Examination of Multichannel Sound-Field Recomposition Utilizing Frequency-Dependent Interaural Cross Correlation (FIACC)*

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The locations of loudspeakers were examined utilizing frequency-dependent interaural cross correlation (FIACC) for optimum sound-field recomposition in multichannel recording and reproduction processes. Experiments were conducted and sets of FIACC measurements compared, with one taken in an original sound field, the other in the reproduced sound field. Several sound-field reproduction methods using different microphone-array geometries and matching loudspeaker-array geometries were considered. The results presented support the ITU recommendation for loudspeaker arrangements in five-channel systems (BS.775-1).

0 INTRODUCTION

The emergence of DVD theater systems accelerates the prevalence of multichannel sound reproduction systems on the market. The origin of multichannel reproduction dates back to an experiment conducted at Bell Laboratories in 1933, when a concert of the Philadelphia Orchestra was transmitted to Washington DC using telephone lines to transmit three channels. In the field of consumer electronics a quadraphonic stereo system was introduced in the 1970s, where much effort was spent on improving the hardware, but the system failed commercially because of inadequate software support.

Despite this failure, studies of multichannel audio associated with high-resolution video reproduction have been conducted continuously. Surround Sound, quite popular today, is considered to be one of the outcomes. However, the best format for multichannel recording and reproduction still remains undetermined. This question has motivated the authors to conduct the study reported in this paper.

1 PREPARATORY EXPERIMENT

Today's multichannel recording and reproduction technology originates in the concept of Olson's 15-channel sound-field transmission system of 1968, as shown in Fig. 1, hereafter called Olson model [1]. Based on this model, the authors tried to find an optimum number of transmission channels and loudspeaker configurations by comparing the interaural cross correlations (IACCs) [2], [3] measured in the original and the reproduced sound fields.

For this purpose a preparatory experiment was conducted using a lecture room. Subsequently a series of field tests applying the same process were carried out in three concert halls. In the preparatory experiment a tiered lecture room was adapted for the original sound field, with an omnidirectional loudspeaker was placed at the center of a lecture desk as the sound source, and a dummy head, substituting for the listener's head, placed at the approximate center of the room. Furthermore 12 omnidirectional

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microphones were placed in an imaginary horizontal circle of 1-m radius, called microphone circle, the center of which coincided with that of the dummy head.

The angle of the azimuth difference of adjacent microphones was set to 30°, and one of the microphones was placed directly in front of the dummy head, as shown in Fig. 2. The setup of the recording site (original site) is shown in Fig. 3. As shown in Fig. 4, the sound reproduction was arranged in an anechoic chamber with the loudspeaker placement around the dummy head arranged identically to that on the recording site. We will call the imaginary circle for locating the loudspeakers the "speaker circle." Fig. 5 gives a view of the experiment, and Fig. 6 shows the dummy head actually used.

On the original site a 30-second pink-noise burst was radiated from the omnidirectional loudspeaker. The binaural sound data obtained with a pair of dummy-head-mounted microphones and the 12 omnidirectional microphones were recorded using a hard disk recorder. Then the sound data recorded by the 12 microphones were reproduced by the 12 loudspeakers on the reproduction site, where another binaural recording was captured on DAT using the same dummy-head-mounted microphones. From the sound data recorded using the dummy-head-mounted microphones on the respective sites, the interaural crosscorrelation was calculated, and the results were compared. The equipment used in the experiment is listed in Table 1.

2 FIELD TESTS

Based on the results obtained in the preparatory experiment, the authors conducted field tests in three concert halls. The specifications of the concert halls are listed in Table 2, and the plans and the experimental setups are shown in Fig. 7. The localieus of the microphones and the dummy-head arrangements in concert hall 2 (site C) are shown in Figs. 8 and 9.

In this paper the lecture room is called site A, concert hall 1 is site B, concert hall 2 is site C, and concert hall 3 is site D.

3 FREQUENCY-DEPENDENT INTERAURAL CROSS CORRELATION (FIACC)

IACC is defined as the cross correlation of the sound waveforms at the left and right ears. Fig. 10 represents a listening situation where $p_l(t)$ and $p_r(t)$ are the respective sound waveforms. The IACC coefficient $\rho(\tau)$ is given by Eq. (1).

$$\rho(\tau) = \frac{\langle p_l(t) \cdot p_r(t+\tau) \rangle}{\sqrt{\langle p_l^2(t) \rangle} \sqrt{\langle p_r^2(t+\tau) \rangle}} \quad (1)$$

where the brackets denote averaging

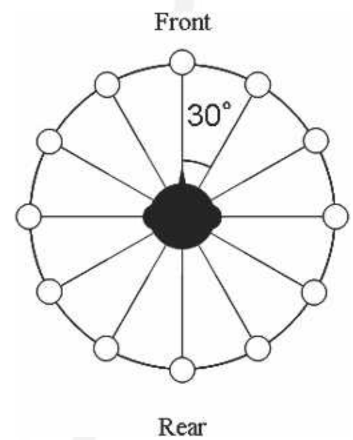

Fig. 2. Microphone placement.

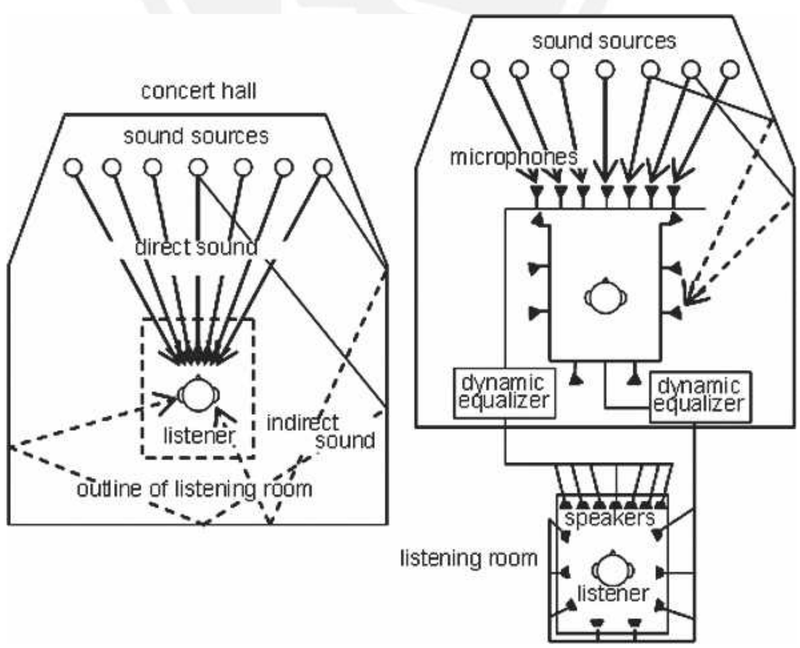

Fig. 1. Configuration of 15-channel Olson model.

In the study of spatial hearing this coefficient is conventionally used as an index measuring spaciousness and a direction [2]–[7]. The value of $\rho(\tau)$ ranges from −1 to 1 and depending on its value, the corresponding listening impression changes as follows:

- $\rho(\tau)$ increasing toward 1: The sound image is localized more toward the center as the L and R channels contain more signal components of the same phase.
- $\rho(\tau) = 0$: The sound image is diffuse as the phases of the L and R channels are random relative to each other:
- $\rho(\tau)$ decreasing toward −1: Unstable sound image as the L and R channels contain more signal components in opposite relative phases.

Furthermore $\rho(\tau)$ reaches a maximum at a certain value of τ, from which the direction of the sound source can be determined. In this study both the sound source and the listening position (dummy head) are located on the centerline of the room, which is symmetrical. Thus the authors consider $\tau = 0$.

The first author of this paper has been making classical music recordings for a long time, and he is convinced that the spatial impression of a sound recording is highly influenced by the frequency characteristics of the IACC. This conviction is the result of having binaurally monitored the outputs of ambient microphones hung from concert hall ceilings.

The IACC is frequency dependent because it is determined by the arrival time difference of the sound waves,

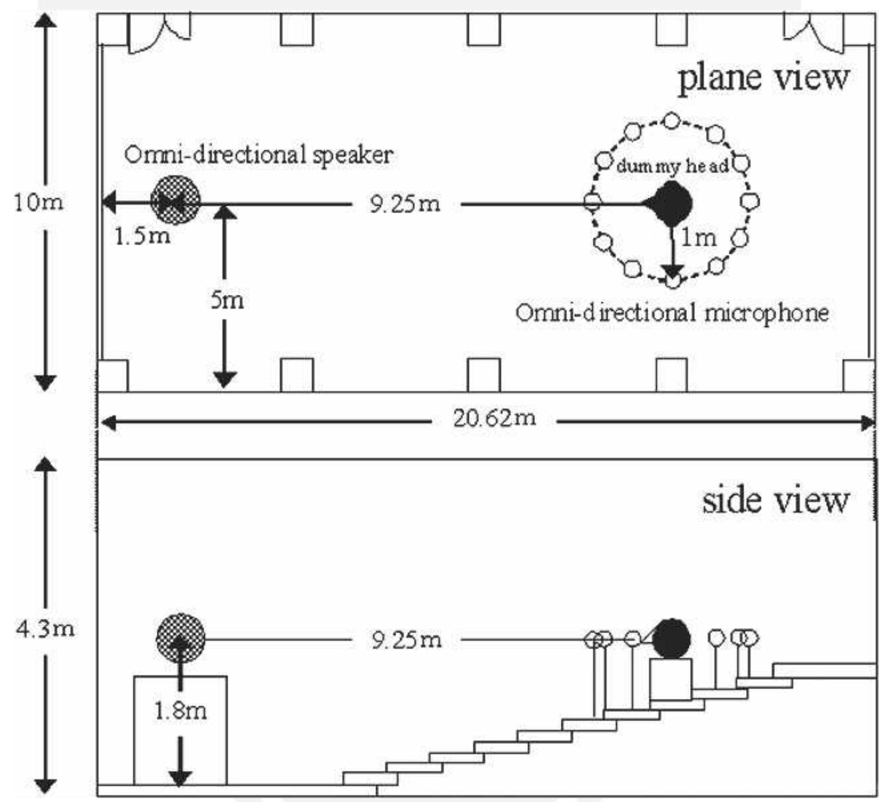

Fig. 3. Views of the recording site for original sound.

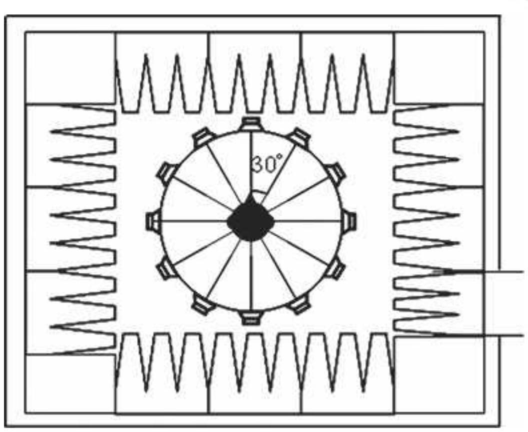

Fig. 4. Plane view of reproduction site.

Fig. 5. Experiment setup.

Fig. 6. Dummy head used.

Table 1. Equipment used for experiment.

	Manufacturer	Model
1. Equipment used for recording		
Hard disk recorder	YAMAHA	AW4410
Omnidirectional loud speaker	VICTOR	GB-10
Omnidirectional microphone	BEHRINGER	ECM8000
2. Equipment used for reproduction		
Power amplifier	YAMAHA	P2040
Loudspeaker	DIATONE	DS-5
3. Equipment used for both recording and reproduction		
Microphone for dummy head	AKG	C-417

Table 2. Specifications of concert halls.

	Site B	Site C	Site D
Seats	1204	1301	1100
Frontage	18 m	18 m	18 m
Depth	15 m	14 m	15 m
Height	8 m	9 m	8 m
Reverberation time	1.9 seconds	1.6 seonds	1.8 seconds

which causes frequency-dependent phase differences between $p_l(t)$ and $p_r(t)$. Tohyama and Suzuki first analyzed the frequency characteristics of the IACC in stereophonic reproduction [8]. Hiyama et al. also paid attention to the frequency characteristics of the IACC and utilized diffuse sound-field synthesis [9]–[11]. The authors tried to apply this concept to the evaluation of recording technology [12]–[15]. Noting that $\rho(0)$ is frequency dependent, and that the frequency characteristics can be utilized as an index of spaciousness, such a frequency-dependent coefficient, denoted by $\rho(\omega)$, is called frequency-dependent interaural cross correlation (FIACC) in this paper. The FIACC, in an ideally diffuse sound field, can be calculated theoretically (see Appendix 1) and is shown in Fig. 11.

4 MEASUREMENT OF FIACC

The FIACC $\rho(\omega)$ is calculated from the sound data obtained by a pair of microphones on the dummy head in

Fig. 8. Side view of microphone arrangement.

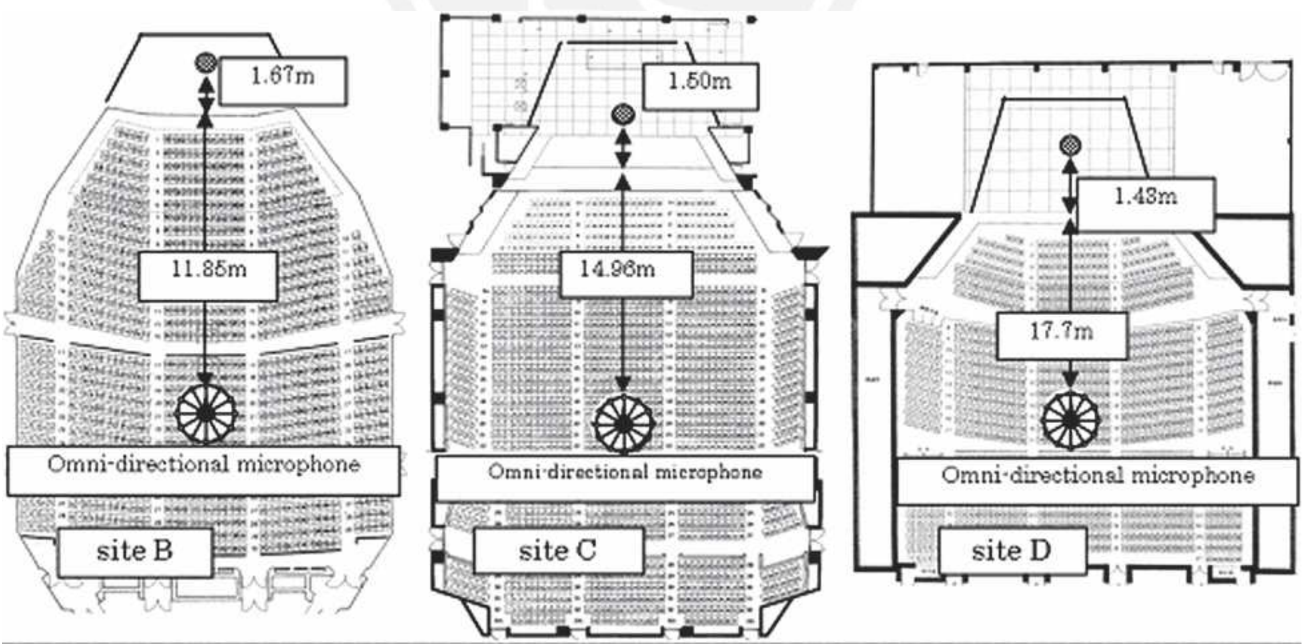

Fig. 7. Configurations of field tests.

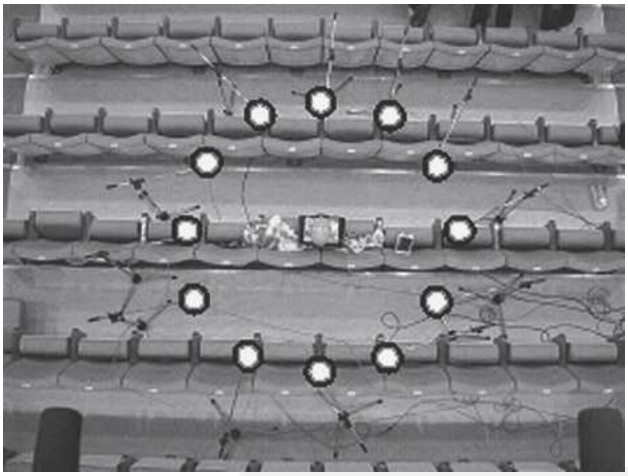

Fig. 9. Overhead view of microphone arrangement.

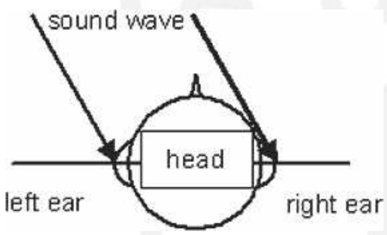

Fig. 10. Configuration of binaural listening.

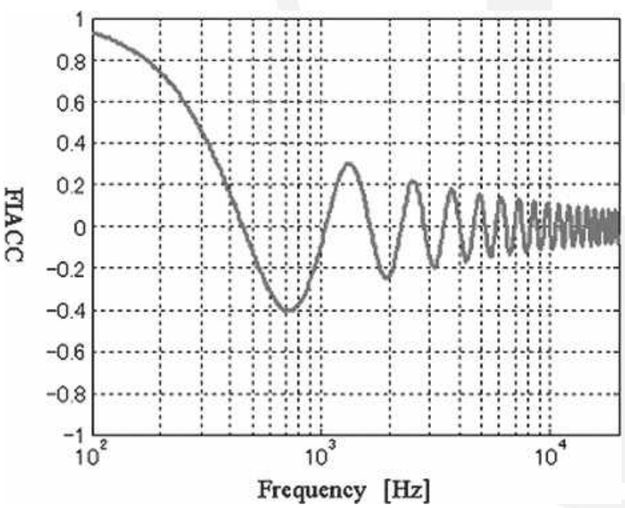

Fig. 11. Theoretical FIACC in diffuse sound field.

both the original and the reproduction sites. The sound data are divided into 32 pairs of band-passed signals using linear-phase one-third-octave band-pass filters, whose normalized frequency characteristics are shown in Fig. 12. A diagram of the measurements is shown in Fig. 13, where time-domain convolution is applied to calculate the FIACC. Sound data are digitized according to the following specifications:

- Sampling frequency: 44.1 kHz
- Quantization: 16 bit.

5 FIACC REPRODUCTION FOR 12-CHANNEL RECORDING/REPRODUCTION SCHEME

5.1 FIACC, Measurement on Original Sites

The FIACC measurements obtained on the original sites are shown in Fig. 14. Comparing the FIACC characteristics on the original sites with those of an ideally diffuse sound field (Fig. 11), it is commonly observed that the values in the range between 500 Hz and 5 kHz are larger. This means that sound waves traveling from the stage to audiences are abundant in this frequency range. The reason may be the pentagonal shape common to concert halls. A variation of the FIACC patterns is considered useful for evaluating the sound diffusion of concert halls. In this experiment the FIACC patterns in Fig. 14 will be used as a reference for the FIACC patterns obtained in the reproduction experiments.

5.2 FIACC Measurements on the Reproduction Sites

Fig. 15 exhibits the FIACC patterns obtained from the sound data recorded in the different concert halls. The heavy solid lines show the FIACC for 12-channel recording and reproduction, at 1-m radius and the dotted lines show the same data at a speaker circle radius of 2 m. The thin lines represent the reference FIACC patterns. These three types of patterns will also be shown in subsequent figures.

The patterns displayed in Fig. 15 show that the FIACC of the reproduced sound field is similar to that of the reference. Also, the FIACC patterns change little with the size of the speaker circle. This means that even if the radius of the speaker circle is changed, the listener's spa-

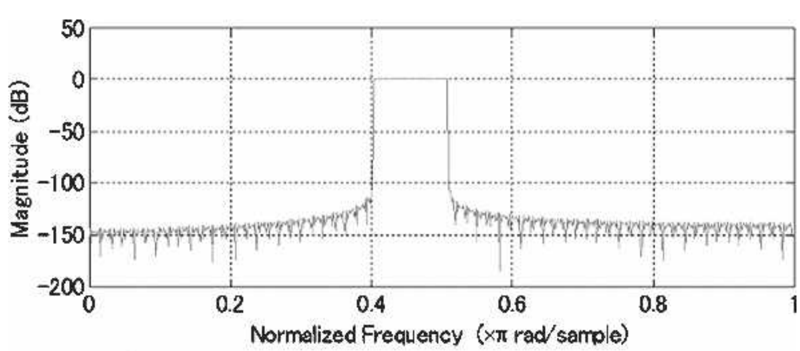

Fig. 12. Normalized frequency characteristics of digital filter.

tial impression remains almost unchanged as long as the azimuth angles of the loudspeakers are maintained.

6 FIACC PATTERNS DEPENDING ON NUMBER OF CHANNELS AND LOUDSPEAKER POSITIONS

In this experiment 12 channels were used to record the original sound data, but in the reproduction the number of channels utilized were 6, 5, 4, 3, and 2. As a result, 72 patterns of loudspeaker placements were chosen, as shown in Fig. 16, with the symmetrical placements of the left and right loudspeakers remaining unchanged and the radius of the speaker circle set at 1 and 2 m.

Considering that the similarity of the FIACC patterns at the original site and the reproduction sites will be an index of sound-field reproduction, the authors monitored the squared error E calculated from the FIACC difference between original site and reproduction sites. E is expressed as

$$E = \frac{\sum_{i=1}^{N}(x_i - y_i)^2}{N} \tag{2}$$

where x_i is the FIACC value at the ith frequency band on the reproduction site, y_i is the FIACC value at the ith frequency band on the original site, and the frequency of the first band is 100 Hz. E is calculated for the "full" band of 100 Hz to 20 kHz, and for the "fundamental" band of 100 Hz to 1 kHz. The frequency range of the fundamental band was determined with reference to studies by Hiyama et al. [9]–[11], who proved experimentally that the FIACC in this range is related to the impression of spaciousness. In Eq (2) $N = 23$ for the full band and $N = 10$ for the fundamental band.

The values of the squared errors E for all loudspeaker placement patterns are shown in Figs. 17–21. From the results it is clear that the E values do not decrease below 0.04 (full band) and 0.02 (fundamental band) when the number of channels exceeds 5. This means that the five-channel system is preferable from the viewpoint of practical use.

Furthermore, based on the following considerations, loudspeaker configurations characterized by excessive or too few rear loudspeakers will be discarded hereafter.

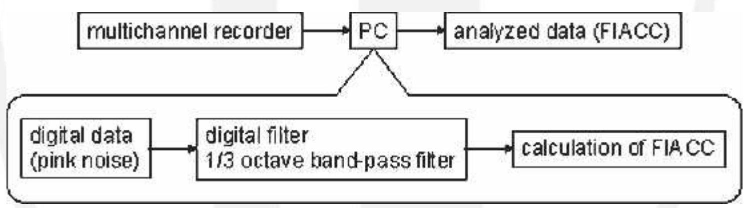

Fig. 13. Diagram for FIACC measuring procedure.

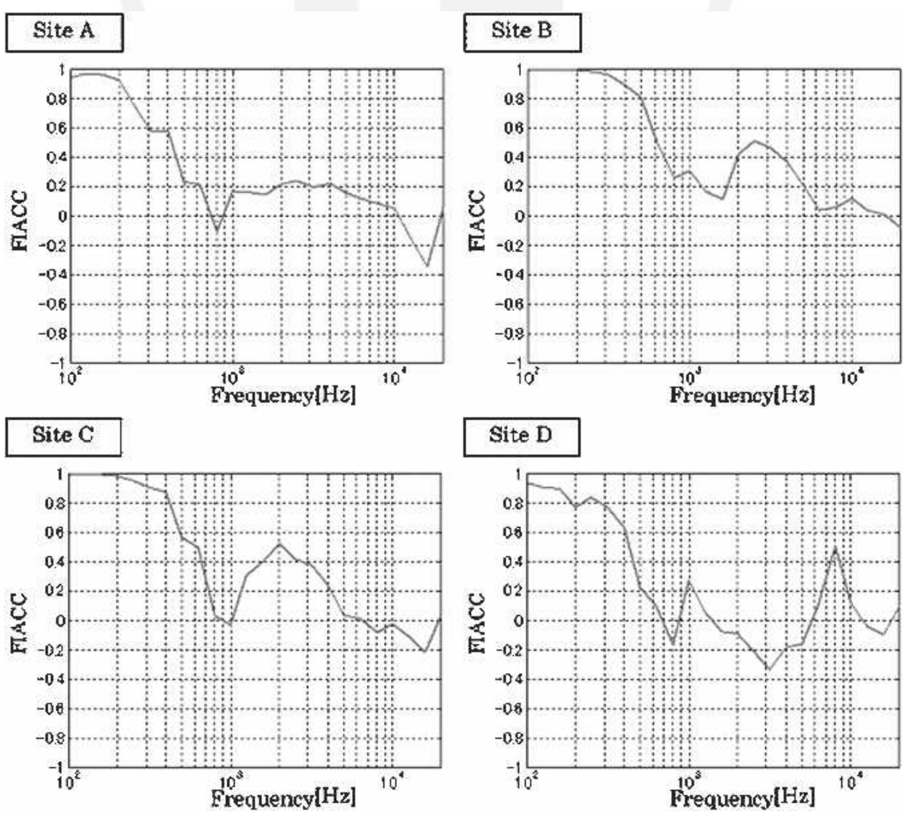

Fig. 14. FIACC measurements on original sites.

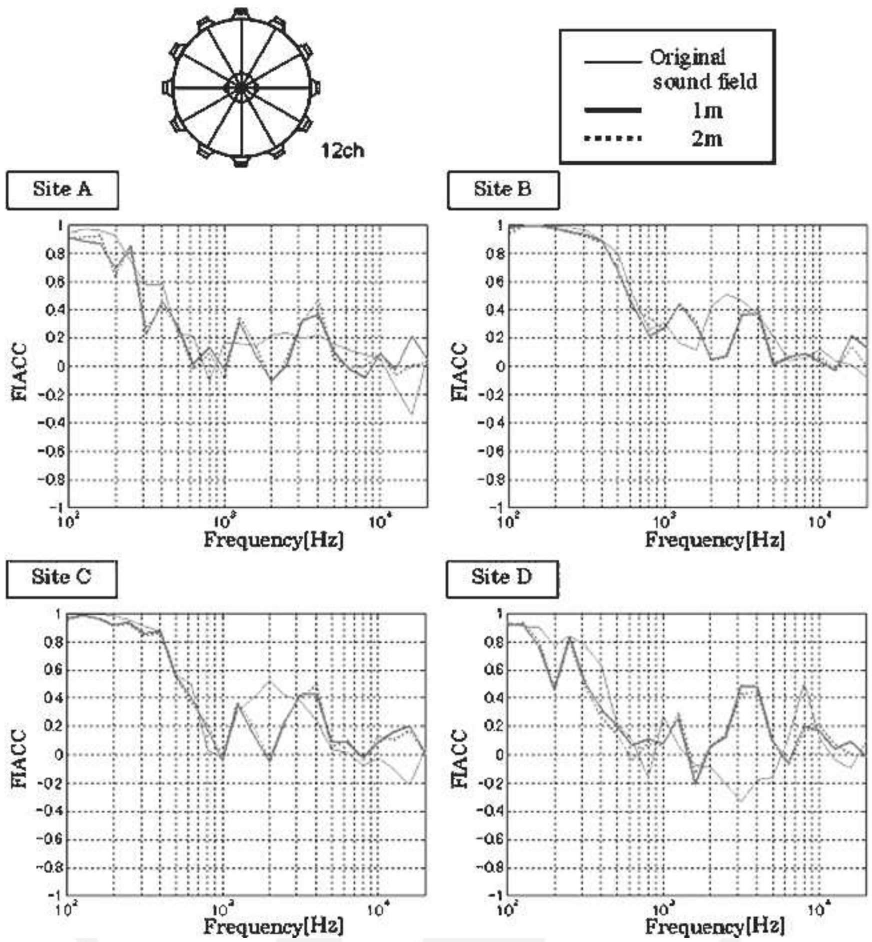

Fig. 15. FIACC measurements on reproduction sites.

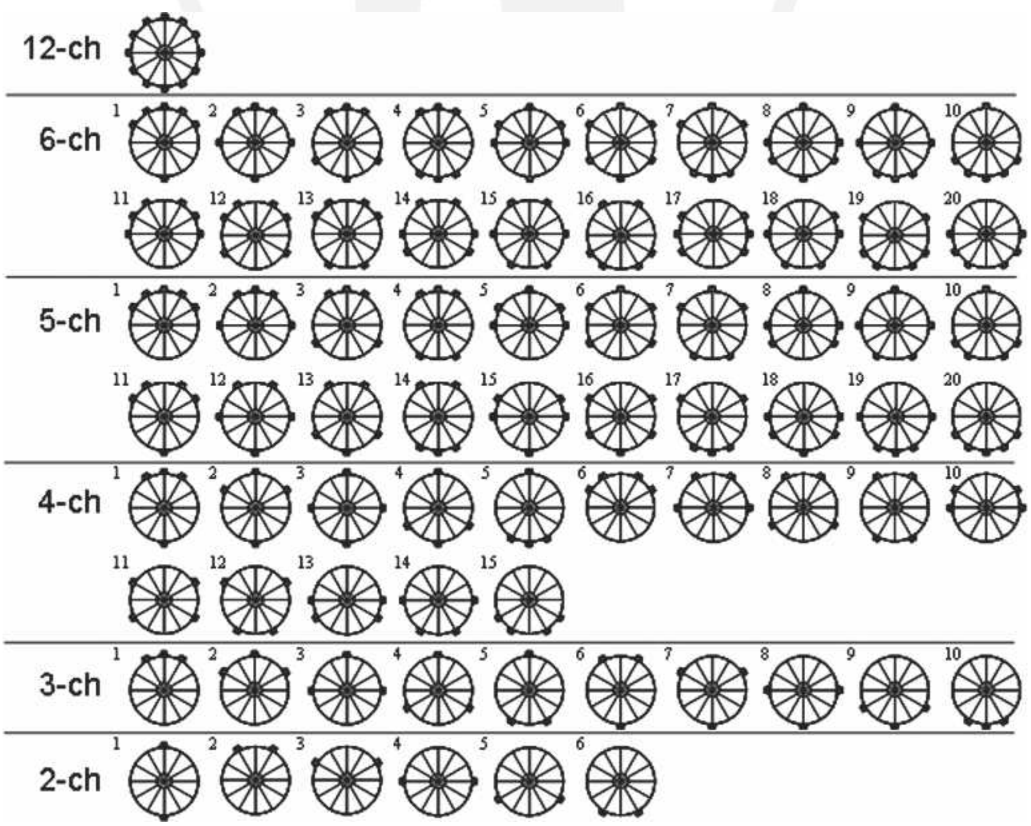

Fig. 16. Configurations of loudspeaker placement.

- More front loudspeakers are advantageous for better sound image localization.
- A certain number of rear loudspeakers are necessary for the reproduction of the surrounding sound field.

7 DISCUSSION OF FIACC REPRODUCTION WITH FEWER TRANSMISSION CHANNELS

In order to identify desirable multichannel recording and reproduction formats, the authors examined the similarity of the FIACC patterns on the original and the reproduction sites. In this regard, if the squared error E is smaller, the listeners on the reproduction site will perceive more spaciousness similar to that on the original site. Besides the squared error E, the authors compared the shape of the FIACC patterns on the original and the reproduction sites. In this examination, front-oriented loudspeaker placements were selected.

7.1 Two-Channel Transmission

Figs. 22 and 23 show a comparison of the FIACC patterns for an azimuth difference of the front loudspeakers of 60 and 120°, respectively. In the case of 60° which generally is used in stereophonic reproduction, the FIACC value turns negative in the frequency range between 1 and 2.5 kHz, which indicates that out-of-phase frequency components are abundant in this range, causing unnatural spaciousness. In the case of 120° the abnormal frequency range shifts to 500 Hz to 1 kHz, which also causes unnatural spaciousness. Consequently two-channel transmission is inadequate for sound-field reproduction.

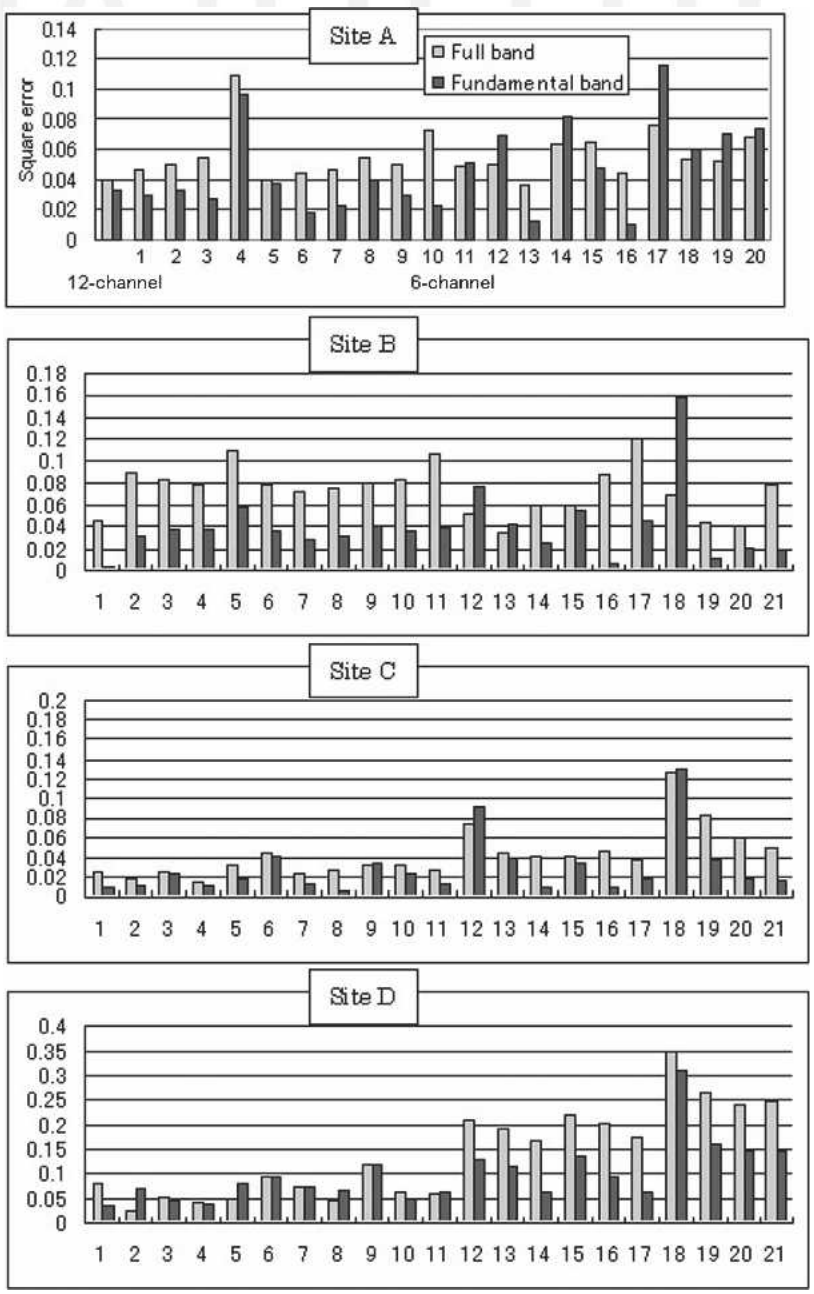

Fig. 17. Squared errors for 12-channel and 6-channel configurations.

7.2 Three-Channel Transmission

In the three-channel experiment a center loudspeaker for the third channel was located between the front left and right loudspeakers, as shown in Figs. 24 and 25. Here it must be noted that the single center loudspeaker provides a frequency-independent FIACC of 1, and that the FIACC reproduced by several sound sources is determined by the weighted sum of the FIACCs reproduced by the respective sound sources (see Appendix 2). In this case the FIACC is the weighted sum of the FIACC values of the center and left and right loudspeakers. This means that the addition of a center loudspeaker results in raising the two-channel FIACC pattern, as observed in Figs. 24 and 25. In Fig. 24 a center loudspeaker is added to the two-channel reproduction illustrated in Fig. 22. In this case, instead of reducing the out-of-phase frequency components, on increase of the in-phase frequency component changes the FIACC value to 1 and will cause a narrower spatial impression. The abnormal FIACC pattern shown in Fig. 25 is corrected fairly well. However, a positive deviation still remains within the frequency range of 1 to 5 kHz. On the other hand, this case is advantageous from the viewpoint of sound-image localization.

7.3 Four-Channel Transmission

Now we have multichannel surround sound systems. Figs. 26 and 27 show the cases of a so-called 2–2 system. In Fig. 26 the azimuth differences of the front and rear loudspeaker pairs are set equally to 60° whereas in Fig. 27

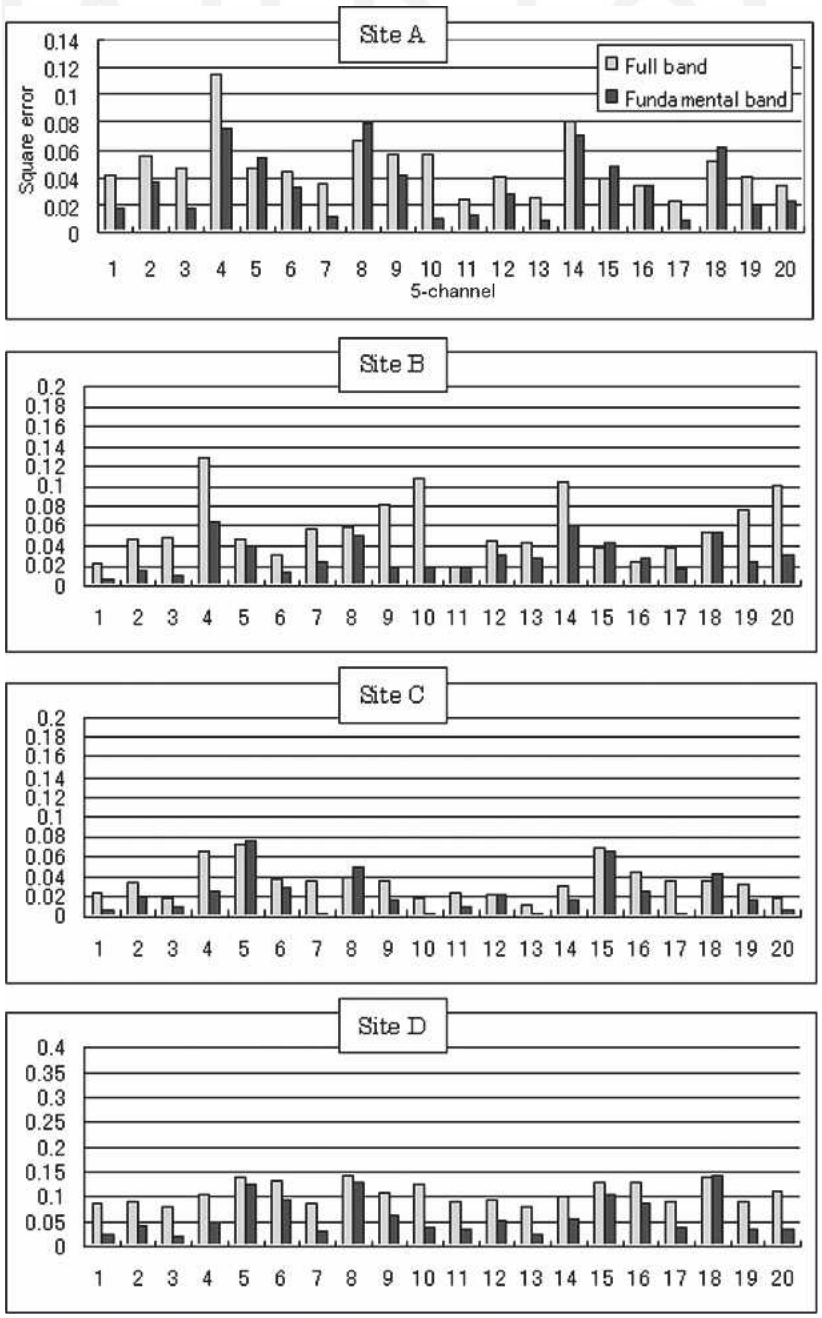

Fig. 18. Squared errors for five-channel configurations.

the azimuth difference of the front loudspeaker pair is set to 60° and that of the rear to 120°.

Fig. 26 indicates that the FIACC of a front-to-rear symmetrical 2-2 system is quite similar to that of two-channel transmission. This proves that the front-to-rear symmetrical 2-2 system is not advantageous for sound-field reproduction.

On the other hand, Fig. 27 exhibits a significant improvement in FIACC reproduction. The loudspeaker location in this case is a superimposition of [2ch-2] and the front-to-rear mirror image of [2ch-3]. Given that the FIACC of [2ch-3] resembles that of its mirror image (if the human head is spherical, they coincide), the FIACC is close to the average of those obtained for [2ch-2] and [2ch-3]. Abnormal deviations of both FIACCs in the frequency range from 500 Hz to 5 kHz are neutralized, which yields a favorable FIACC pattern. However, a small negative deviation is still observed.

7.4 Five-Channel Transmission

In five-channel transmission the FIACC patterns exhibit remarkable improvements, as shown in Figs. 28 and 29. The loudspeaker configuration [5ch-3] results from the addition of a center loudspeaker in [4ch-8]. Thanks to the increasing effect of the center loudspeaker, a more favorable FIACC pattern is obtained, as shown in Fig. 28. In the case of [5ch-7], a favorable FIACC pattern is also obtained, as shown in Fig. 29. However, [5ch-3] should be preferred, taking frontal sound-image localization into consideration.

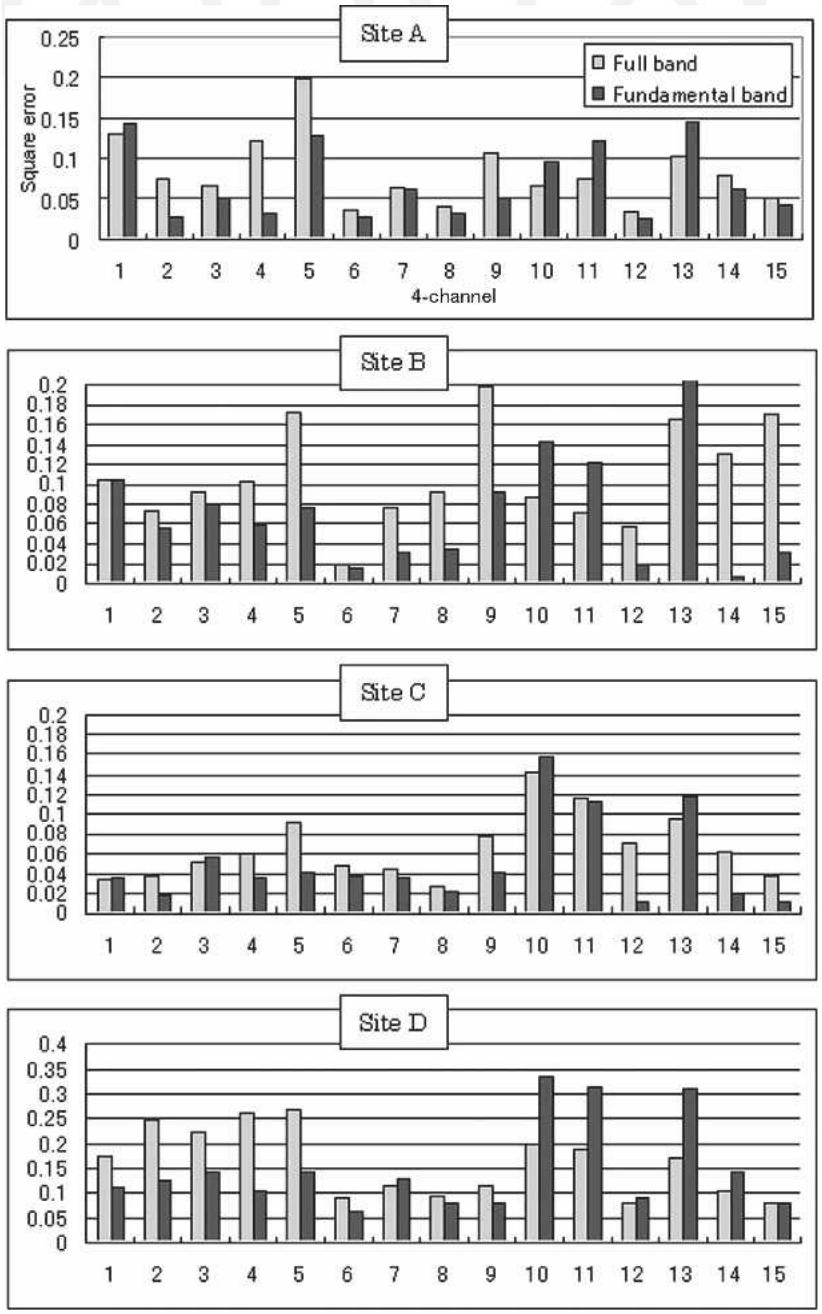

Fig. 19. Squared errors for four-channel configurations.

7.5 Six-Channel Transmission

In six-channel transmission two uniformly configured loudspeaker layouts exhibit quite different FIACC patterns, as shown in Figs. 30 and 31. The configuration [6ch-6] is a simple superimposition of [3ch-2] and its mirror image. Therefore the resulting FIACC pattern is almost the same as that of [3ch-2]. In the case of [6ch-15], two loudspeakers are placed alongside in addition to the locations of [4ch-9]. Some abnormal deviations of the FIACC pattern are suppressed, but the result is not satisfactory.

7.6 12-Channel Transmission

The results for 12-channel transmission were already shown in Fig. 15. They are generally good but not the best.

8 OPTIMUM NUMBER OF CHANNELS AND LOUDSPEAKER CONFIGURATION FOR THE OLSON MODEL

As discussed in the foregoing, the five-channel transmission [5ch-3] exhibited a good performance, as shown in Fig. 28, and it is supported by the value of the squared error *E* in the FIACC between the original and the reproduction sites. Furthermore, [5ch-3] coincides with the loudspeaker location of ITU Recommendation BS.775-1, which is shown in Fig. 32 [15].

In our view the [5ch-3] system, which has a smaller front loudspeaker angle, is advantageous from the viewpoint of frontal sound-image localization. Moreover, recent studies based on subjective listening deduced that

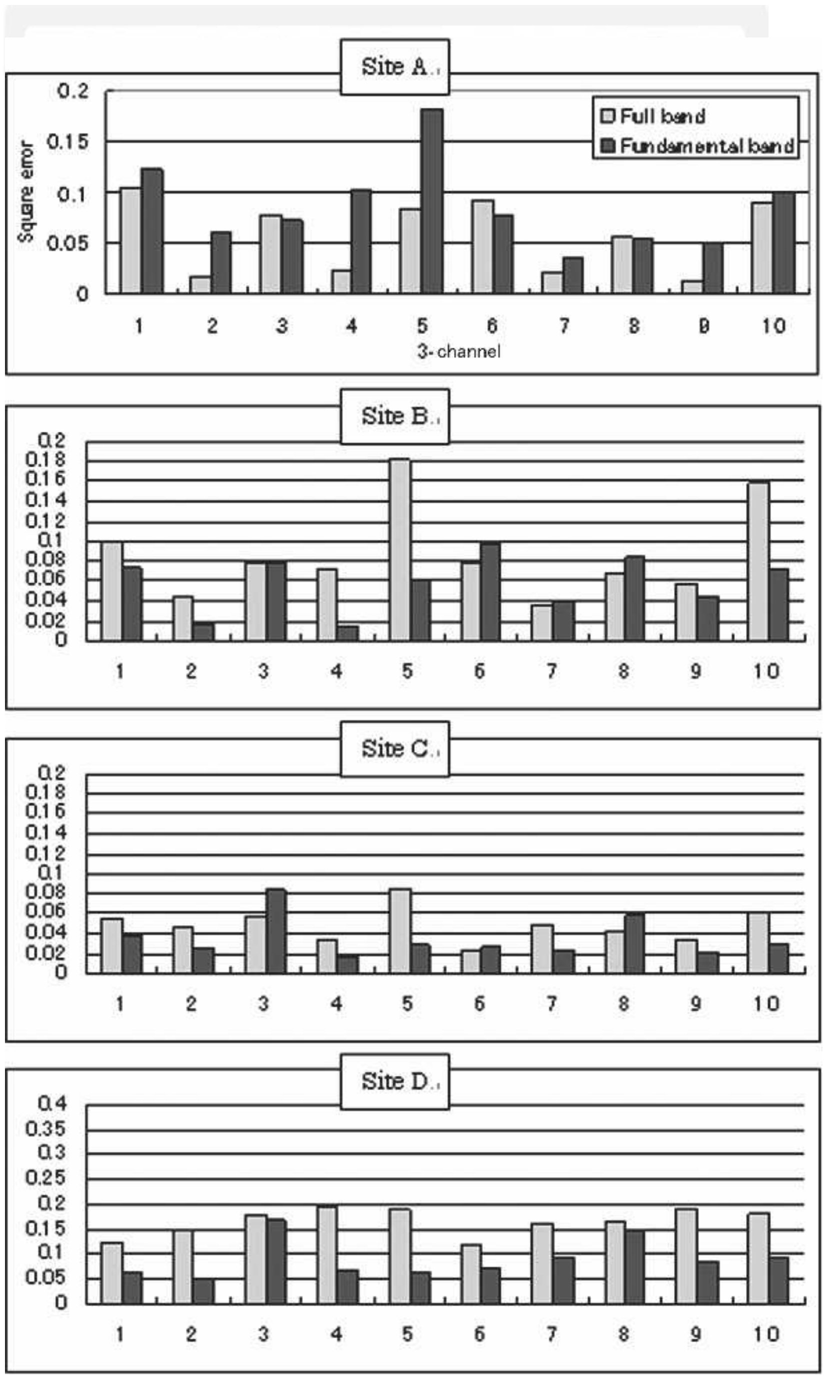

Fig. 20. Squared errors for three-channel configurations.

according to the International Telecommunication Union, the five-channel system is the optimum format for multichannel recording and reproduction [13], [14].

9 PROPOSAL OF AMBIENT MICROPHONE ARRAY FOR FIVE-CHANNEL SOUND SYSTEM

As a result of the experiments described in this paper, the authors propose a new ambient microphone array for the five-channel sound system as shown in Fig. 33. The array should be placed in the most reverberant position of the concert hall by being suspended from the ceiling, as illustrated in Fig. 34. The localization of individual instruments will be improved by utilizing stage microphones.

10 CONCLUSION

The authors have compared various microphone–loudspeaker-array geometries to arrive at an optimum number of channels and optimum loudspeaker placement for multichannel recording and reproduction systems. The experiments were based on the Olson model and used frequency-dependent interaural cross correlation (FIACC) as a physical and objective measure of the listener's spatial impression. FIACC data were measured using a dummy head on both the recording and the reproduction sites. The number of channels used was 12, 6, 5, 4, 3 and 2. A comparison of the FIACC patterns measured for 72 different loudspeaker configurations to that of the original

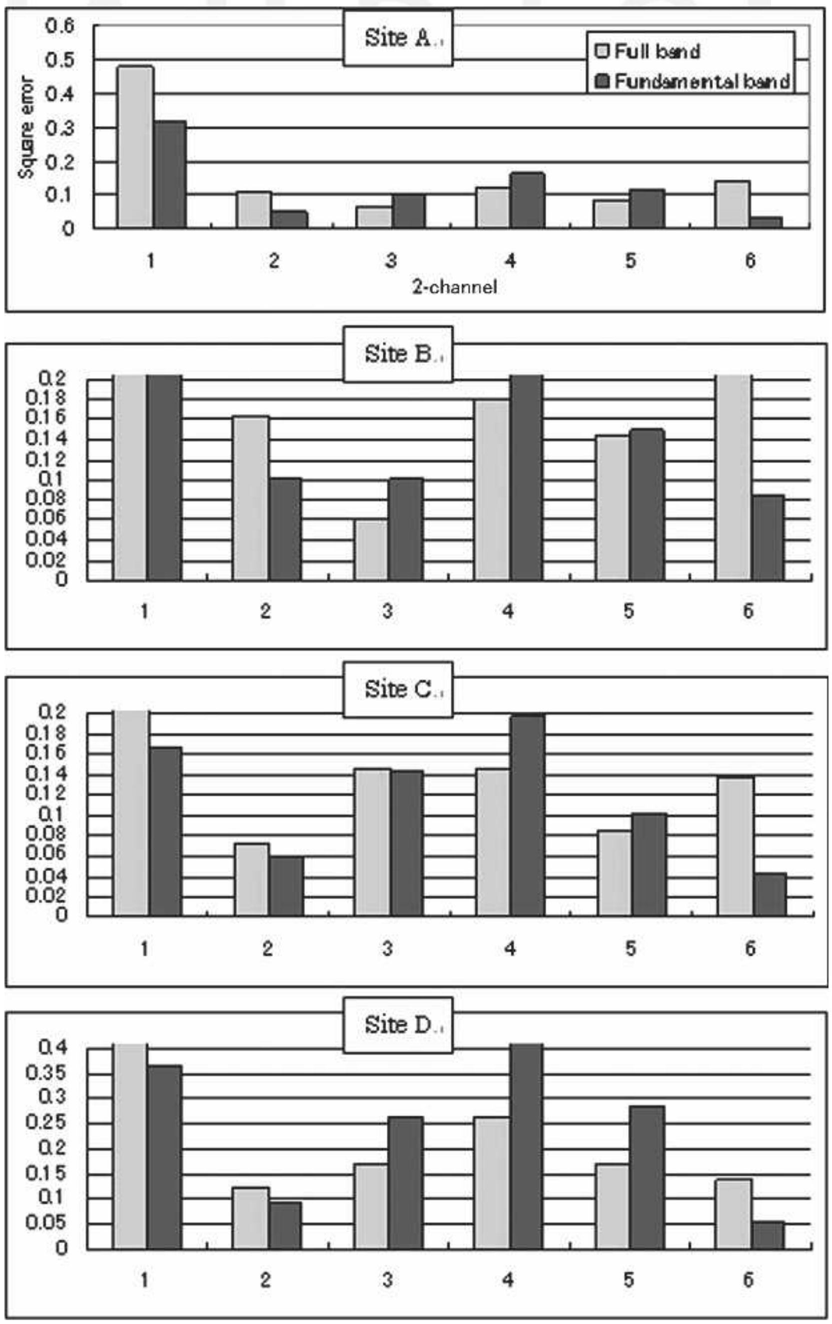

Fig. 21. Squared errors for two channel configurations.

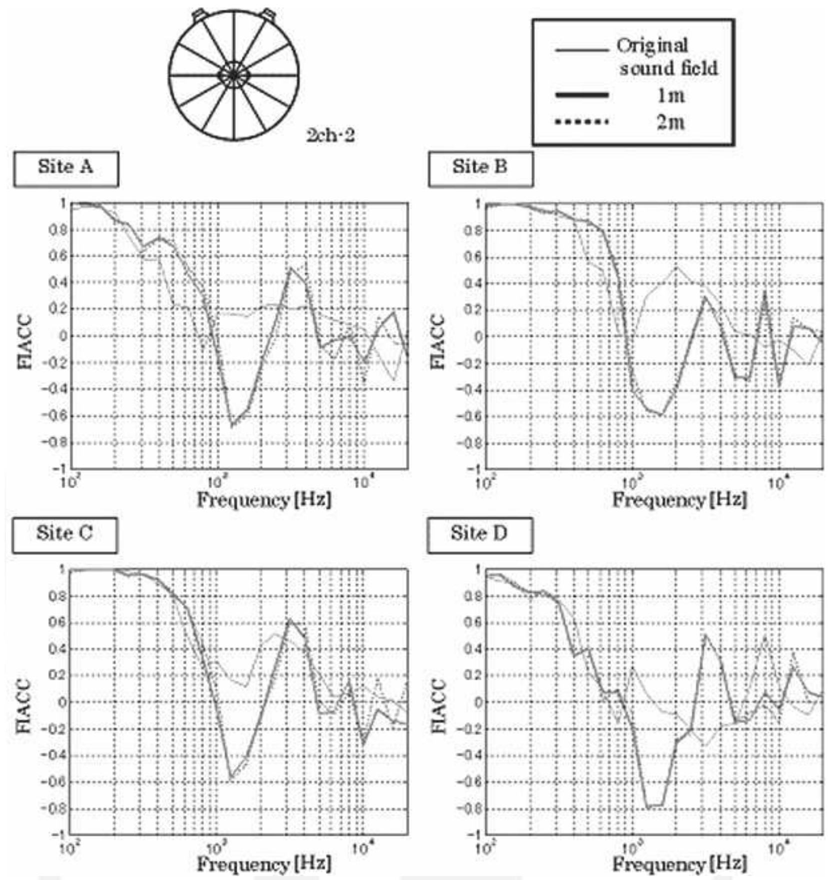

Fig. 22. FIACC results for configuration [2ch-2].

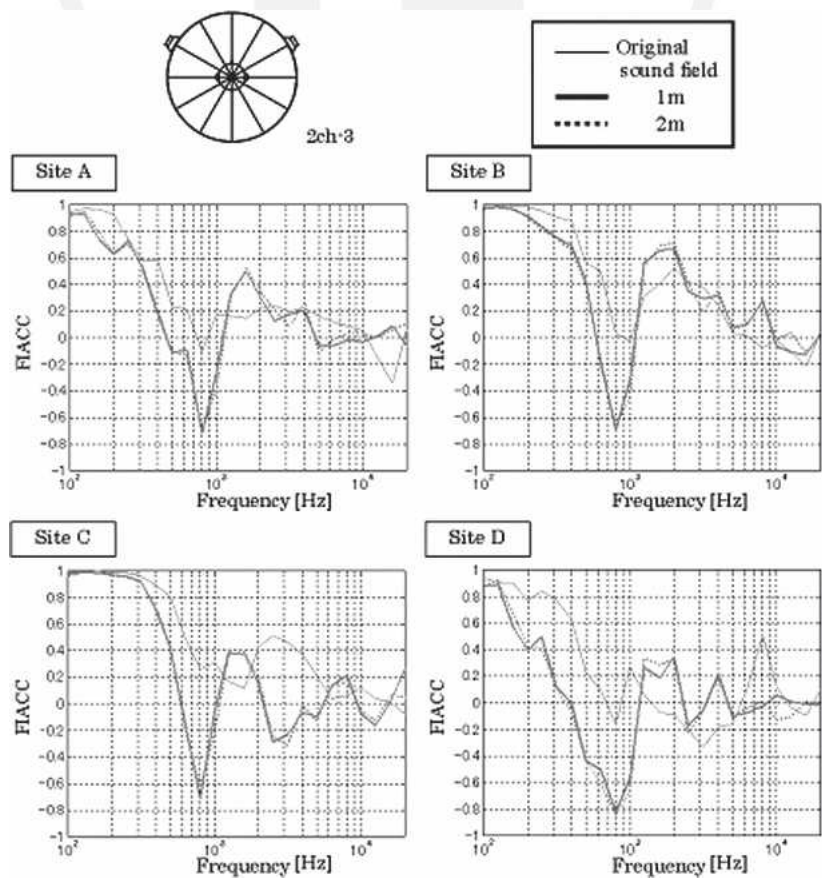

Fig. 23. FIACC results for configuration [2ch-3].

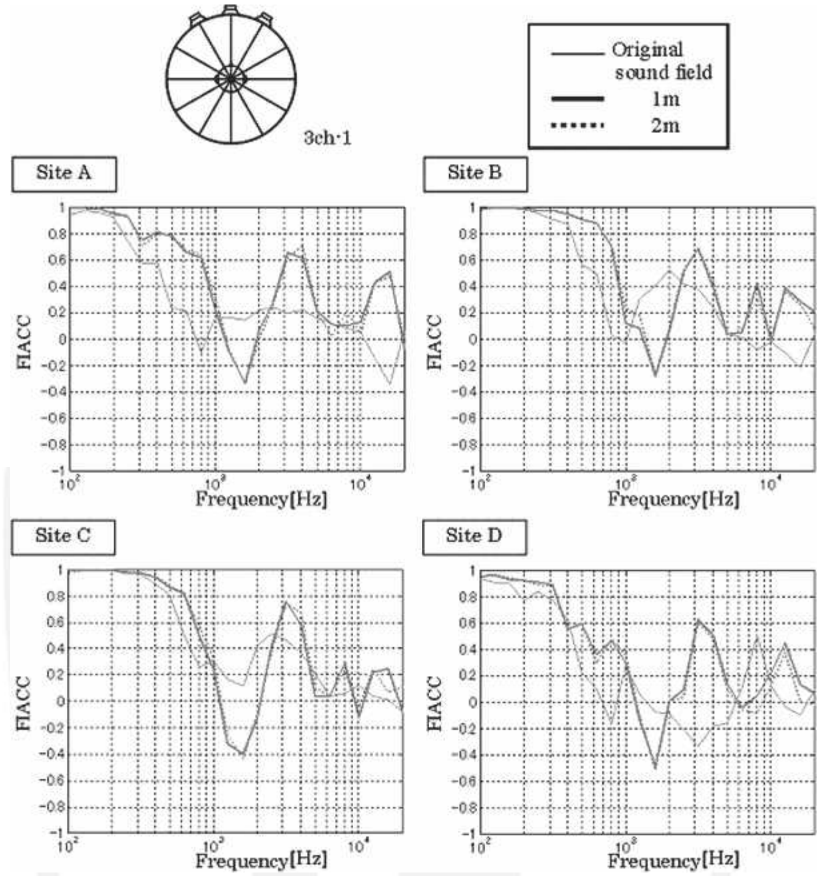

Fig. 24. FIACC results for configuration [3ch-1].

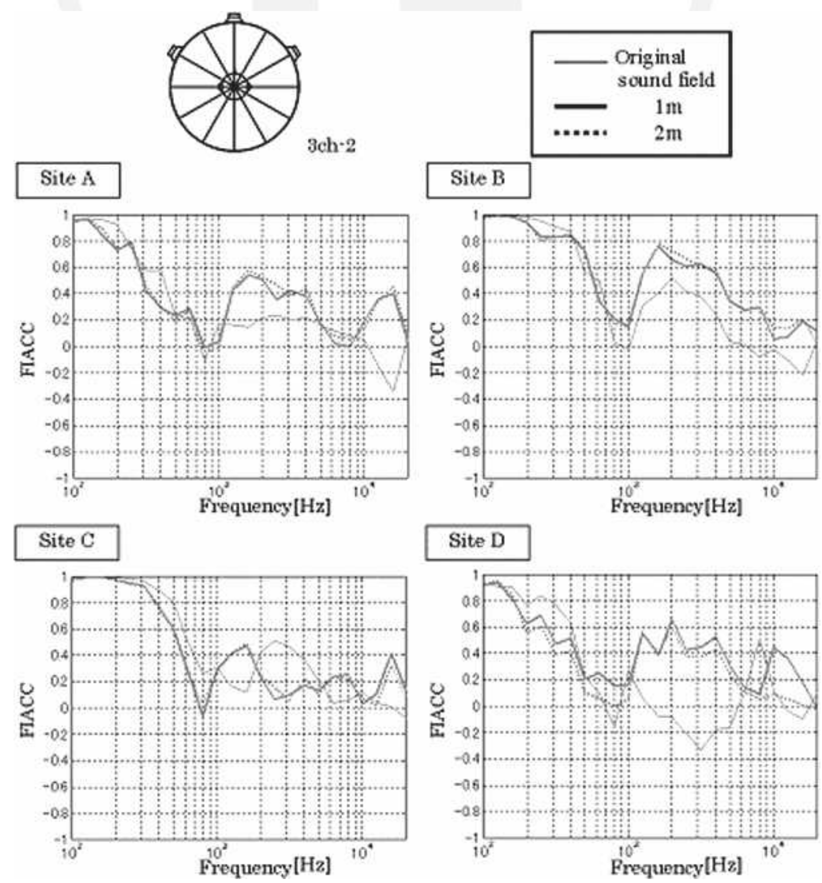

Fig. 25. FIACC results for configuration [3ch-2].

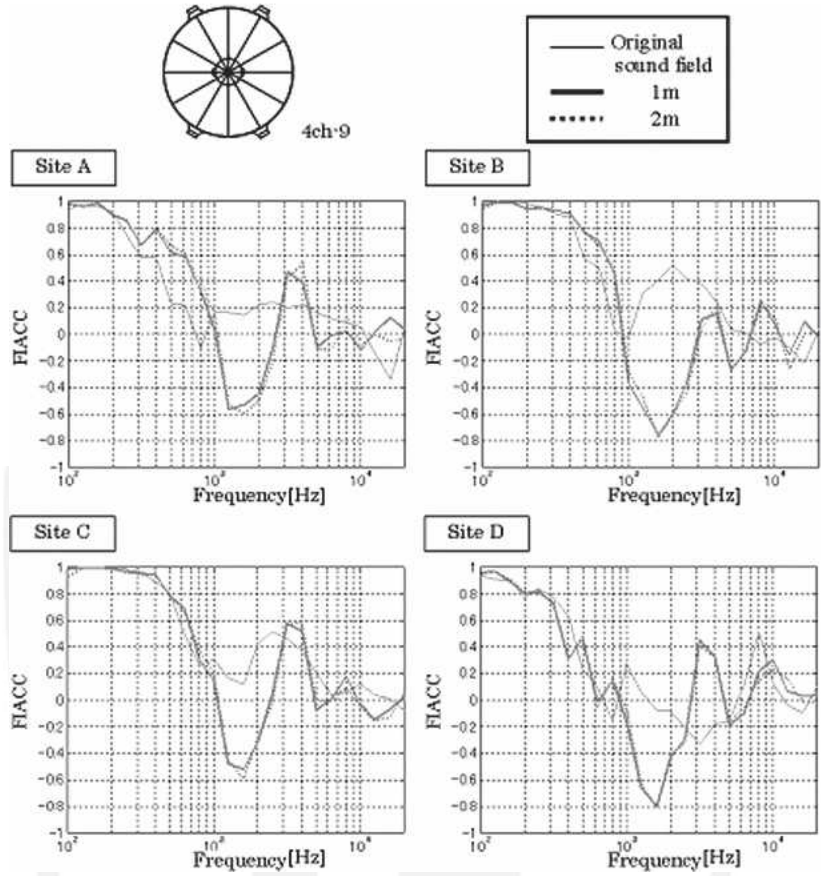

Fig. 26. FIACC results for configuration [4ch-9].

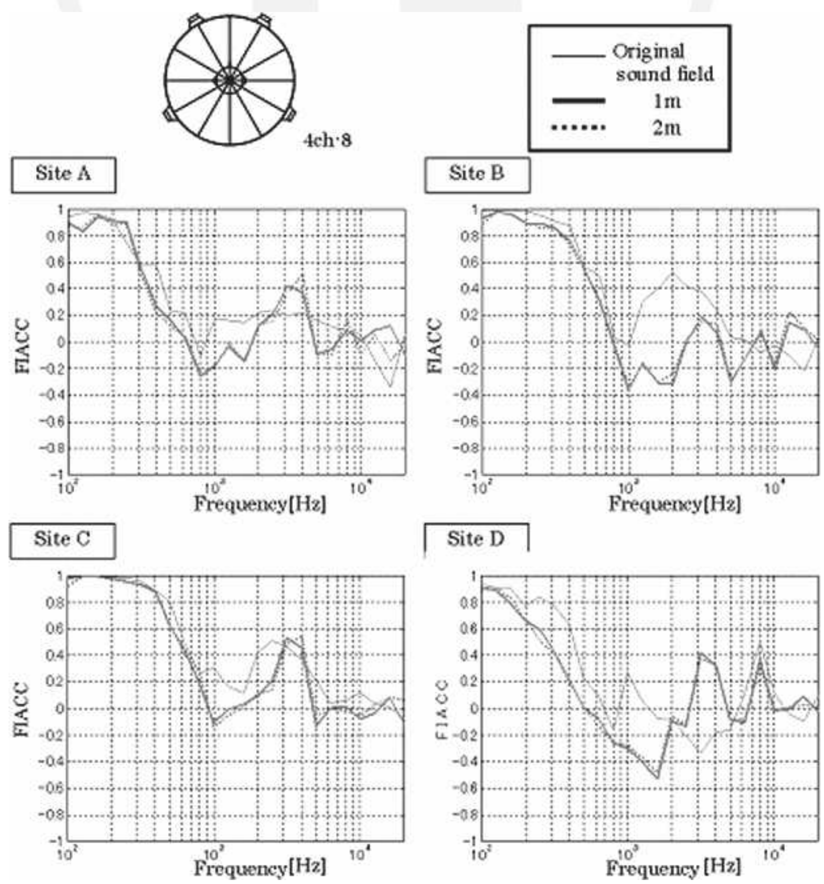

Fig. 27. FIACC results for configuration [4ch-8].

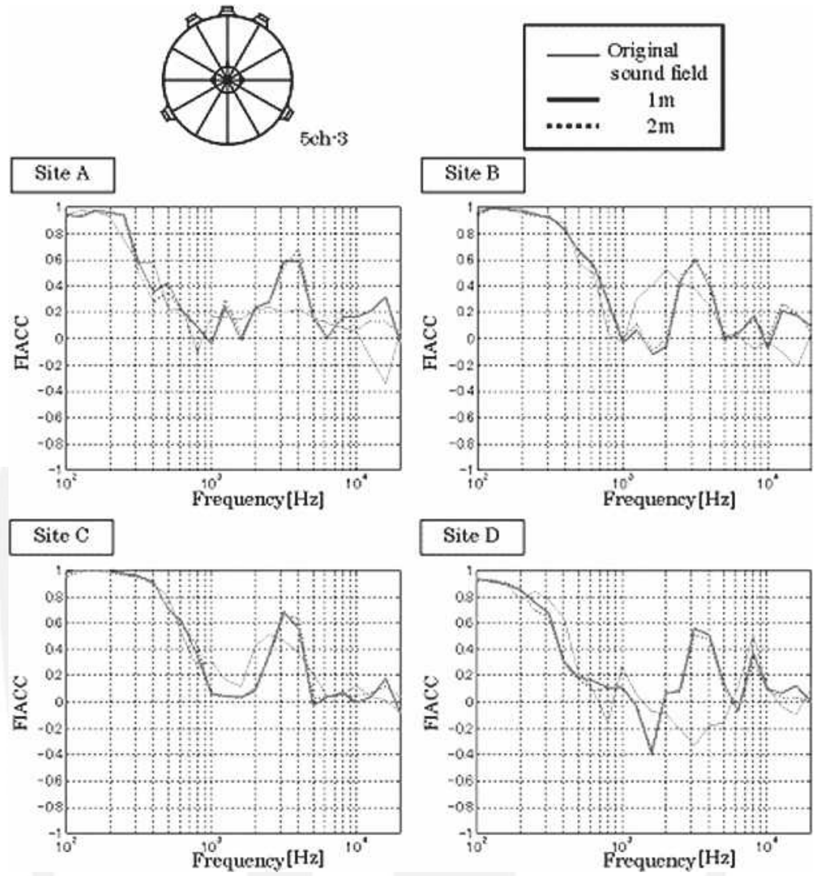

Fig. 28. FIACC results for configuration [5ch-3].

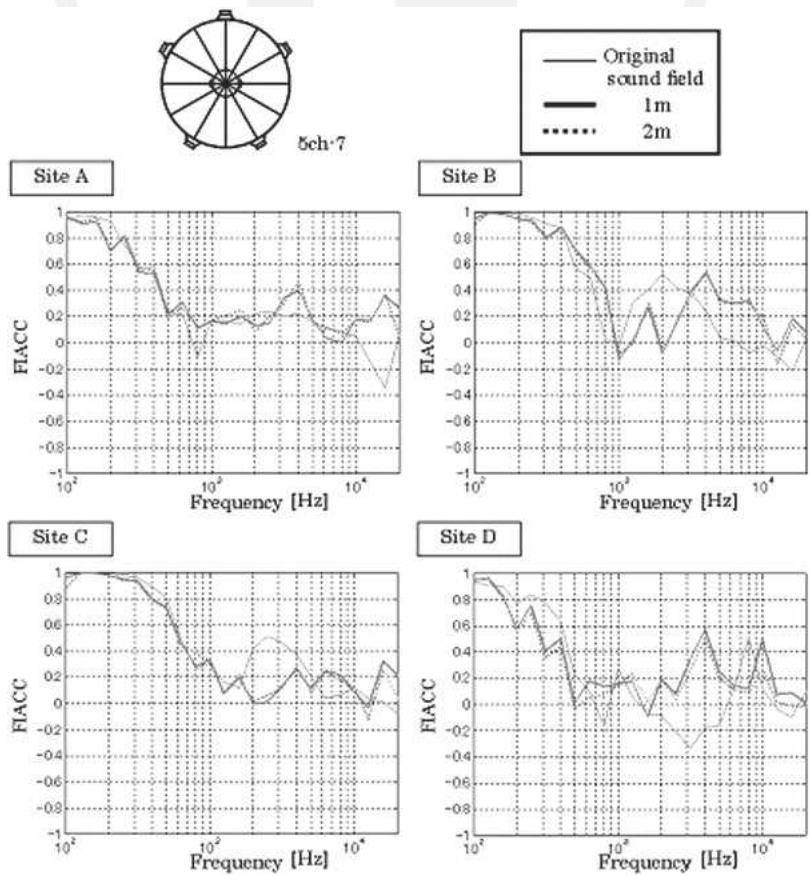

Fig. 29. FIACC results for configuration [5ch-7].

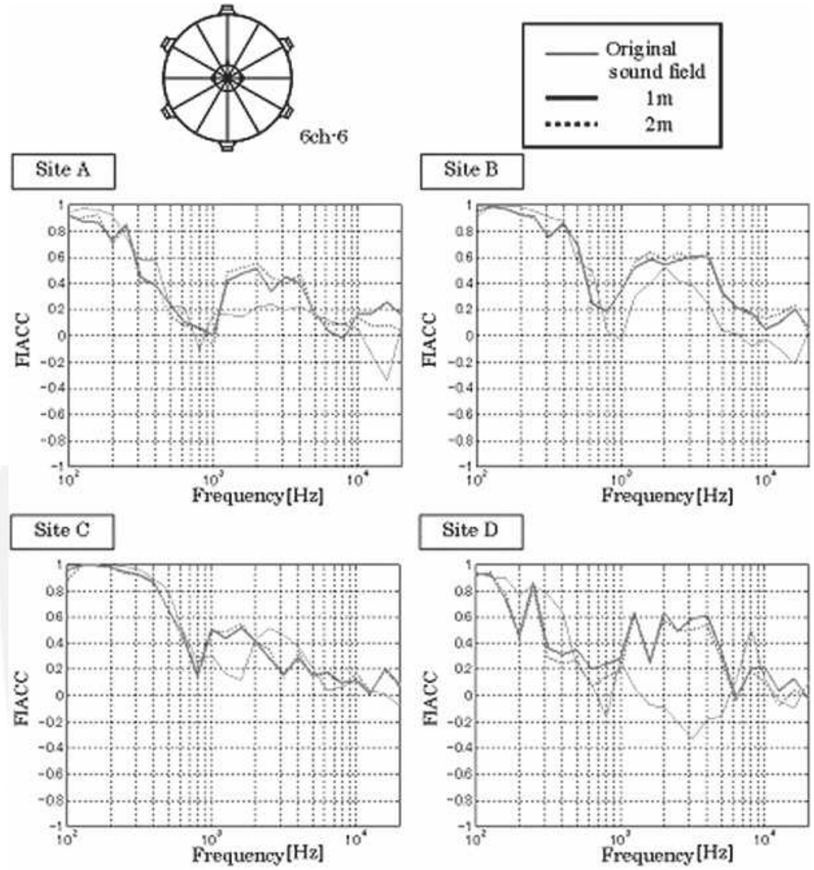

Fig. 30. FIACC results for configuration [6ch-6].

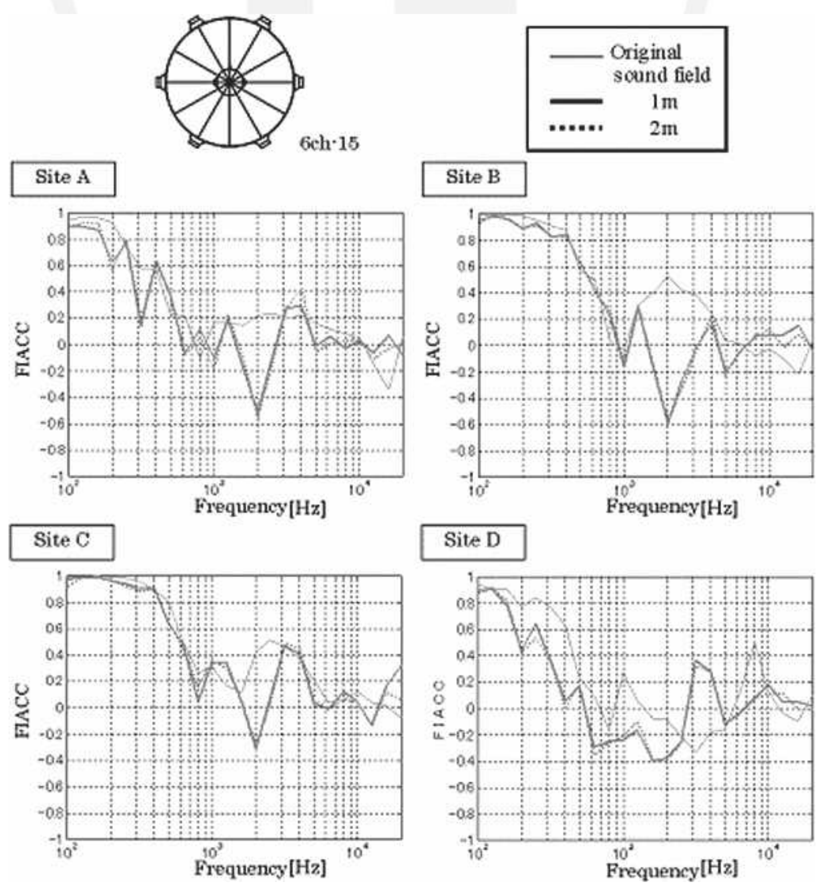

Fig. 31. FIACC results for configuration [6ch-15].

sound field found the five-channel system described in the ITU recommendation to be optimum.

11 REFERENCES

[1] H. Olson, "Home Entertainment: Audio 1988," *J. Audio Eng. Soc.,* vol. 17, p. 390 (1969).

[2] P. Damaske, *Acoustica,* vol. 19, pp. 199–213 (1967/1968).

[3] T. Anazawa, H. Yanagawa, and Itoh, "Study of Spaciousness and Interaural Correlations," Inst. Elect., Info. and Comm. Eng., EA70-13 (1970).

[4] Y. Ando and P. Damaske, "Interaural Cross Correlation for Multichannel Loudspeaker Reproduction," *Acoustica,* vol. 27 (1972).

[5] H. Yanagawa, S. Toshu, and S. Mori, "Study of Spaciousness and Interaural Correlations by Using Dummy Head," Rep., AST Techn. Comm. of Psychological and Physiological Acoustics (1976).

[6] Y. Hirata, "Perception of Spaciousness in Reproduced Sound Field," Inst. Elect., Info. and Comm. Eng., EA80-71 (1980).

[7] Yanagawa, "Study of Evaluation and Control of Reproduced Sound Field," Ph.D. thesis, Wasada University, Wasada, Japan (1990).

[8] M. Tohyama and A. Suzuki, "Interaural Cross–Correlation Coefficients in Stereo Reproduced Sound Fields," *J. Acoust. Soc. Am.,* vol. 85, pp. 780–786 (1989).

[9] K. Hiyama, H. Ohkubo, and S. Komiyama, "Examination of Optimum Speaker Layout in Multispeaker Sound Field Reproduction," presented at the Spring Conference of AST (2000 Mar.).

[10] K. Hiyama, S. Komiyama, and K. Hamasaki, "The Minimum Number of Loudspeakers and Its Arrangement for Reproducing the Spatial Impression of Diffuse Sound Field," presented at the 113th Convention of the Audio Engineering Society, *J. Audio Eng. Soc.* (*Abstracts*), vol. 50, p. 964 (2002 Nov.), convention paper 5674.

[11] K. Hiyama, H. Ohkubo, S. Komiyama, and K. Hamasaki, "Examination of Optimum Speaker Layout for Restoration of Diffusive Sound Field," presented at the Fall Conference of AST (2003 Sept.).

[12] T. Muraoka, M. Ichikawa, and T. Nakazato, "Microphone Arrangements Related to Sound Field Reproduction in Stereophonic Recording and Reproduction Process," *J. Acoust. Soc. Jpn.,* vol. 43, no. 10 (2003).

[13] T. Muraoka, M. Ichikawa, and T. Nakazato, "Evaluation by Interaural Correlation Coefficient on Spaciousness in Stereophonic Recording and Reproduction Dependent on Microphone Arrangements," *J. Acoust. Soc. Jpn.,* vol. 44, no. 5/6 (2004).

[14] T. Muraoka, T. Nakazato, and M. Ichikawa, "Evaluation of Sound Field Reproduction in Multichannel Recording-Reproducing by Interaural Correlation Coefficient," *J. Acoust. Soc. Jpn.,* vol. 44, no. 10 (2004).

[15] ITU-R BS.775-1, "Multichannel Stereophonic

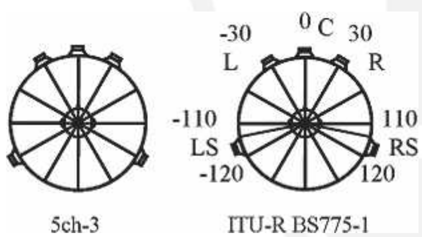

Fig. 32. Loudspeaker placements for configuration [5ch-3] and ITU-R BS.775-1.

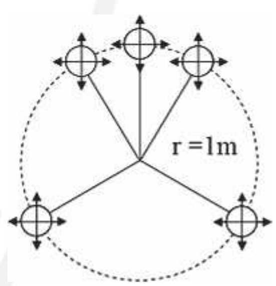

Fig. 33. Proposed ambient microphone array for five-channel sound system.

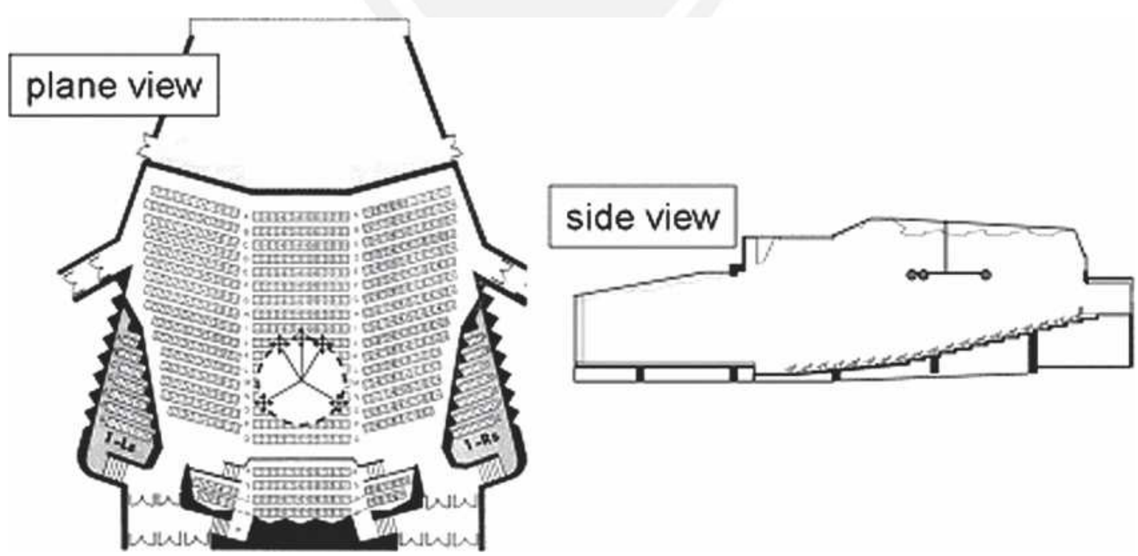

Fig. 34. Ambient microphone array in a concert hall.

Sound System with and without Accompanying Picture," International Telecommunication Union, Geneva, Switzerland (1992).

[16] Y. Yasuda and A. Imai, "On Subjective Diffuseness of Two-Dimensional and Three-Dimensional Diffuse Sound Field," presented at the Spring Meeting of the Acoustical Society of Japan (2002).

APPENDIX 1

Theoretical Calculation of FIACC in Diffuse Sound Field

Let us assume that the listening points M_1 and M_2 (both ears) are located in a space where a plane wave is propagating, as shown in Fig. 35. The distance between M_1 and M_2 is r, and the angle between the line connecting M_1 and M_2 and the line indicating the wave propagation is θ. The sound waves at points M_1 and M_2 are $p_1(t)$ and $p_2(t)$, respectively. They are expressed as

$$p_1(t) = A\cos\omega t$$

$$p_2 = A\cos(\omega t + kr\cos\theta) \tag{3}$$

where ω is the frequency of sound, k is a wavelength constant, and c is the sound velocity.

The cross correlation ρ_0 between $p_1(t)$ and $p_2(t)$ can be derived by substituting Eqs. (3) into Eq. (1), which is the definition of cross correlation,

$$\rho_0 = \frac{\langle A\cos\omega t \cdot A\cos(\omega t + kr\cos\theta)\rangle}{\sqrt{\langle A^2\cos^2\omega t\rangle}\sqrt{\langle A^2\cos^2(\omega t + kr\cos\theta)\rangle}}. \tag{4}$$

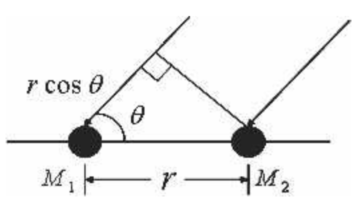

Fig. 35. Incident plane wave.

The numerator in Eq. (4) is rearranged as

$$\begin{aligned}&\langle A\cos\omega t \cdot A\cos(\omega t + kr\cos\theta)\rangle\\ &= \frac{1}{T}\int_0^T A\cos\omega t \cdot A\cos(\omega t + kr\cos\theta)\\ &= \frac{\omega}{2\pi}\int_0^{2\pi/\omega} A\cos\omega t \cdot A\cos(\omega t + kr\cos\theta)\,dt\\ &= \frac{A^2}{2}\cos(kr\cos\theta)\end{aligned} \tag{5}$$

and the denominator is rearranged as

$$\begin{aligned}&\sqrt{\langle A^2\cos^2\omega t\rangle}\sqrt{\langle A^2\cos^2(\omega t + kr\cos\theta)\rangle}\\ &= \sqrt{\frac{1}{T}\int_0^T A^2\cos^2\omega t\,dt}\sqrt{\frac{1}{T}\int_0^T A^2\cos^2(\omega t + kr\cos\theta)\,dt}\\ &= \sqrt{\frac{\omega}{2\pi}\int_0^{2\pi/\omega} A^2\cos^2\omega t\,dt}\sqrt{\frac{\omega}{2\pi}\int_0^{2\pi/\omega} A^2\cos^2(\omega t + kr\cos\theta)\,dt}\\ &= \frac{A^2}{2}\end{aligned} \tag{6}$$

where T denotes the period of the sound. Accordingly, the spatial cross correlation ρ_0 is obtained as

$$\rho_0 = \frac{A^2}{2}\cos(kr\cos\theta)\bigg/\frac{A^2}{2} = \cos(kr\cos\theta). \tag{7}$$

In a diffuse sound field, sound waves with random intensity and frequency travel from random directions. Thus the spatial cross correlation in the two-dimensional diffuse sound field ρ_2d, for example, it obtained by integrating Eq. (7) in the range of $0 \le \theta \le \pi$,

$$\rho_{2d} = \frac{1}{\pi}\int_0^\pi \cos(kr\cos\theta)\,d\theta = J_0\left(\frac{r}{c}\omega\right). \tag{8}$$

In a three-dimensional diffuse sound field the spatial cross correlation ρ_{3d} is obtained as

$$\rho_{3d} = \frac{\sin kr}{kr} = \frac{c\sin[(r/c)\omega]}{r\omega}. \tag{9}$$

The spatial cross correlation values ρ_{2d} and ρ_{2d} are functions of the frequency ω, corresponding to the FIACCs in two- and three-dimensional diffuse sound fields, respectively. The actual FIACC is obtained by setting the equivalent ear distance r, which is known to be 28.5 mm in the two-dimensional sound field and 320 mm in the three-dimensional sound field. (The effects of the shape of the human head are not considered in this analysis.) The theoretical FIACC_(the frequency characteristics of ρ_{2d}) in a two-dimensional diffuse sound field is calculated as shown in Fig. 11.

Fig. 36 shows the FIACC measured in the authors' reverberant room using the dummy head employed in the experiments. The dashed curve represents ρ_{2d}, which is in sufficient agreement within the frequency range below 3 kHz.

The FIACCs in the two- and three-dimensional diffuse sound fields exhibit nearly the same pattern, and the difference in auditory effects is reported to be inaudible [16]. For this reason the authors used the two-dimensional FIACC as the reference.

APPENDIX 2

Synthesis of FIACC by Several Sound Sources

Let us assume that several sound sources are located around a listener's head, as shown in Fig. 37. Here the distances from listener's head to sound sources are sufficiently far, and the sound sources are noncorrelative with each other. S_1 causes the sound pressures $p_{11}(t)$ and $p_{21}(t)$ at the listening points M_1 and M_2, and S_2 causes $p_{12}(t)$, $p_{22}(t)$ at the same points. The cross correlation between M_1 and M_2 is given as follows:

$$\rho = \frac{\langle\{p_{11}(t) + p_{21}(t)\}\{p_{12}(t) + p_{22}(t)\}\rangle}{\sqrt{\langle\{p_{11}(t) + p_{21}(t)\}^2\rangle} \cdot \sqrt{\langle\{p_{12}(t) + p_{22}(t)\}^2\rangle}} \tag{10}$$

where

$$\langle p_{11}(t) \cdot p_{21}(t)\rangle = 0, \qquad \langle p_{12}(t) \cdot p_{22}(t)\rangle = 0 \tag{11}$$

$$\langle p_{11}(t) \cdot p_{22}(t)\rangle = 0, \qquad \langle p_{12}(t) \cdot p_{21}(t)\rangle = 0. \tag{12}$$

Eq. (10) is rearranged as follows:

$$\rho = \frac{\langle p_{11}(t) \cdot p_{12}(t)\rangle + \langle p_{21}(t) \cdot p_{22}(t)\rangle}{\sqrt{\langle p_{11}^2(t) + p_{12}^2(t)\rangle} \cdot \sqrt{\langle p_{21}^2(t) + p_{22}^2(t)\rangle}}. \tag{13}$$

Taking into account that the distance of the sound sources are sufficiently far, the following relationships exist:

$$\sqrt{\langle p_{11}^2(t)\rangle} = \sqrt{\langle p_{12}^2(t)\rangle} = \sqrt{\langle p_1^2(t)\rangle} \tag{14}$$

$$\sqrt{\langle p_{21}^2(t)\rangle} = \sqrt{\langle p_{22}^2(t)\rangle} = \sqrt{\langle p_2^2(t)\rangle}. \tag{15}$$

Furthermore let us define the rms values of the sound pressures due to S_1 and S_2 as L_1 and L_2. Then Eq. (13) can be expressed as

$$\rho = \frac{1}{L_1^2 + L_2^2}(L_1^2\rho_1 + L_2^2\rho_2) \tag{16}$$

where ρ_1 is the FIACC of S_1 and ρ_1 is that of S_2.

By extending this reasoning, we can obtain the FIACC of n-sound sources,

$$\rho = \frac{\sum_{i=1}^{k} L_i^2\rho_i}{\sum_{i=1}^{k} L_i^2} \tag{17}$$

where L_k is the rms value of the sound pressure due to S_k. For example, the FIACC of [4ch-8] can be calculatd by Eq. (17), using those of [2ch-2] and [2ch-5] (or [2ch-3]),

$$\rho_{4ch\text{-}8}(\omega) = \frac{\rho_{2ch\text{-}2}(\omega) + \rho_{2ch\text{-}5}(\omega)}{2}. \tag{18}$$

This relationship is useful to estimate an FIACC pattern without practical measurements. As an example, the synthesis of the FIACC for [4ch-6], when combining [2ch-2] and [2ch-3], is exhibited in Fig. 38. The solid line shows the synthesized value, the broken line the values actually measured.

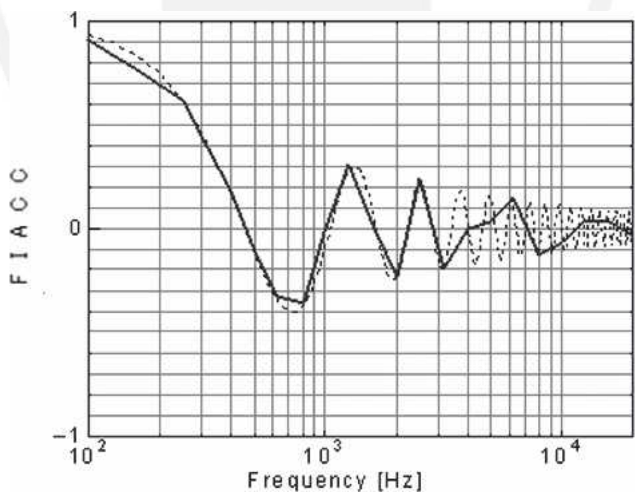

Fig. 36. Actual FIACC in reverberant room.

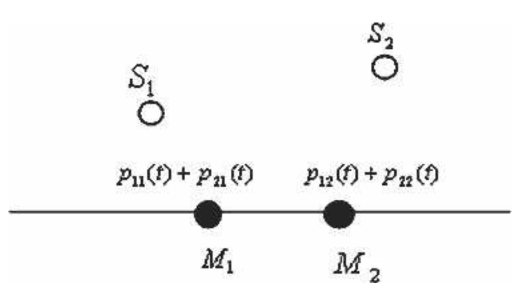

Fig. 37. Sound sources and head of listener.

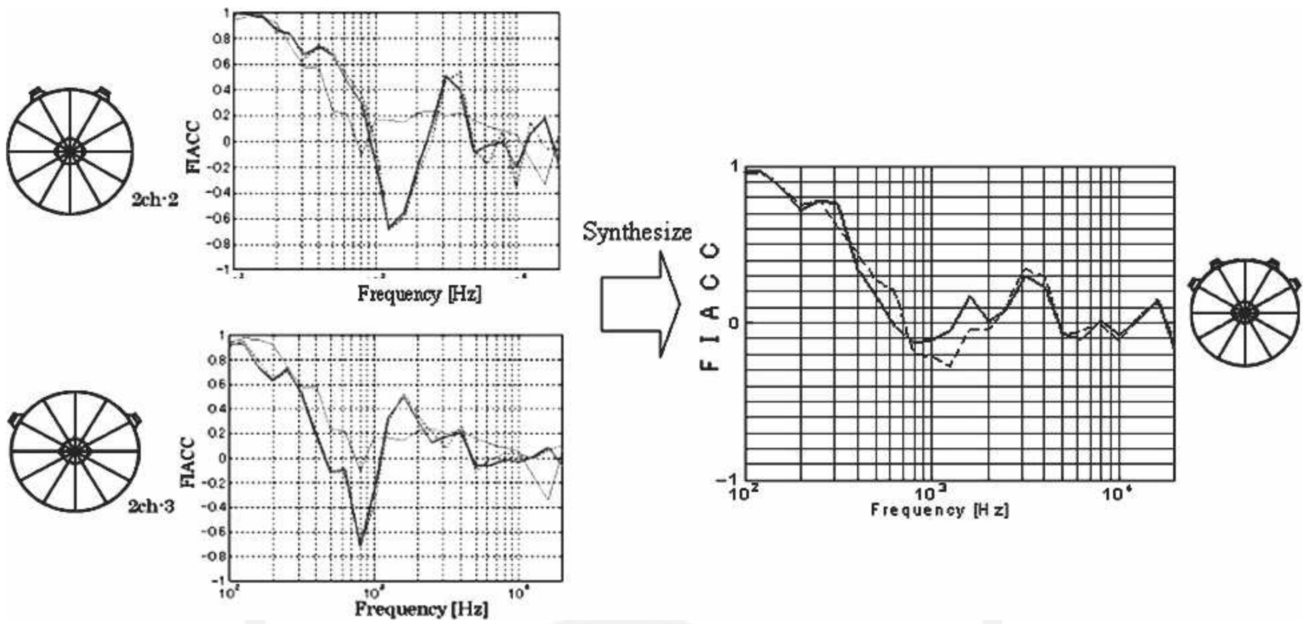

Fig. 38. Synthesis of FIACC.

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●

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