rendered the scheme aesthetically unacceptable since the loudspeakers were visually obtrusive.

The investigation into using small multi-driver column loudspeakers presented an acceptable solution from a performance perspective. The loudspeakers would need to be mounted on either floor standing poles or ceiling mounted drop rods. The ceiling mounted drop rod solution was again aesthetically unaccepted. The floor standing poles were operationally impractical since they would impede passenger flow.

The intelligent line array solution produced the best performance predictions since their characteristics effectively increase the direct to reverberant ratio, since they propagate as a line source, and have vertical control over long distances. The Intellivox 6C chassis is 5m long and contains internal dsp control, 32 cone drivers and 16 amplifiers. The design for the entire Brunel shed comprised 8 loudspeakers. Given that we were able to cover a large area with a few loudspeakers and produce compliant ST1 values the Railtrack architects decided to entertain the proposal and work with us on defining precise locations.

The Electro Acoustic design

Having determined the criteria for the system and the most eligible solution the acceptable mounting positions were determined.

The concourse has a listed metal structure called the tracery which has a central upstrut in each span. This is the obvious location for a steerable line array column. The Railtrack architects were willing to entertain this idea since the loudspeakers width matched that of the tracery strut and would therefore be essentially invisible. The tracery starts at a height of 5m from finished floor level which determined the lowest mounting point of the loudspeaker.

The acoustic centre of the line array is the position of the lowest driver and all of the intelligent aiming originates from this point. This position should be approximately 3.2m from the finished floor level on the concourse. The construction of this array is as follows:

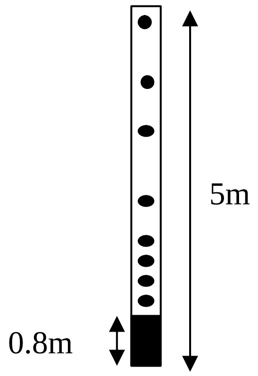

Fig 2

If the loudspeaker was to go into its ideal position it would hang below the tracery which was not acceptable and the following compromise was achieved:

<u>Span 2 Tracery with Line Array Loudspeaker</u>

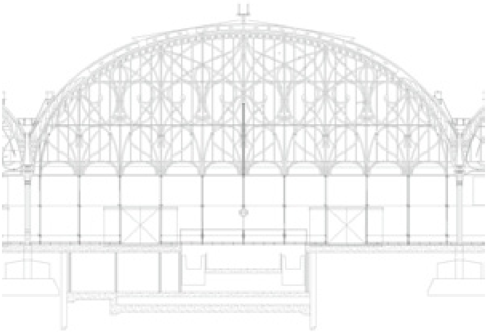

Fig .3

By reconstructing the loudspeaker and accepting the limitations on the acoustic centre we were able to satisfy the architects. Essentially, the amplifier pack was built on the top of the column. For maintenance it is impractical to have the amplifiers at llm from finished floor level and so a second connection panel was built in to the bottom of the unit.

The compromise on the acoustic centre of the loudspeaker gave rise to reduced coverage in the shaded area shown below:

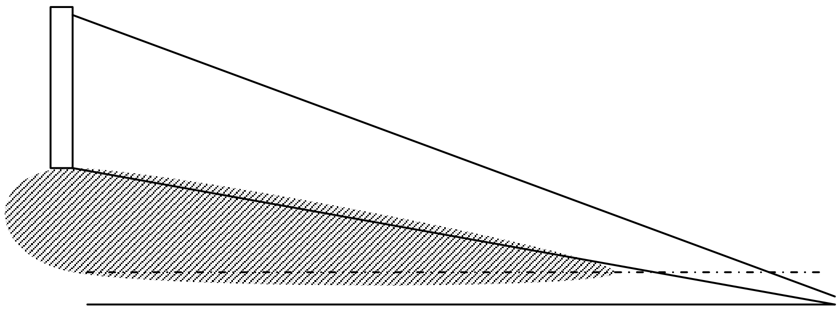

Fig. 4

The manufacturers were able to accelerate their production of their DDS software which is able to make curiously shaped lobes and we then had a tool to correct the problem of our mounting point:

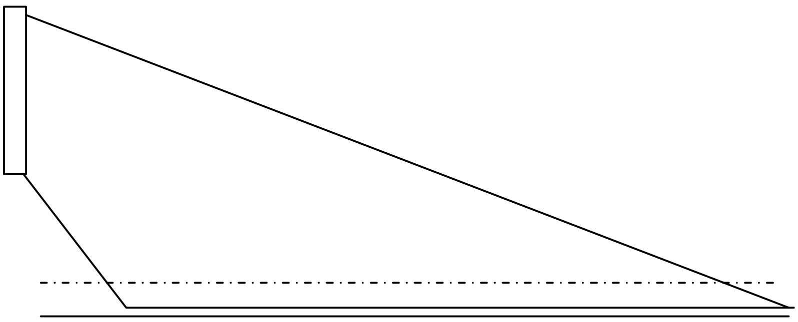

Fig. 5

This essentially creates an underbelly, which fills in the previously uncovered area. This acoustic modelling confirmed that the trade off with the creation of the lobe was sound pressure level. This was now reduced to approx. 85dBA. Clearly this would give rise to reduced intelligibility given the inherent noise level. Again, with the manufacturer, we went back to the drawing board and the four lowest case drivers were replaced with the horn loaded drivers.

At this point we were able to model the required sound pressure level coverage and to predict improved intelligibility. Couple this with the professional audio quality of the loudspeaker, we now had a proposal that could be issued for approval on both a technical and aesthetic acceptability.

Concourse Coverage from the Tracery

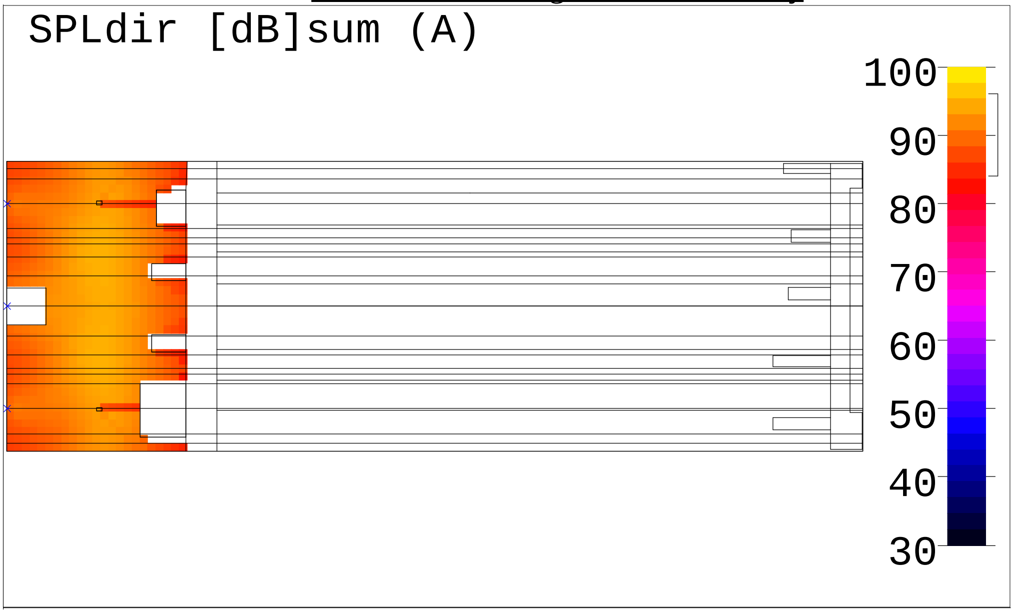

Fig. 6

3D Section through the Span 2 Line Array

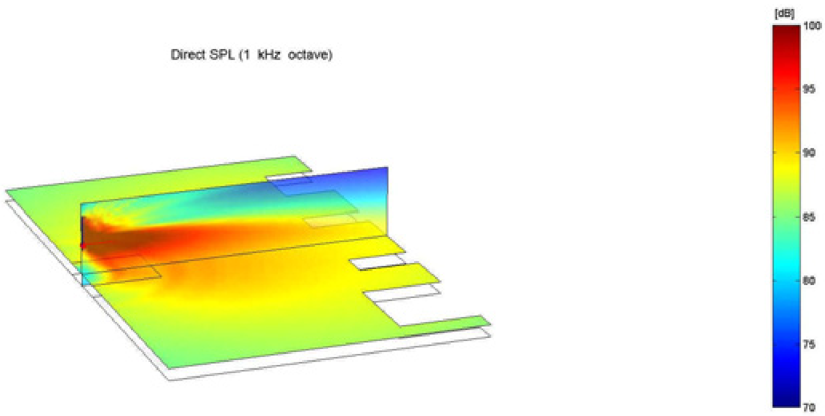

Fig. 7

The predicted intelligibility was now an average STI of: 0.48

We then turned our attention to refitting the design for platforms 1-8 that are 55m from the tracery. Going back to the platform layout we can see a single platform followed by 3 double platforms and a further wide single as shown in fig. 8 below:

Coverage of Platforms 1-8 inside Brunel shed

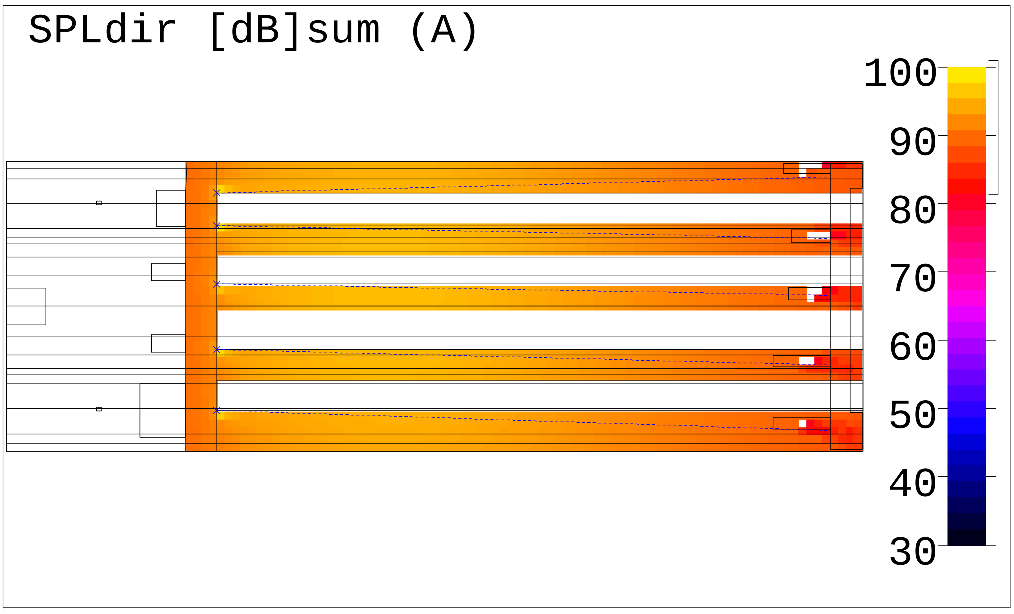

Fig. 8

Our original proposal was to suspend the loudspeakers from the roof, with the acoustic centre at 3.5m from finished floor level. This height is the minimum clearance height at the station as cherry picker access is required along the lengths of the platforms for high-level maintenance. The location of the loudspeakers was to be in the centre of each platform. The average distance was to be 90m steered down vertically ie: away from the overbridge and country end glass tracery. The theory then was to aim the acoustic power away from the roof and thus increase the direct to reverberant ratio. There were architectural concerns over the placement of the loudspeaker. It was thought that it would interrupt the line of the building. The Railtrack architects were persuaded to indulge the proposal and a wooden replica of the loudspeaker chassis was hung in position on Platform l. English Heritage were invited to visit the site and make comment. After two visits they had not been able to locate the black box and so a formal visit was arranged. Once the model was pointed out to them, they immediately rejected the proposal and despite the Railtrack architects arguments, that they couldn't find it without their assistance, refused to reconsider their position. The project was advised that an alternative location needed to be found.

At the end of each platform there is a metal structure called a 'goal post' whose main function is to connect the overhead power cables at the Paddington terminus. This structure was the only other possible location and despite its less than ideal lateral position, would be materially changed. We still need the acoustic centre to be 3.2m and so again the loudspeaker was modified, this time the chassis extrusion was lengthened and the amplifier pack dropped to give a total loudspeaker length of over 6m. The goal posts were to become rugby posts.

<u>Photograph of a "Rugby" Post</u>

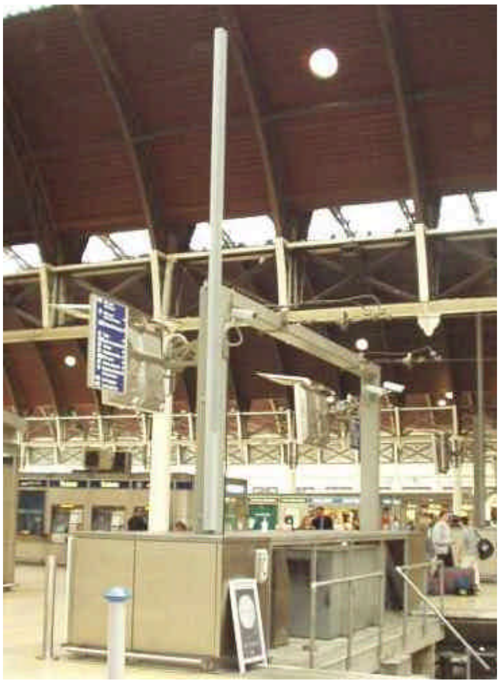

Fig. 9

The acoustic modelling showed the coverage to be even, the sound pressure level acceptable with the horn loaded drivers and the intelligibility achieved the mathematical optimum for the space. The Railtrack architects were happy to take this proposal to English Heritage on the understanding of the extended extrusion and a colour to match the goal posts.

The predictions of STI were carried out using our own in house STI prediction engine, since we prefer not to use the ray tracing methodology of the propriety packages. Our ST1 prediction engine has been verified over hundreds of projects and the predictions for Paddington Station were as follows:

STI prediction using the AMS Acoustics Prediction Engine

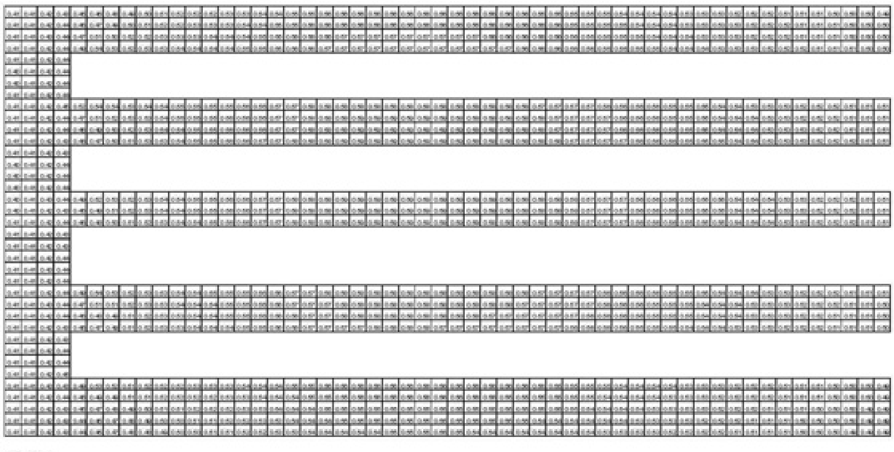

Fig.10

Consideration of time

As previously described the Brunel shed is over 200m long and has a raised overbridge at the country end. Covering this long area with minimal loudspeakers and intergrating it with the existing 100V line system on the overbridge needed some consideration. Given that the line arrays have a delay circuit built into their dsp we only had to introduce a separate delay unit for the overbridge.

The acoustic design relied on encouraging the acoustic energy out into the opening under the overbridge. We also wanted to achieve coherent sound for anyone walking the length of the platform. Given this design philosophy the tracery loudspeakers become T0 and the other loudspeakers were delayed accordingly as follows:

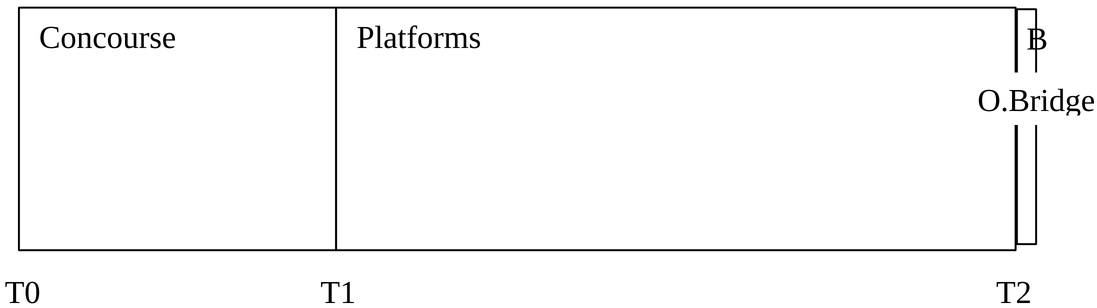

Fig. 11

Considerable investigation was done into two other time effects. Firstly the rear radiated energy from the goal post position and second in the horizontal integration of the platform loudspeakers. Our concerns were that the energy going back towards the concourse would be too strong and negate the desired effect of the tracery being T0. Clearly, we could not entertain acoustic baffles behind the loudspeakers on the goal posts for aesthetic reasons. Although full vertical control of the line array is possible, it is not possible to have any horizontal control and we considered potential comb filtering at the overlap points of wave fronts. The acoustic model determined to our satisfaction that these issues were not a problem.

Given that the loudspeaker data in CATT acoustic is measurement data we were satisfied. Also having used this technology previously, we had measured the front to back ratio to be 8dB, well within the recommended limits and neither heard or measured comb filtering effects in the horizontal plan. Notwithstanding our opinion and modelling evidence, the third party design checker was not satisfied. Consequently the five goal post loudspeakers were set up in the designed locations in a field at the manufacturers facility in Holland. During this day of measuring and listening the third party design checker too was convinced and the design technically sanctioned.

<u>Other design features</u>

We also had other practical issues to consider with this design in the form of practical maintenance and monitoring. The line arrays monitor their components and report any fault conditions back to a computer which reports to the Voice Alarm System main rack, who in turn reports to the Station Fire Alarm Panel. The requirements of a Voice Alarm System demand that any faults must be immediately reported so that the operators can take actions accordingly. This data network monitoring facility was purely a concept prior to this project progressing to installation. Again the manufacturer had to accelerate an in house design programme to realise the fully monitored intelligent line array. The power, data and audio feeds are monitored, as are the cones, horns, dsp's and amplifiers. Any fault triggers a response from the computer, which constantly scans and a detailed log is kept of all faults.

As this is a life safety critical system, we had to consider what would happen in the event of a mains failure. The British standards require 24 hours standby followed by 30 minutes full load to be allowed. We therefore undertook the design of a large UPS system which again has to self monitor and report in the event of a failure.

Throughout the design phases, maintainability was considered a priority since this is a working system, without which the station is unable to open to the public. Should it fail the maintainer needs to know very quickly what parts are required and where the specific fault lies. The system has the facility to dial its maintainer and manufacturer with faults and this can also be dialled into. It goes without saying that the monitoring system itself has internal watchdog features, in case it too fails.

As previously mentioned, the connections to the loudspeakers were made accessible for both the tracery and goal post. The introduction to the station highlighted the corrosive conditions into which this sophisticated equipment is being placed. It was determined that within 6 months the diesel and dust sucked into the loudspeakers would be both physically and visually taking its toll on the grills. For this reason we asked for the loudspeakers to be supplied with grilles in manageable lengths and replacements so that the asset maintenance team can be given 6 months to remove the diesel, dust and brake dust from the grilles.

Any system is only as good as the input signal, commonly accepted as the "garbage in, garbage out" rule. We therefore turned our attention to the speech being input into the system. We determined that the VA messages were in need of re-recording as the speech rate was too fast for the reverberation time, thus increased mashing occurred, and that the stresses within the current sentences were on the wrong words. The messages are now being recorded with the consideration given to the environment. Further the live announcement operators have been given full training on the annunciation requirements of their space.

The outcome

At the time of writing the installation is still underway and the project is in delay due to the practical problems of the site. However, it has been possible to set up the Brunel Shed for subjective listening and all parties are pleased with the improvement. We cannot undertake a full set up and equalisation exercise until the new 100V line PA/VA equipment is installed. At this point the data network PC is fully tested and set up as is the UPS. The loudspeakers have preliminary steering and equalisation on them. From the time of an interim demonstration the station management have been using the system in its unopened state as they prefer it to the original system.

In its unoptionised condition we have measured the following data:

Max. Sound Pressure level	:	92dBA
THD	:	<0.1%
STI Average	:	0.48

The frequency response is currently as shown on the MLSSA plot in figure 12 and clearly can be improved with equalisation:

Average Frequency Response of Tracery line array

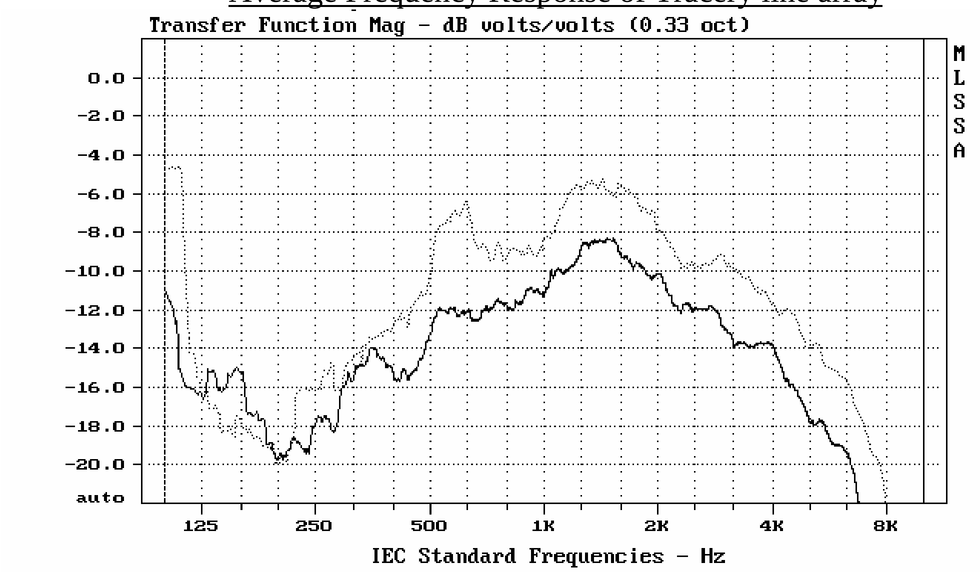

Fig.12

Once the head end equipment is installed with the professional ? rd octave band equalisers for each line array we fully expect to be able to increase the STI average to 0.50 giving Paddington Station a fully compliant, state of the art Voice Alarm System in the Brunel train shed.

This project has been years in design and consultation with interested parties and will hopefully set a new benchmark in the design of VA systems which will raise intelligibility targets, embrace new technology and improve the perception of the Public Address Systems.