RASTI Measurements in St. Paul's Cathedral, London

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Introduction

St. Paul's Cathedral in London is one of the largest buildings in Great Britain. Its internal space, of volume 152000 m^3, is dominated by a dome at the crossing of internal height 66m. The dome is seen in Fig.1, which shows the external elevation as viewed from the South. The Cathedral is also well known for its whispering gallery. The reverberation time in the Cathedral is large, as much as 12s at low frequencies, and not surprisingly the intelligibility of speech is generally poor without the use of a speech reinforcement system.

Fig. Elevation of the Cathedral from the South

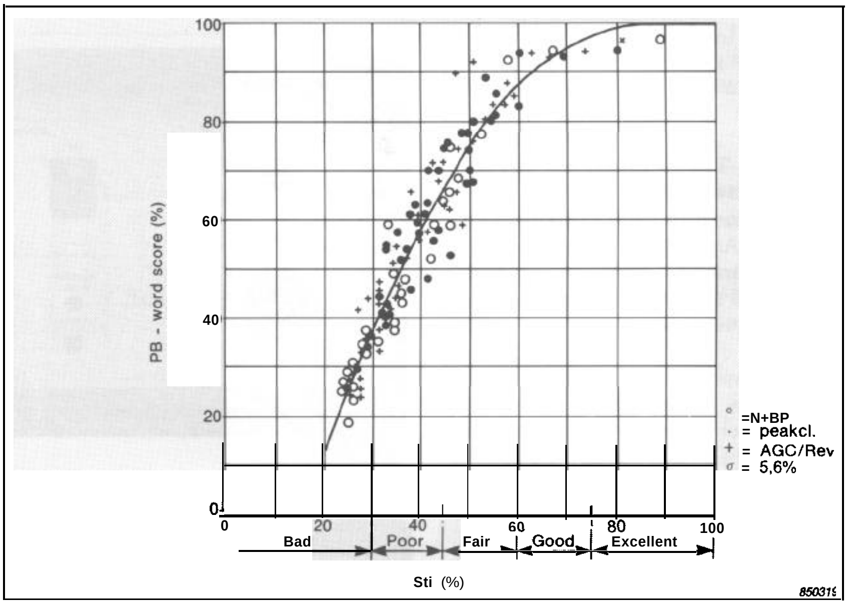


Fig. 2. Relation between the objective STI and PB-word score for 167 different transmission channels. The disturbances were combinations of bandpass limiting, noise, peak clipping, automatic gain control and reverberation. From reference 5

Traditionally the method used to assess speech intelligibility, and carried out previously in the Cathedral (Ref.[1]), is for different speakers to read out a series of phonetically balanced words in which each word is buried in a carrier sentence so that it cannot be recognised from the context. Listeners in different locations write down what they hear the words to be. The method is described in detail by Beranek (Ref.[2]). Normally if a word is misunderstood it is because the consonants are not heard properly. The number of words understood out of the total is a fraction less than unity which, when expressed as a percentage, is almost the same as the phonetically balanced (PB) word score. The PB word score correlates well with an index of speech intelligibility, the speech transmission index (STI) (Ref.[3]), as shown in Fig.2.

The measurement of the PB word score may be described as a subjective method as it depends upon the clarity of the speakers and the personal assessments of the listeners. These tests also require a great deal of time and organisation. An objective method, using a loudspeaker and electronic equipment, has been developed by Houtgast and Steeneken and their colleagues at the Institute for Perception TN0 in the Netherlands (Ref. [3, 4, 5]). However, even this method ~ quires 98 measurements and consequently a rapid speech transmission index (RASTI) has been devised which requires only 9 measurements. Apparatus for the measurement of RASTI is now commercially available from Briiel & Kjær.

The availability of this new instrument presented an opportunity to perform measurements of the rapid speech transmission index and compare them with earlier subjectively obtained results for speech intelligibility in the Cathedral. Furthermore, it is now possible to take quickly a large number of measurements at different positions so that iso-RASTI contours may be constructed. These tests are described in this Application Note.

The RASTI-Method

As already mentioned, the RASTI-method is based on the Speech Transmission Index (STI). The RASTI-method is very quick; it is possible to measure the intelligibility at one listening position in less than 10 seconds.

The RASTI-method is being standardized by the IEC (Ref.[7]). The method relies on the use of a special transmitter and receiver. The transmitter sends out an acoustic test signal ("an artificial voice") which contains information about the frequency range covered by speech, and the fluctuations in the voice. The transmitter is placed at the speaker's position and simulates the real speaker.

The receiver is placed at the listener's position. It measures how the test signal has been modified. The change in the signal (reduction in the modulation) at the listener's position is quantified in terms of the modulation transfer function for nine different modulation frequencies. The reduction of the modulation is interpreted in terms of an apparent signal-to-noise ratio, irrespective of the cause of the reduction, which can be reverberation, echoes or background noise.

The final RASTI-value is based upon these nine modulation indices. The RASTI-value ranges from 0 (= no intelligibility) to 1 (= complete intelligibility).

The RASTI-method can be used in many different applications, among them being:

- evaluation of speech intelligibility in rooms
- evaluation of reinforcement – and PA-systems
- intelligibility in industrial facilities
- assessment of sound masking systems

The B & K RASTI-Instruments

Brüel & Kjær produces RASTI-instruments (system 3361) which fulfil the requirements of the IEC draft standard (Ref.[7]), and which give further useful information. A short description is given below of each of the two instruments which make up the system.

Speech Transmission Meter, Transmitter 4225

The Transmitter 4225 produces the special "RASTI-sound" and sends it out by means of a built-in loudspeaker. In Fig.3 the front and the back of the instrument are shown.

The power On/Off switch (battery powered) is located at the front. The output level is the reference level as given in the IEC-standard (a speech level of $L_{eq,A}$ = 60 dB at 1 m distance). A further + 10 dB compared to the standard level may also be selected. The latter output level can be used to evaluate the influence of background noise in the room.

Three different output possibilities exist: the internal loudspeaker, output to an external loudspeaker or an electrical output. For each of these outputs it is possible to calibrate the output level.

The internal loudspeaker is located at the back along with connectors for External Power and Remote Control, and the battery box. Provision is also made for mounting the microphone during calibration.

The internal loudspeaker mounted in the transmitter has a directivity index similar to that of the voice of a human being, and fulfils the IEC draft standard with regard to directivity.

Fig. 3. Front and rear panels of the Speech Transmission Meter, Transmitter 4225. Note the loudspeaker on the left of the rear panel

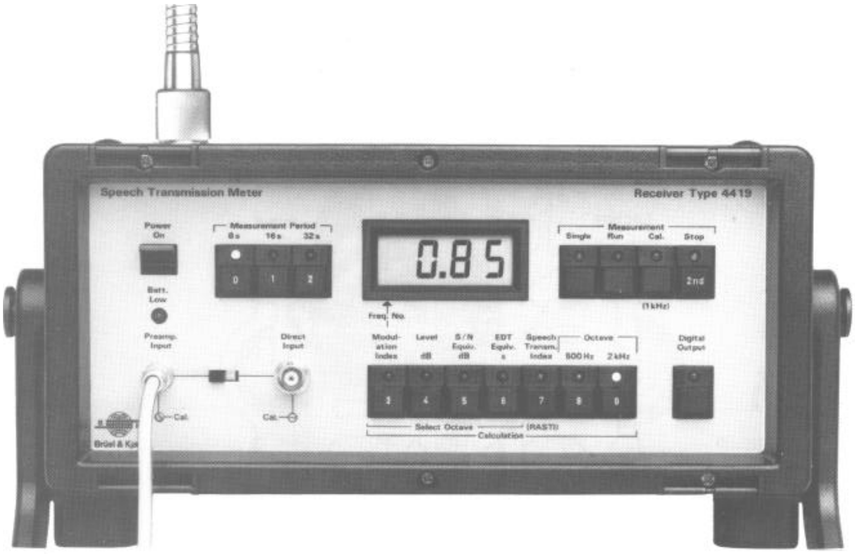


Fig. 4 Front panel *of the Speech Transmission Meter, Receiver 4419*

Speech Transmission Meter, Receiver 44 19

The Speech Transmission Meter, Receiver 4419 receives the test signal at the listener position by means of a prepolarized microphone. In the 4419 the signal passes through an auto-range stage and through an anti-aliasing filter. The rest of the treatment is in digital form. Each of the modulation frequencies is found by means of a Discrete Fourier Transform. After that, the different values are calculated. The instrument is shown in Fig.4.

The 4419 has two inputs, a preamplifier input and a direct input. In the measurement in St. Paul's a 4129 Microphone and 2642 Preamplifier were connected via a 30m extension cable to the preamplifier input.

Before a measurement is started a calibration is performed using a B&K 4230 calibrator. After this calibration the measurement time is chosen (8, 16 or 32 seconds) and the measurement is started by pressing Single or Run. In Run the instrument will start a new measurement again after the previous one is finished. A longer measurement time will produce a more accurate RASTI-value. When the measurement is finished the RASTI-value is displayed. The RASTI-value is based on the 9 modulation reduction indices, and it is possible to read out each of these values. Four of these modulation reduction indices are obtained in the 500 Hz octave band and five in the 2000 Hz octave band. By means of these values it is possible to evaluate whether an intelligibility problem comes from background noise or from reverberation. Also the RASTI-value for both octave bands may be read out. The level in each octave band may be displayed.

RASTI-values less than one can be caused by background noise or by reverberation in the room. It is not possible by means of the RASTI-method to evaluate which of these parameters is more important. But the instrument can calculate a S/N ratio if it is assumed that the reverberation time is zero; and, conversely, if it is assumed that the S/N ratio is ⩾ 15 dB the reverberation time can be calculated. These two values are called S/N Equivalent and EDT Equivalent. Pressing "S/N Equiv. dB", the RASTI-value is translated to the S/N in the room, assuming that the reverberation time is zero in the room. Usually it is possible to evaluate if background noise or reverberation time is the most important parameter, and the instrument can give the value.

In connection with the RASTI-method, the reverberation time considered is Early Decay Time (EDT), because the measurement corresponds to the first 5 dB of the decay curve. Furthermore, it is the reverberation as measured between the speaker and the listener positions, so it can differ from the reverberation of the room as a whole.

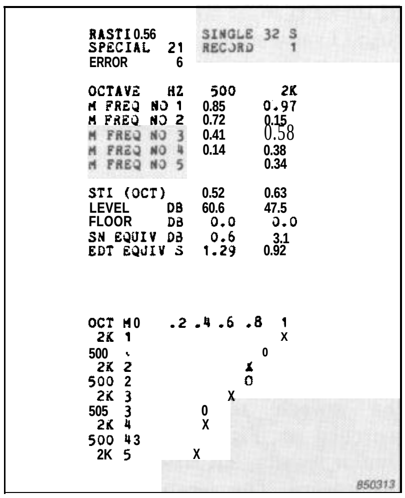
All the above mentioned values can be displayed. By use of the Digital Output all the values may be output through the serial interface (RS 232). This can be done automatically after each measurement or by, pressing Digital Output. There are different output formats, one is shown in Fig.5. It is also possible to control the instrument through the interface.

In the measurement in St. Paul's a portable Epson computer was used to print out the result. The RASTI instrument checks for errors during the measurement and if these occur, error codes are generated.

Measurement Procedure

The Brüel & Kjær Type 4225 was used as the sound source and the Type 4419 was connected to a microphone placed at the receiver positions. At each receiver position at least one measurement of 32 seconds duration was performed.

Source positions: in order to obtain a direct comparison with the earlier tests (Ref.[l]) the sound source (Type 4225) was placed at either the pulpit or the lectern, both of which are indicated in the plan shown in Fig.6. The sound source was placed on its tripod at a position where the head of the clergyman or preacher would normally be. At both the pulpit and the lectern the axis of the source was pointed down the nave, as shown by the dotted lines in Fig.6. The level of the source was + 10 dB compared with the IEC RASTI standard level.



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RASTI 0.56          SINGLE 32 S
SPECIAL   21        RECORD    1
ERROR      6

OCTAVE    HZ    500     2K
M FREQ NO 1     0.85    0.97
M FREQ NO 2     0.72    0.15
M FREQ NO 3     0.41    0.58
M FREQ NO 4     0.14    0.38
M FREQ NO 5             0.34

STI (OCT)       0.52    0.63
LEVEL     DB    60.6    47.5
FLOOR     DB     0.0     0.0
SN EQUIV  DB     0.6     3.1
EDT EQUIV S     1.29    0.92


OCT M0    .2 .4 .6 .8  1
 2K 1                  X
500                 0
 2K 2             X
500 2             O
 2K 3          X
505 3       0
 2K 4       X
500 43
 2K 5     X
                         850313
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Fig. 5. An example of printout from 4419

It is important to note that the pulpit was elevated above the floor of the cathedral, whereas the lectern rested on the floor. Above the pulpit was a canopy, but the lectern was not covered.

Receiver position: in the first series of tests the receiver was placed at the positions marked A to F in Fig.6. These positions had been used in the earlier tests. In the second test series the receiver was moved around to different positions on a pre-arranged grid that covered the floor space of the area below the dome, the nave and transepts. In all cases the receiver height was 1.2 m.

The first series of tests, with receiver positions A to F, was carried out with the source both at the lectern and in the pulpit, and with the speech reinforcement on and off, i.e. four sets of measurements.

In the second series in which measurements at grid points were obtained for the iso-RASTI contours the source was placed in the pulpit only, and measurements were made when the speech reinforcement system was both on and off.

All of these measurements took less than four hours and took place during two evenings (11 and 12 of September, 1984) when the Cathedral was empty apart from the experimenters. The empty Cathedral without any speech reinforcement is referred to as the normal state.

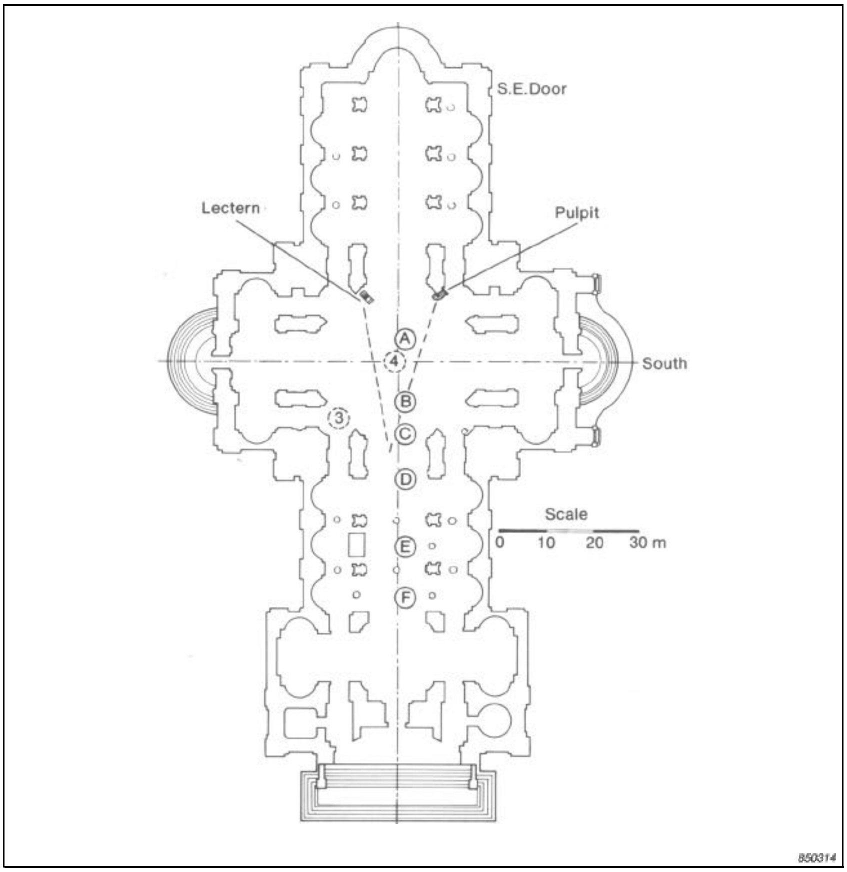

Fig. 6. Plan of the Cathedral showing the measuring postitions

Results

The RASTI values may be converted into PB word scores using Fig.2. A RASTI value above 0,75 indicates that speech intelligibility is excellent. From 0,6 to 0.74 it is good; from 0,45 to 0,59 fair; 0,3 to 0,44 poor; and below 0,3 bad.

Fig.7a shows a comparison of the phonetically balanced (PB) word scores for the source in the pulpit of the Cathedral in its normal state (speech reinforcement system off) for the earlier subjective tests (Ref.[l]) and the present RASTI tests. Fig.7b shows a similar comparison, but with the speech reinforcement system switched on. Figures 8a and 8b show similar results, but with the source on the lectern. The receiver positions A to F are shown in relation to the dome in Figs.7 and 8. The results will be discussed below.

From the second series of tests the iso-RASTI contours of Fig.9 were drawn from the measurements at the grid positions. For these contours the Cathedral was in the normal state and the source was placed in the pulpit. The RASTI value is an average of results in the 500 Hz and 2000 Hz octave bands. It is possible to construct contours based on the results in the 500 Hz and 2000 Hz bands and these are shown in Fig.10.

Discussion

In Fig.7a the comparison between the subjective tests (Ref.[l]) and the RASTI tests is quite good. The PB word score for the subjective test is in general slightly greater. With the earlier tests the two speakers who read out the sentences with the PB words were both clear speakers who projected their voices well. One of the speakers was a clergyman at the Cathedral. The fact that the speakers read with above average clarity might account for the higher score in the subjective tests. In addition it it known that speaking in the Cathedral is difficult, so speakers do try harder. The earlier subjective tests were based on meaningful English words buried out of context in a carrier sentence. The conversion of STI- and RASTI-indices in Fig. 2 is based on nonsense words which are not so easily understood, and this is an additional reason why the subjective method gives greater values. It is interesting to note that in a similar comparative test in the Grundtvigs Kirk in Copenhagen in which the speaker and RASTI source were at the altar, the subjective articulation test also resulted in PB word scores slightly greater than those obtained with the RASTI equipment.

As mentioned previously, the pulpit in St. Paul's is covered by a canopy. This canopy reflects sound radiated upwards from the source or speaker and prevents the first reflection of sound from occurring in the dome.

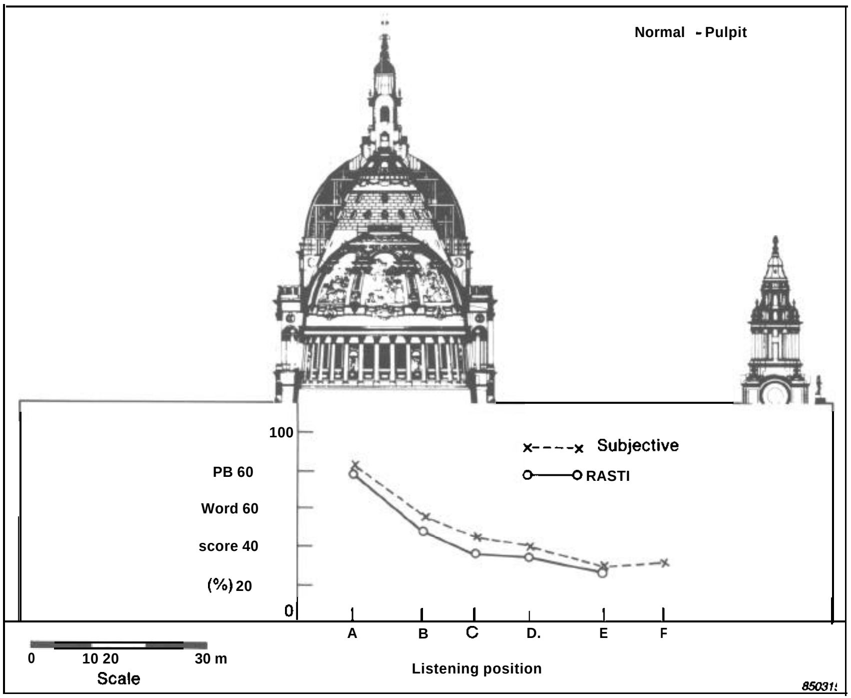

Fig. 7a. Comparison of results for the Transmitter placed at the pulpit, without speech reinforcement

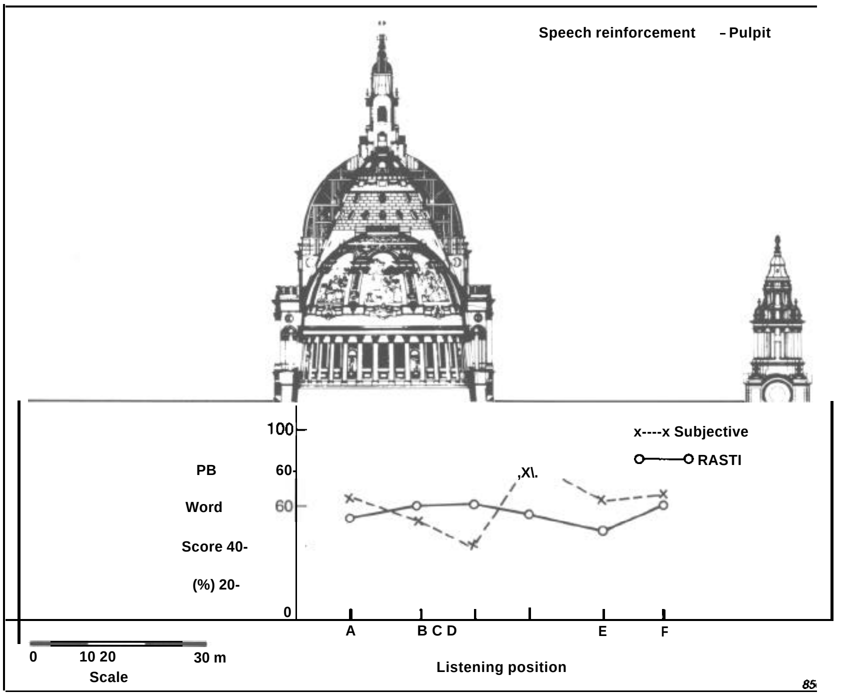

Fig 7b. Comparison of results for the Transmitter placed at the pulpit, with speech reinforcement

With the speaker at the lectern, the situation is quite different, and from this position a great deal of sound is radiated directly into the dome. The lack of a canopy over the lectern may be one reason why there is a poor comparison between the subjective and RASTI results for the source at the lectern, as shown in Fig. 8a. Of course, sound is radiated into the dome for both the human speaker and for the RASTI source, but once again the human speaker may automatically compensate for the known disadvantage by increasing his volume. In St. Paul's he is also able to hear the decay of the reverberant sound, particularly at the lectern, and as a result tends to reduce his speaking rate. Furthermore we have to take into account the standard deviation in the RASTI results and especially in the subjective results.

The comparisons with the speech reinforcement system in Figs.7b and 8b, are not believed to be of much significance because some adjustments to the system had been made in the period between the two tests.

It is proposed that the RASTI method should be restricted to auditoria where the reverberation time is not strongly dependent on frequency (Ref.[6]). In a huge space like St. Paul's Cathedral, air absorption becomes important at high frequencies, and causes the reverberation time to decrease. This decrease in reverberation time with frequency is shown in Fig.11 for the source in the pulpit and the receiver at the positions which are indicated as 3 and 4 on the Cathedral plan in Fig.6. These measurements were obtained in the empty Cathedral using conventional apparatus (a random noise generator Type 1024, third octave filters Type 2112 and level recorder Type 2305) in third octave bands. At the octave frequencies of 500 Hz and 2000 Hz used for the RASTI method the reverberation time was measured to be about 11 s and 7 s, respectively. The full Speech Transmission Index method makes use of octave bands from 125 Hz to 8 kHz, and for the rapid (RASTI) method to be successful the speech intelligibility at 500 Hz and 2 kHz should be representative of the entire octave range of speech. The full STI method might be expected to give rise to a higher PB word score than the RASTI method because the full analysis would take into account results at 4 kHz and 8 kHz where the reverberation time is lower, and hence the speech intelligibility better. On the other hand, the average speech level is lower for the higher frequencies so these frequencies contribute less to the intelligibility.

The most noticeable feature about the iso-RASTI contours is that relatively high values are obtained, with the Cathedral in its normal state and the sound source in the pulpit, in an area within the dome almost diametrically opposite from the pulpit. The improved intelligibility occurs particularly in the octave band at 2000 Hz, as shown in Fig.lOb. This area is just in front of one of the great stone pillars which support the dome. Such a pillar is shown in Fig. 12. Saucer domes form the arches between the piers flanking the transepts.

In the area of better speech intelligibility listeners receive direct sound from the elevated pulpit and also sound reflected behind from the stone pillars. As the transmission paths are not much different in length there is no noticeable echo and both transmission paths contribute to the understanding of speech. The beneficial effect of the reflection is more pronounced at the higher frequency of 2000 Hz because at that frequency the sound radiates like rays and is reflected in a similar manner to light, whereas at the lower frequency of 500 Hz the sound is in part scattered in all directions. Furthermore the reverberation time is longer for 500 Hz than for 2000 Hz.

The saucer domes may also play a part in reflecting the sound into the area of improved speech intelligibility.

Because the reinforcement system had been changed since the earlier subjective tests were made, these results are not described in detail here. But it should be emphasized that the RASTI-method is an excellent method for evaluation and adjustment of reinforcement – and PA systems. By means of this method it is possible to examine the effect of such systems accurately and quickly.

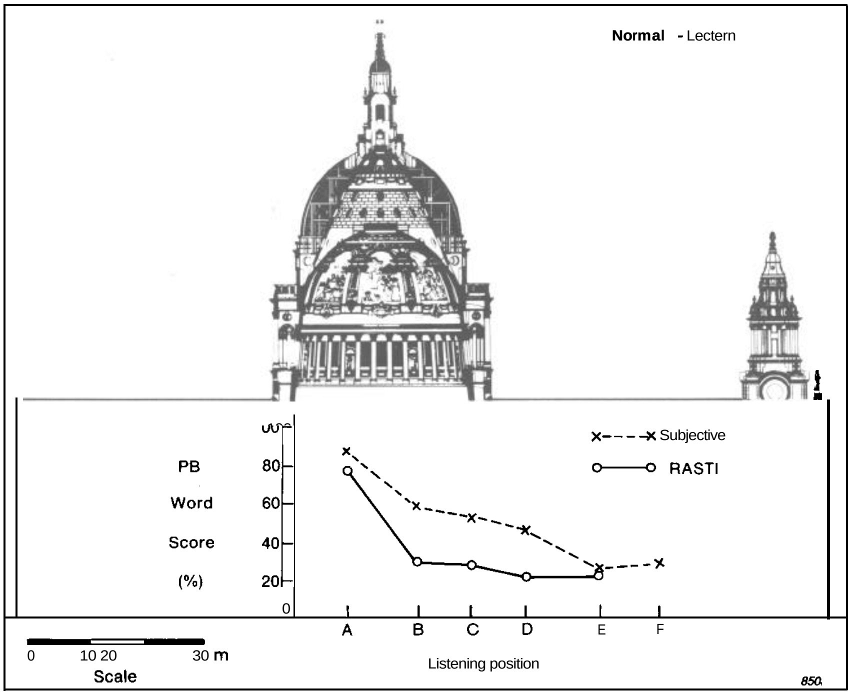

Fig 8a Comparison of results for the Transmitter placed at the lectern, without speech reinforcement

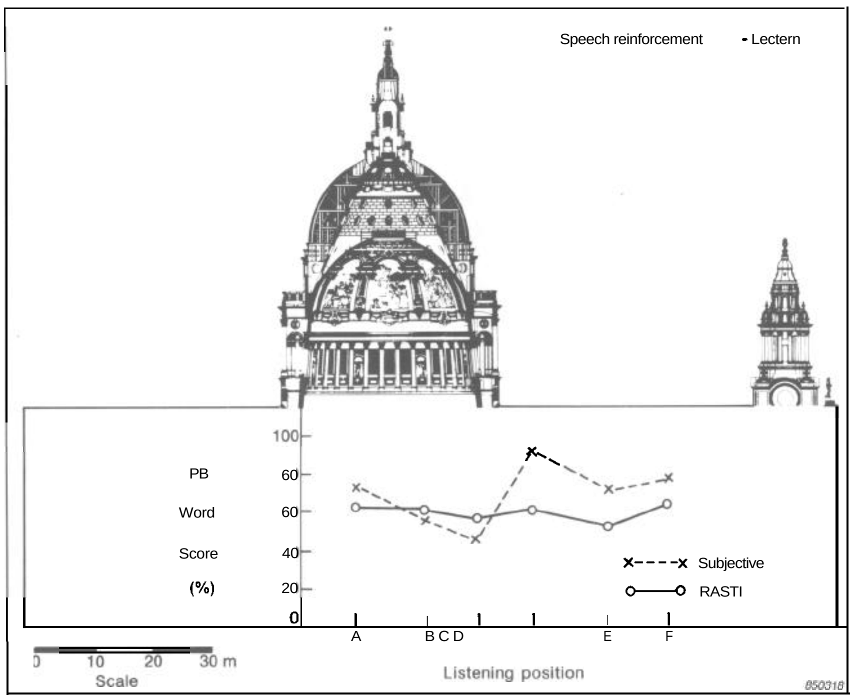

Fig 8b Comparison of results for the Transmitter placed at the lectern, with speech reinforcement

Conclusion

The RASTI method has been applied to a large, reverberant space, St. Paul's Cathedral in London. Results have been compared with previously obtained speech articulation tests using speakers and listeners. With the source in an elevated pulpit below a canopy, the RASTI method gave a phonetically balanced word score slightly lower than that of the subjective tests. With the source at the lectern the RASTI results were in some

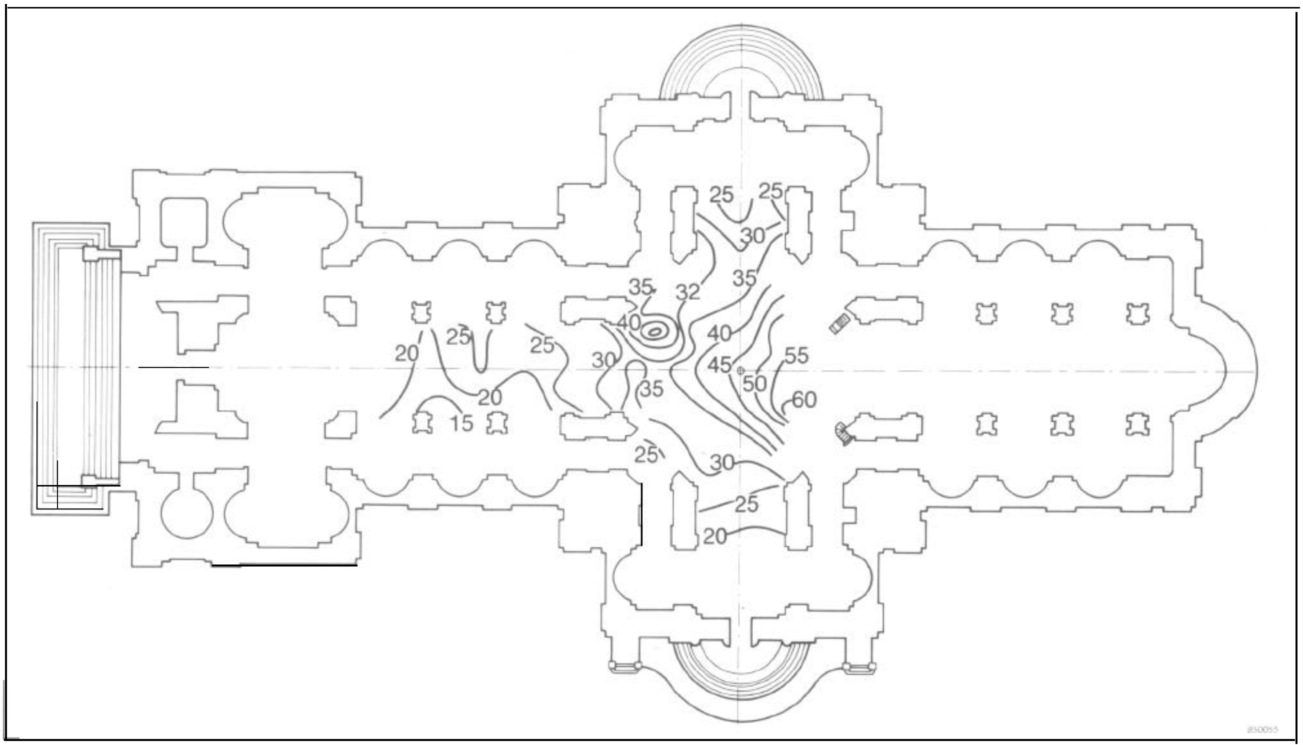

Fig. 9. The iso-RASTI contours for the source in the pulpit without reinforcement (maximum value = 45)

cases considerably lower. The RASTI method is believed to have given different values in this application because:

a) speakers make more effort to project their voice and speak more slowly in a large, reverberant space which is known to have poor acoustics,

b) the subjective method was based on meaningful words, whereas the conversion of the RASTI results to a PB-word score is based on nonsense words,

c) the RASTI method does not take into account octave frequencies at 4 kHz and 8 kHz where the reverberation time is much less and speech intelligibility better.

a) would indicate that the RASTI values are more correct than the subjective, whereas c) indicates that the RASTI method is underestimating speech intelligibility. However, the errors from c) are not likely to be as great as those in the subjective method described in a).

St. Paul's Cathedral is a particularly severe test of the RASTI method and the agreement with the subjective method shown in Fig.7a is encouraging.

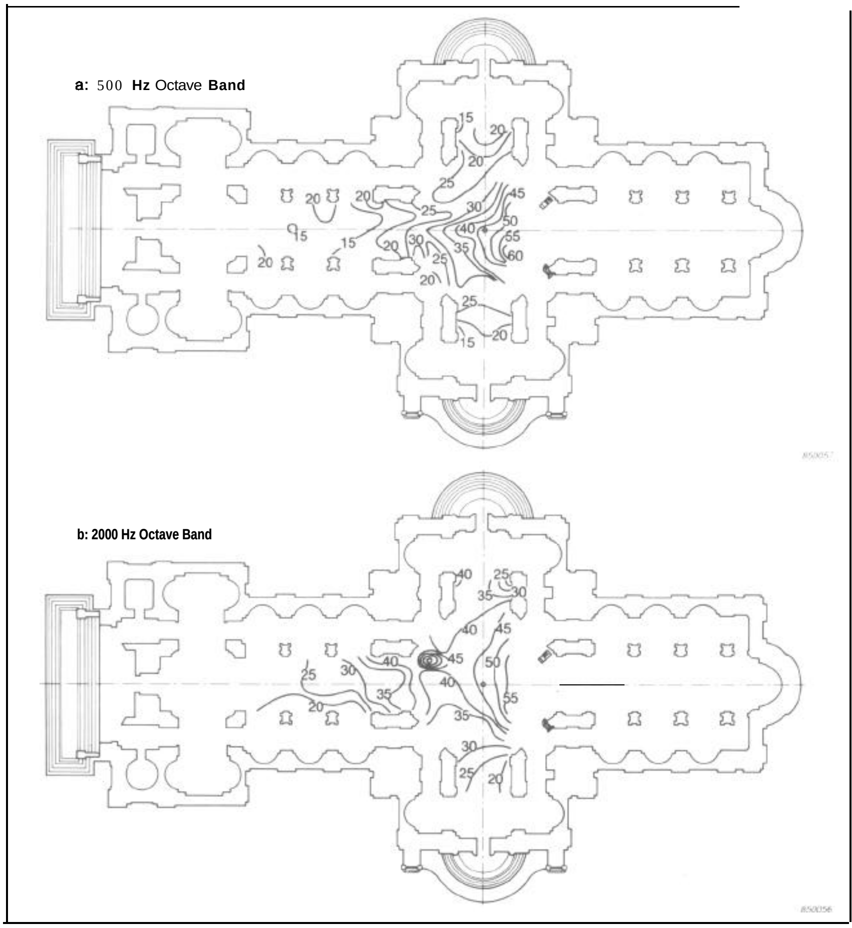

Fig. 10. The iso-RASTI contours for the source in the pulpit for each octave band (maximum value for 2000 Hz octave = 60)

Acknowledgements

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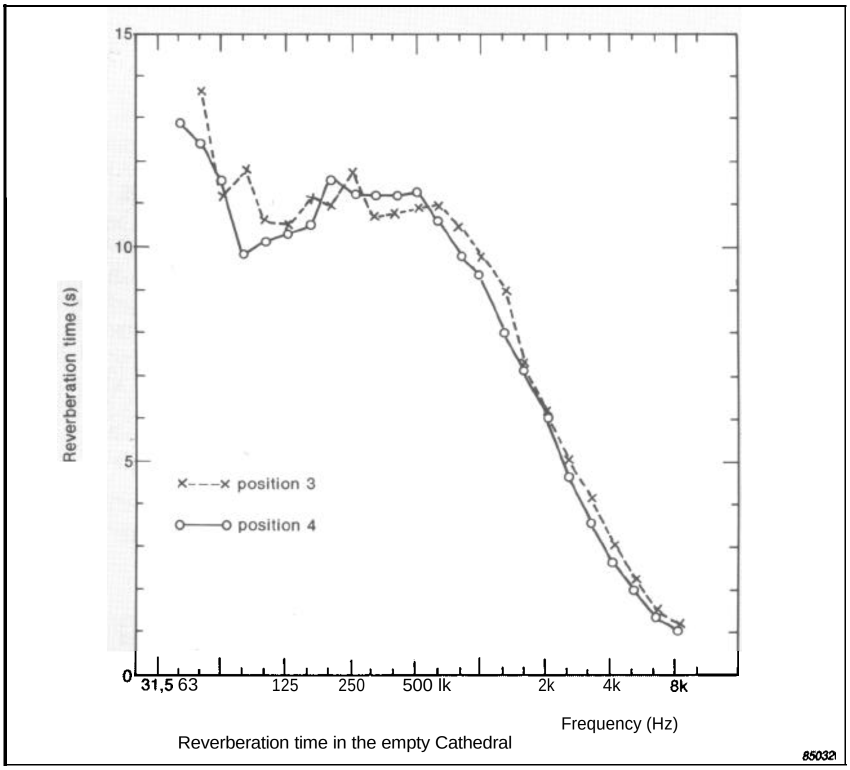

Fig 11. Reverberation time in the empty Cathedral

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Fig. 12. Stone pillars which support the dome

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