**glossario aes**

3.2
**reference axis**
line that passes through the reference point

NOTE The direction of the reference axis shall be specified by the manufacturer and shall be used as the zero reference axis for frequency response and polar-data measurements.

3.3
**point of rotation**
point about which the loudspeaker or loudspeaker system is rotated in a set of polar-data measurements

NOTE The point of rotation, which should be the same as the reference point as described in 3.1, shall be specified by the manufacturer.

3.4
**acoustic center**
center of curvature of the wave fronts generated by a sound-emitting transducer in its far field

NOTE The acoustic center is frequency dependent and does not include the inherent transducer and sound propagation time delays. Therefore, the acoustic center is not the same as the acoustic or time origin. The acoustic center is primarily of interest in connection with the installation and positional alignment of the individual devices in a sound system. See reference 1, annex E.

3.5
**acoustic origin**
**time origin**
point specified for a given frequency and transducer orientation, lying on the line defined by the observation point and the point of rotation of the transducer, whose distance r from the observation point is such that the total measured phase delay in the signal path, from the input terminals of the transducer to the observation point, is equal to the distance r divided by the propagation speed of sound

NOTE The time origin, which can lie outside and behind the transducer, is primarily of interest in connection with the installation and positional alignment of the individual devices in a sound system. See reference 1, annex E.

3.6
**measuring axis**
line joining the microphone to the point of rotation

3.7 **Frequency response**

| **magnitude response** | generated sound pressure level as a function of frequency, measured under free-field or simulated free-field conditions, with a constant voltage source and at a stated position with respect to the reference axis and point |
|---|---|
| phase response | phase angle of the sound pressure minus the phase angle of the loudspeaker input voltage as a function of frequency, measured under free-field or simulated free-field conditions, with a constant voltage source and at a stated position with respect to the reference axis and point |
| complex data | data for which each data point is represented by a real and an imaginary part or by a magnitude and a phase value |
| transfer function | complex ratio between generated sound pressure and loudspeaker input voltage as a function of frequency, measured under free-field or simulated free-field conditions, with a constant voltage |

| | |
|---|---|
| | source and at a stated position with respect to the reference axis and point |

3.8

**plane polar data**

r.m.s. sound-pressure magnitude, phase, or any quantity related to the direct-sound field from a source as a function of angle (between the measuring axis and the chosen reference axis) and the frequency or frequency band of the radiated sound, measured under free-field or simulated free-field conditions, in a specified plane

3.9

**spherical polar data**

r.m.s. sound pressure magnitude, phase or any quantity related to the direct-sound field from a source as a function of the spherical coordinates describing the orientation of the measuring axis with respect to the chosen reference axis and the frequency or frequency band of the radiated sound, measured under free-field or simulated free-field conditions, on a sphere centered at the reference point

3.10

complex, plane polar data

complex r.m.s. sound pressure as a function of angle (between the measuring axis and the chosen reference axis) and the frequency of the radiated sound, measured under free-field or simulated free-field conditions, in a specified plane

NOTE The complex r.m.s. sound pressure shall be represented by its magnitude and phase or its real and imaginary parts.

3.11

complex, spherical polar data

complex r.m.s. sound pressure as a function of the spherical coordinates describing the orientation of the measuring axis in relation to the chosen reference axis and the frequency of the radiated sound, measured under free-field or simulated free-field conditions on a sphere centered at the reference point

NOTE The complex r.m.s. sound pressure shall be represented by its magnitude and phase or its real and imaginary parts.

3.12

beamwidth

angle between two measurement axes located on either side of the reference axis of a single device, in a plane containing this axis, within which the sound pressure level at the measuring distance has decreased 6 dB with respect to the sound pressure on the reference axis for a given frequency or frequency band
[See 5.3]

3.13

**frequency resolution**

interval equal to 1/T, where T is the length of the impulse response segment used in a fast Fourier transform (FFT) or the length of the equivalent time window used in time-delay spectrometry (TDS)

NOTE This interval is the true frequency resolution. The question of frequency resolution arises when measuring techniques based on digital signal processing such as the FFT are applied. Displayed frequency resolution is given as the sample rate divided by the FFT size. It is thus possible to have a fine display resolution but a rather coarse true resolution in which case the displayed resolution is a simple interpolation of the true resolution.

3.14

**high resolution**

frequency resolution finer than 96th octave

3.15

amplitude smoothing

modification of measured quantities by averaging on a mean-square basis over a band of frequencies

NOTE Amplitude smoothing can be done in successive bands by, for example, using third-octave bands per ISO 266 and their center frequencies, or in a continuous or sliding way by using the FFT bin frequencies as center frequencies. A sufficient number of frequency lines need to be present within a given band in order for smoothing to be valid. This modification is often called "frequency smoothing" or "bandwidth smoothing."

3.16
bandwidth resolution
bandwidth in 1/n octaves, where n = 1, 2, 3, ..., as it is applied in amplitude smoothing

NOTE It should be stated as relative bandwidth in fractional octaves, for example, third octaves.

3.17
angular resolution in stepped polar-data measurements
applied measurement-angle step size in degrees

NOTE Angular resolution in displayed or stored polar data is the displayed- or stored-angle step size in degrees. The applied measurement-angle step size in degrees shall be less than or equal to the displayed- or stored-angle step size in degrees.

3.18
far field
part of the radiated sound field more distant from the radiator in which the inverse-distance law (that is, sound pressure is inversely proportional to distance) is obeyed, as opposed to the near field, where the angular field distribution is dependent on the distance from the radiator
[see 4.2]

3.19
power summation
summation of the squared magnitudes from the individual direction-dependent device transfer functions in which the inverse-distance law losses corresponding to the distances from the devices to the measurement point are included

NOTE Because phase information is not included in the computation, power summation cannot predict cancellation effects in polar patterns and frequency responses.

3.20
complex summation
vector summation of the complex values from the individual direction-dependent device transfer functions in which both the inverse-distance law losses corresponding to the distances from the devices to the measurement point and the corresponding propagation delay times are included

## 4 Measurement of polar data

### 4.1 Measurement environment

To avoid measurement errors caused by sound-reflecting objects, a qualified anechoic chamber as described in annex C should be used as the measurement environment.

Large non-anechoic spaces may be used to simulate a reflection-free environment if certain techniques are applied as described in annex C.

### 4.2 Near-field and far-field measurements

Measurements should be carried out in the far field if the polar data are intended to be applied for distances other than the measuring distance. Far-field conditions can be obtained if the distance r from the sound source fulfills the following requirements:
r 1>> Dmax

r 2/Dmax
where D
max
>> D
max
(1)
and
/??
(2)
is the largest diameter or dimension of the sound source,??? is the wavelength, and r is the distance from the sound source to the measurement location.

True far-field conditions, where pressure is inversely proportionate to distance, can require very large measuring distances. However, far-field conditions may be approximated using the following basic guideline.
The distance r should be determined by using a size factor of 4 in equation 1, giving r 1 = 4Dmax factor of 2 in equation 2 giving r 2 = 2(Dmax
, and a size
) /?. Then, r 1 should be compared with r 2 and the greater of the two
2
values should be used. The reference point for the measuring distance shall be the point of rotation, which for a horn loudspeaker usually lies in the plane of the throat flange and for an enclosed loudspeaker system on the reference axis behind the front baffle. Annex D, citation 4 and annex E, citation 1 contain additional information.

The user is cautioned, however, that preliminary research indicates that far-field measuring distances are a function of the frequency range of measurement, angular range of measurement, loudspeaker type and size, and accuracy. It is not known at this time what possible errors approximated far-field distances can yield, where error is defined as the difference between measurement values obtained in the true far field and those obtained in the approximated far-field.

Near-field measurements shall only be applied to loudspeakers that specifically are intended for near-field applications. If near-field measurements have been applied it shall be so stated in the presentation of the polar data.

## 4.3 Measuring techniques

### 4.3.1 Analog techniques

Conventional polar data that include only magnitude may be measured with analog measuring equipment. The loudspeaker is usually rotated on a turntable and the sound-pressure level is continuously recorded on polar paper. Amplitude smoothing is obtained by driving the loudspeaker with filtered pink noise.

### 4.3.2 Digital techniques

Complex polar data are based on transfer-function measurements, therefore a digital measuring technique should be used (for example, impulse response measurements and FFT or TDS). Amplitude smoothing shall be implemented by the post-processing of raw measurement data. Because transfer-function measurements can only be taken at discrete fixed positions around the loudspeaker, a stepped rotation method with a specified angular resolution shall be applied.

## 4.4 Measurement uncertainty

The uncertainty or accuracy of a compound measurement such as the measurement of polar data is determined by the law of accumulation of uncertainties. In short, that law states that the uncertainty of a compound measurement result, expressed as the error variance (the square of the standard deviation) of the result, equals the sum of the error variances in the partial measuring processes of which the compound measurement is composed.

### 4.4.1 Sources of error

The error sources in the measurement of polar data are found in four partial measuring processes:

a) transformation of the acoustic output from the loudspeaker through the measurement environment (anechoic or simulated anechoic chamber) to the sound pressure at the measuring microphone, a process that includes reflections due to the loudspeaker mounting and rotation equipment as well as uncertainty of the positioning of the loudspeaker relative to the microphone;

b) conversion of the sound pressure to an electrical voltage at the output of the measuring microphone;

c) processing of the microphone signal by an electronic measuring instrument (dedicated or computer-based) in which the processing algorithms can have artifacts or can introduce rounding errors, or both;

d) errors resulting from signal processing, which are under consideration.

Error source 4.4.1(a) probably contributes most to the variance in measured polar data. It is estimated that a qualified anechoic chamber (see annex C) and the mounting and rotation equipment (designed as sound invisible as possible) would contribute a minimum error variance of 1 dB to 2 dB at both low and high frequencies and less at the mid frequencies. The accumulated error variance from error sources 4.4.1(b) and 4.4.1(c) can, with the best measuring microphones and instrumentation, be reduced to about 1 dB from 20 Hz to 20 kHz. Therefore, under the best conditions, the total variance in (or accuracy of) measured polar data is estimated to be 1.5 dB to 2 dB.

NOTE A laser should be used to determine the exact position of the microphone relative to the reference axis of the device to be measured.

### 4.5 Frequency resolution in polar-data measurements and error

Polar patterns or frequency-response curves drawn in a bandwidth resolution of twelfth octave, or coarser, and an angular resolution of 1 ° and derived from data with a frequency resolution of measurement of 36th octave or finer are found to not deviate, on the average, by more than 1 dB from polar patterns or frequency-response curves having corresponding bandwidth and angular resolutions but derived from high-resolution measurement data. This observation assumes that the measured frequency response of each device does not vary more than 25 dB within any octave band in the frequency range of interest. It also assumes a maximum angular resolution in measurement of 1 ° as in 4.6.

4.5.1 Therefore, a frequency resolution of measurement of 36th octave or finer shall be used.

4.5.2 Figures A.1 to A.5 in annex A may be used as guidelines to estimate the frequency resolution with which polar data should be measured given frequency-response variation and user-selected values of bandwidth resolution, and average and maximum error.

4.5.2.1 User-selected values shall maintain compliance with clause 5.

4.5.2.2 Users shall state the selected values with any presented data.

NOTE Annex D, citations 3, contains additional information.

### 4.6 Angular resolution in polar-data measurements and error

An angular resolution of measurement of 1 ° or finer shall be used. See application in 4.5.

NOTE Annex D, citation 3, contains additional information.

## 5 Presentation of measured data

### 5.1 Bandwidth resolution in polar-pattern presentation and error

Polar data presented in a bandwidth resolution of twelfth octave and an angular resolution of 1° will not differ, on the average, more than 4 dB from the high-resolution measured data from which the amplitude-smoothed data were derived. The average error associated with sixth-octave-bandwidth-resolution polar patterns is about 8 dB and the average error associated with octave-bandwidth-resolution polar patterns is about 12 dB.

Annex
B contains additional information about error definition and error calculation.

5.1.1 Therefore, a bandwidth resolution no coarser than twelfth octave should be used in polar-pattern presentation.

5.1.2 Figure B.1 in annex B may be used as a guideline to choose the bandwidth resolution for presentation of polar data based on user-selected error values that shall be stated as in 4.5.

NOTE Annex D, citations 3, contains additional information.

### 5.2 Angular resolution in polar-pattern presentation and error

When the bandwidth resolution is held constant at twelfth octave and the angular resolution is varied to 2°, 5°, and 10°, significant deviations from twelfth-octave, 1° resolution polar patterns can be observed. On the average, errors of 2.3 dB are seen with a 2° angular resolution while the average error increases to 6.5 dB with a 5° resolution and to 9.2 dB with a 10° resolution. These errors, however, refer only to the depth of the nulls (see annex B). When the angular resolution is decreased from 1°, jagged polar patterns are produced. Additional smoothing would have to be applied to make these polar patterns look rounded instead of jagged. This
smoothing, however, would increase the error associated with these polar patterns by an amount dependent on the technique and extent of smoothing applied.

5.2.1 Therefore, an angular resolution of 1° should be used in polar-pattern presentation.

5.2.2 Figure B.2 in annex B may be used as a guideline to choose the angular resolution for presentation of polar data based on user-selected error values.

NOTE Annex D, citations 3, contains additional information.

### 5.3 Beamwidth-chart presentation

5.3.1 Because beamwidth charts are used only in a general way to show the sound coverage of a single device or an array of devices, a coarse resolution of one octave and 5° should be used to smooth the data from which the beamwidth will be determined.

5.3.2 The tolerance of the beamwidth is described by the errors associated with the frequency resolution and angular resolution applied to the data from which the beamwidth is determined as shown in Figures B.1 and
B.2 in annex B, but need not be stated with the presentation of the beamwidth.

5.3.3 The common description of a horn as an X by Y horn (for example, a 60 by 40 horn) shall be supplemented by descriptors of both the angular resolution and the bandwidth resolution that have been applied to the data from which the beamwidth is determined, as well as descriptors of the frequency range over which the stated beamwidth exists.

5.3.4 The descriptors in 5.3.3 shall be stated with the presentation of the beamwidth chart.

## 6 Application of measured polar data for direct-field sound-system modeling

### 6.1 Frequency resolution of measurement and accuracy in predictions

When measuring a single device for the purpose of making direct-field array predictions, a frequency resolution of 36th octave or finer and an angular resolution of 1 ° or finer shall be used to predict twelfth-octave or coarser resolution, r.m.s.-averaged array polar patterns or frequency responses. Such predictions will not deviate more than 3 dB from array polar patterns or frequency-response curves drawn with corresponding resolutions but derived from high-resolution measurements on actual arrays.

NOTE This requirement does not include production tolerances and assumes that the high-resolution frequency response measured from the actual device does not vary by more than 30 dB within any octave band in the frequency range of interest. Interference effects between the devices in an array (sound shadowing and scattering) are also not included in this requirement.

## 6.2 Prediction and interference effects (sound shadowing and scattering)

Significant interference effects can occur depending on the mutual placement of the individual devices in an array. The prediction of interference effects is generally not feasible with sufficient accuracy. Research and development of new methods are needed in this area. Predictions of reasonably accurate array polar patterns and frequency responses are therefore usually limited to the frontal hemisphere of an array in the angle range ± ° around the main axis of the array. Specific values of cannot be given as ø depends on the geometry of the array and the mechanical design of the individual devices in an array.

NOTE Annex D, citation 3, contains additional information.

## 6.3 Power summation compared with complex pressure-summation techniques

Complex summation and power summation can produce results that deviate from one another by as much as 16 dB. Deviations of more than 20 dB can occur between high-resolution power-summation predictions and measurements. If a third-octave- or octave-bandwidth resolution is applied, the complex summation and the power summation can be expected to differ by no more than about 1 dB in the frequency range where the difference between the distances from each of two devices to the observation point is more than about 2??. The corresponding propagation-time difference is large enough to decorrelate the two signals arriving at the observation point, and power summation therefore may be used. At low frequencies, where the difference between the distances from each of two devices in the array to the observation point is much less than???/2, simple summation of the magnitudes of the pressures, which is a special case of complex-pressure summation, can work much more precisely than power summation and should be used.

Complex summation can predict, in a twelfth-octave bandwidth or coarser, array performance (polar patterns and frequency response) with a deviation of no more than 3 dB from the directly measured performance, in the corresponding bandwidth resolution, twelfth octave or coarser, if the frequency resolution of the measurements to be summed is 36th octave or finer and their angular resolution is 1 ° or finer, and if there are no interference effects (sound shadowing or scattering) between the devices in the array. It is still assumed that the measured levels in the data do not vary by more than 25 dB to 30 dB within each octave band that complies with ISO 266 from 1 kHz to 10 kHz. Complex summation should therefore be used, if possible.

NOTE Annex D, citation 3, contains additional information.

## Annex A
(normative)

## Amplitude-smoothing error as a function of frequency resolution of measurement

When digital measuring techniques are used, raw measurement data are usually post-processed to generate amplitude-smoothed frequency responses and polar patterns for data presentation. As a result, an amplitude- smoothing error arises from the post-processing, which is in part a function of the ratio between the frequency resolution of measurement and the bandwidth resolution of data presentation.

To prepare this document, a series of off-axis transfer functions were measured for single devices and two- device arrays. These data were measured with high resolution. Post-processed transfer functions, with frequency resolutions of 96th, 48th, 24th, twelfth, and third octave, were computed from the high-resolution measurement data for different off-axis positions. These fractional-octave frequency resolutions were derived by skipping data points in the high-resolution transfer functions such that, in each case, the fractional-octave frequency resolution remained constant over the frequency range. Although this condition was achieved by post-processing the measured data, the result is as if the data had actually been measured at 96th-, 48th-, 24th-, twelfth-, and third-octave frequency resolutions.

Next, from these selected fractional-octave-frequency-resolution transfer functions, amplitude smoothing was used to compute frequency responses in twelfth-, sixth-, third- and octave-bandwidth resolutions. Each of these amplitude-smoothed curves was compared to a curve with a corresponding bandwidth resolution but derived directly from the high-resolution, unprocessed, measured data.

Amplitude smoothing errors, defined as differences in the absolute values of the levels in decibels between each of the two curves with a corresponding bandwidth, were tabulated. These errors were found to vary with frequency, so for each frequency response both maximum and average errors over the frequency range were determined.

Figures A.1 to A.5 result from exponential curve fitting. The error data to which the curves were fit were calculated for a variety of array types at varying off-axis locations. The range of level variation in the frequency responses from which the error curves in Figures A.1 to A.3 are derived is 25 dB to 30 dB. This range is typical of off-axis array behavior and is caused by the interfering sound-pressure contributions from different array devices. Additional error curves, shown in Figures A.4 and A.5 for twelfth-octave-bandwidth, amplitude- smoothed frequency responses, were computed from frequency responses having approximate level variation ranges of 5 dB, 25 dB, and 40 dB.

Sample off-axis frequency responses should be measured in compliance with 4.5.1 to determine the range of level variation of the device or devices to be measured.

Figures A.1 to A.5 should be used as follows. If the bandwidth resolution of presentation is chosen to be twelfth octave and the range of level variation in the frequency response of the device or devices is 25 dB to 30 dB, use Figure A.1. Figure A.1 shows that for frequency responses presented in twelfth-octave-band resolution, a frequency resolution of measurement of 36th octave yields an average amplitude-smoothing error of 1 dB and a maximum amplitude-smoothing error of 4 dB. Figures A.4 and A.5 can be used for different ranges of level variation in the frequency response. If the bandwidth resolution of presentation is chosen to be third octave and the range of level variation in the frequency response of the device or devices is 25 dB to 30 dB, use Figure A.3. Figure A.3 shows that for frequency responses presented in third-octave-band resolution, a frequency resolution of measurement of twelfth octave yields an average amplitude-smoothing error of 1 dB and a maximum amplitude-smoothing error of about 3.8 dB.

The overall post-processing error in polar-data presentation is a compound error consisting of the amplitude- smoothing error shown in Figures A.1 to A.5 as well as the errors discussed in annex B.

Therefore, for a given bandwidth resolution of presentation (see annex B), Figures A.1 to A.5 should be used to determine the frequency resolution of measurement necessary such that average amplitude-smoothing errors of 1 dB or less are incurred.

NOTE Annex D, citations 3, contains additional information.

8.00
7.00

6.00
5.00

4.00

3.00
2.00

1.00
0.00
1/96
1/48

Frequency resolution of measurements in octaves
1/24

Figure A.1 - Amplitude-smoothing error versus frequency resolution of measurement for computed twelfth-octave-band frequency responses; upper curve: maximum error, lower curve: average error

8.00

7.00

6.00

5.00

4.00

3.00

2.00

1.00

0.00
1/96
1/48
1/24
1/12
Frequency resolution of measurement in octaves

Figure A.2 - Amplitude-smoothing error versus frequency resolution of measurement for computed sixth-octave-band frequency response; upper curve: maximum error, lower curve: average error

10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
1/96 oct
1/48 oct
1/24 oct
1/12 oct
1/6 oct
Frequency resolution of measurements in octaves

Figure A.3 - Amplitude-smoothing error versus frequency resolution of measurement for computed third-octave-band frequency response; upper curve: maximum error, lower curve: average error

16

14

12

10

8

6

4

2

0
1/96
1/48

Frequency resolution of measurement in octaves
1/24
Figure A.4 - Maximum amplitude-smoothing error versus frequency resolution of measurement for computed twelfth-octave-band frequency response with three different ranges of level variation; upper curve: 40 dB, middle curve: 25 dB, lower curve: 5 dB

4.00

3.50

3.00

2.50

2.00

1.50

1.00

0.50

0.00
1/96
1/48

Frequency resolution of measurement in octaves
1/24
Figure A.5 - Average amplitude-smoothing error versus frequency resolution of measurement for
computed twelfth-octave-band frequency response with three different ranges of level variation; upper curve: 40 dB, middle curve: 25 dB, lower curve: 5 dB

## Annex B
(normative)

## Errors in polar data presentation as a function of bandwidth and angular resolution

When polar data are collected using digital measuring techniques, the raw measurement data are usually post- processed to generate amplitude-smoothed polar patterns or frequency responses for presentation. Errors, in terms of loss of information, arise as higher resolution measurement data are averaged together to generate lower resolution amplitude-smoothed data. Errors also arise in polar-pattern presentation as a function of the angular resolution with which polar data are gathered. These errors in combination with the amplitude-smoothing error discussed in annex A constitute the overall post-processing error in polar-data presentation.

To prepare data for this document, a polar pattern for a simple two-horn array at a given center frequency was drawn directly from raw measurement data in an angular resolution of 1° and a frequency resolution of 36th octave or finer. Next, holding the angular resolution constant at 1°, r.m.s.

averaging techniques were used to draw a series of polar patterns with varying bandwidth resolutions: twelfth octave, sixth octave, third octave, and octave. For each given center frequency, comparisons were made between each of the amplitude-smoothed polar patterns and the polar pattern drawn directly from the measurement data.

In addition, another series of polar patterns were drawn and compared in which the bandwidth resolution was held constant at twelfth octave while the angular resolution was varied to 2°, 5°, and 10°. Varying angular resolutions were achieved by skipping data points as if measurements had only been made every 2°, 5°, or 10°.

From these comparisons, average and maximum errors were determined by calculating the amount by which the depth of all the nulls in a given polar pattern decreased as the resolution decreased. These errors were calculated for a variety of horns in different array formations and at different center frequencies and are shown in Figures B.1 and B.2. The curves in Figures B.1 and B.2 are the result of logarithmic, polynomial, and linear curve fitting.

Similar comparisons were made between amplitude-smoothed and non-smoothed frequency responses, measured both on- and off-axis for single horns and two-horn arrays. From these comparisons, average and maximum errors were determined by calculating the amount by which the depth of the nulls decreased as the bandwidth resolution decreased. These calculations yielded the same results as those shown in Figure B.1, assuming that the range of level variations in the frequency responses is about 25 dB and that only nulls with a width of sixth octave or wider were considered.

NOTE Annex D, citation 3, contains additional information.

14.00

12.00

10.00

8.00

6.00

4.00

2.00

0.00
1/12
1/6
1/3
1
Bandwidth resolution in octaves
Figure B.1 - Average presentation error versus bandwidth resolution with a constant-angular resolution
25.00

20.00

15.00

10.00

5.00

0.00
1
2
3
4
5

6
7
8
9
10
Angular resolution in degrees

Figure B.2 - Presentation error versus angular resolution with a constant-bandwidth resolution of twelfth octave; upper curve: maximum error, lower curve: average error

## Annex C
(normative)

## Measurement environment

### C.1 Qualification of an anechoic chamber

Anechoic chambers may be qualified by establishing the frequency and distance range in which measurement results do not deviate by more than 1 dB from the sound-pressure level described by the free-field inverse-distance law (that is, sound pressure from a point source is inversely proportional to distance). Such a qualification is usually satisfactory for on-axis loudspeaker frequency-response measurements.

However, for polar-data measurements on directive loudspeakers, the inverse-distance-law qualification procedure is inadequate. With certain high-directivity loudspeakers there is a risk in off-axis measurements that the first-order reflections arriving at the measurement microphone can interfere with the directly arriving off-axis sound, thereby creating measurement errors in the polar data.

Based on impulse-response measurements on high-directivity horns, to get measuring errors that are less than 1 dB, reflections in an anechoic chamber shall not increase the energy of the impulse response, in the 50-ms range after the arrival time of the first reflection, by more than 1 dB. The 1-dB energy requirement means that the reflection coefficient (the pressure of the reflected wave divided by the pressure of the incident wave) of the absorption material in the anechoic chamber must be less than 0.05 (the absorption coefficient must be greater than 0.9975). Such values of reflection or absorption coefficient can be realized by the use of suitable wedge-shaped absorbents. Annex D, citation 1, contains additional information. Annex D, citation 2, describes a method for in-situ measurements of the reflection coefficient of the absorption material in an anechoic chamber.

### C.2 Simulated anechoic environment

Large non-anechoic spaces may be used to simulate a reflection-free environment by putting a time window on a measured impulse response before applying a FFT or by using TDS measurements to exclude the reflections.
However, these techniques have limitations related to the size of the measuring space.

The length T of the time window determines the frequency resolution of measurement as 1/T. 4.5 states that a measurement resolution of 36th octave shall be used; 36th octave at 1 kHz corresponds to a measurement resolution of 20 Hz, which requires a time window of 50 ms. The time window corresponds to a difference in distance between the distance from the loudspeaker via a reflection point to the microphone and the direct distance between the loudspeaker and the microphone. Therefore, in conformity to 4.5, to use a 50-ms time window the difference shall be more than 17.2 m. At low frequencies, the necessary measuring space can be unrealistically large.

The 36th-octave frequency resolution of measurement and thus the derived space requirements assume a level variation of 25 dB to 30 dB within each octave band of interest. If the level variation is less than 25 dB to 30 dB, which often is the case at low frequencies, the necessary frequency resolution of measurement is reduced as indicated in Figures A.4 and A.5 in annex A. This means that the necessary size of the measuring space is also reduced.

Further reductions in the frequency resolution of measurement can be gained by applying the technique of adding augmenting or padding zeros to the sampled impulse response. The maximum length of the time window to which an impulse response can be subjected in order to exclude reflections from the boundaries of the measuring space is determined by the size of the measurement space itself. A given measuring space will thus define a maximum T, which again defines a maximum frequency resolution. Though this resolution may not be fine enough according to the arguments set forth in 4.5, T can be increased artificially by adding augmenting zeros to the sampled impulse response as a cure for inadequate frequency resolution.

If $f_s$ is the sampling frequency and $N_s$ is the number of samples corresponding to $T = N/f$ and the frequency resolution $f = 1/T$, then the number of augmenting zeros $N_z$ is chosen to yield the desired resolution $f_0 = f_s/(N_s + N_z)$.

For example, the frequency response of an array of three two-way enclosures has been measured in an anechoic chamber 30° off-axis with a frequency resolution of measurement of 3.7 Hz. 3.7 Hz corresponds to a time window T = 270.3 ms, which would require an unrealistically large non-anechoic measuring space. A time window of 23 ms would include the important portion of the impulse response and would reduce the necessary size of a non-anechoic measuring space considerably. A time window of 23 ms corresponds to a sound-propagation path difference between direct and reflected sound of 7.9 m. However, a direct FFT of the impulse response would create a frequency response that, at low frequencies, would be too coarse, because 23 ms corresponds to a frequency resolution of 43.5 Hz. Augmenting the 23-ms impulse response to a 270.3-ms impulse response by adding zeros will, however, after application of the FFT, yield a satisfactory frequency response. In an example shown in annex D, citation 3, the 23-ms impulse response is transformed by a 1408-point FFT while the augmented 23-ms impulse response, now a 270.3-ms impulse response, is transformed by a 16384-point FFT.

As a provisional rule of thumb, measurement results based on a short time window and the augmenting zero technique can deviate less than 1 dB to 2 dB from true high-resolution measurement results above the frequency that is equal to 2 divided by the length of the short time window. Deviations between true-anechoic high-resolution frequency-response measurements and simulated-anechoic frequency-response measurements using the augmenting-zero technique can appear at low frequencies. In the example given, the deviation reaches a maximum of 3 dB at 40 Hz . The dependency of the deviation on the length of the time window is significant and needs further research. Caution should therefore be taken when a short time window and the augmenting-zero technique are applied.
s s

## Annex D
(informative)

## Bibliography

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2) KUTTRUFF, H. and BRUCHMÜLLER, HG. On Measuring Technique for the Examination of Anechoic Rooms. Acustica, 1974, vol. 30, no. 6, p. 342-349. (Abstract in English, text in German.)

3) SEIDEL, F. and STAFFELDT, H. Frequency and Angular Resolution for Measuring, Presenting and Predicting Loudspeaker Polar Data. J. Audio Eng. Soc, July/August 1996, vol. 44, no. 7/8, p. 555-568.

4) BERANEK, LL. Acoustics. New York : American Institute of Physics, 1986.

## Annex E
(informative)

## Informative references

1) AES2-1984, AES Recommended Practice - Specification of Loudspeaker Components Used in Professional Audio and Sound Reinforcement. New York : Audio Engineering Society, 1984.

2) IEC 268-5, Sound system equipment, Part 5: Loudspeakers. Geneva, Switzerland : International Electrotechnical Commission, 1989.

3) IEC 1260, Electroacoustics - Octave-band and fractional-octave-band filters. Geneva, Switzerland : International Electrotechnical Commission, 1995.

## Annex F
(informative)

## Comments on draft of document

This annex contains comments received during the period of the call for comment, together with replies to those comments. The comments are included to provide additional information or to satisfy the objections of the commenters, or both.

### F.1 Comments of W. A. Anhert, 1996-09-06

### F.1.1 Comments offered based on participation in working group

[Comments edited from original copy.]

My objection to the draft is based on own experiences in addition to discussions with Professor Blauert in Bochum, who has been supervising a Ph.D. thesis by Frank Giron of the Ruhr University, titled "Investigations
1) I object to 4.6. "An angular resolution of measurement of 1 ° or finer shall be used." According to the work of Giron, the angular resolution is size dependent. The bigger the loudspeaker the higher must be the angular resolution to model a speaker. Mr. Giron has measured in the time domain with an upper frequency limit. He developed a formula to reproduce an optimum number to measure around a loudspeaker.

For very high frequencies (normally not modeled) it reveals a resolution of 1. Accordingly, if you work always with a resolution of 1 you can work with a maximum loudspeaker dimension of 2 m at a frequency of 10 kHz (upper limit of modeling). Perhaps, if the draft is intended exclusively for such large loudspeakers it can be applicable.

2) The frequency resolution is not considered directly in the Giron thesis. His measurements are in the time domain. Because such measurements are normally done with computer-controlled devices (MLSSA, TEF, etc.) one will always have the time response measured to a certain angular resolution. A modeling program software can then be allowed to deviate to its own resolutions.

Because of memory restrictions in PC computers I believe that while sixth-octave resolution is sufficient, we have to live with third-octave resolution. EASE for Windows, for example, is intended to make possible special investigations in higher frequency resolution. However, usually we work with third-octave resolution. From psychoacoustical investigations we also know that dips and notches that are not visible during third-octave averaging are more or less inaudible even for educated sound engineers.

Why should we make greater efforts than our ears can deal with? I hope you will understand that this draft should be modified. For me it is an approach based on measurements only including optical comparisons. I would like to ask the authors of the draft to read the work of Giron better to understand the needs and the background in order to formulate a rule measuring loudspeaker data for loudspeaker modeling.

### F.1.2 Reply by working group chairs , 1997-01-13

We have examined the Ph.D. thesis by Frank Giron: Investigations about the directivity of sound sources. (Shaker Verlag, Aachen, Germany 1996).

#### F.1.2.1 Comment 1

We have studied the report and must conclude that the procedure quoted for the determination of the number of measuring points on the measuring sphere is not applicable for the type of far-field measurements dealt with in this document.

The quoted procedure is related to measurements made in spherical acoustic holography in the transition region between near field and far field, i.e., in the proximity of a loudspeaker. The data from such measurements cannot be used directly but can only, through extensive mathematical transformations and under a set of theoretically based assumptions applied in spherical acoustic holography, be used to obtain the far-field sound pressure and directivity pattern of a loudspeaker. The Ph.D. report demonstrates this application on two loudspeakers, but the predicted far-field results are not compared to data measured directly in the far field, so the accuracy of the method cannot be evaluated.

If the quoted procedure is tried on the two-horn parallel array having the polar pattern shown in Figure 8 in Seidel and Staffeldt (annex D), the number of measuring points on the measuring sphere should be 1470 for the array dimension 0.74 m and the frequency 4 kHz. 1470 measuring points correspond to an angular resolution of approximately 6°, which, by comparison with the polar pattern in the cited Figure 8, clearly shows that the quoted procedure is underestimating the number of measuring points and the angular resolution.

F.1.2.2 Comment 2

We will still, based on our investigations, maintain that a measurement frequency resolution of 36th octave is needed so that polar patterns and frequency responses presented with a bandwidth resolution of twelfth octave do not vary by more than 4 dB from high resolution data. AES-5id-1997 is not addressing psychoacoustic criteria. It is only making objective statements about errors.

We do not think that there are any problems concerning memory and data storage with modern computers applying high-density hard disks and CD-ROMs.

F.2 Comments of R. F. Campbell, 1996-09-15

I would like to report on a related research effort sponsored by Eastern Acoustic Works (EAW) that is being carried out by five Worcester Polytechic Institute (WPI) students as their major undergraduate project. This major qualifying project (MQP) group is attempting to design and build a loudspeaker measuring system along the general description of the desires of the AES SC-04-03 working group in committee reports and of the draft document cited.

The work is divided into five major sections:

a) a motor control system capable of accurately positioning a heavy and large loudspeaker;

b) a microphone array consisting of inexpensive but long-term stable miniature electret microphones, including preamplifiers and a calibrator;

c) a high-speed multi-channel data acquisition system which is tightly coupled to both the positioning system and the MLS signal processor; the current design is 100 Hz to 20 kHz, 8 channels, 12-bit data with correctable time skew;

d) a signal processing element consisting of an MLS generator with acquired-signal post-processing to the impulse response, data storage management, and acquisition control;

e) a data analysis and display element, which produces global loudspeaker radiation data sets suitable for AES-5id presentation as, envisaged by SC-04-03.

This project is just now getting under way, so there is little detail to report. The MQP final report will be written in 1997-04. EAW is sponsoring this research because, like all other loudspeaker manufacturers, it is concerned about the vast increase in data density specified by the working group and the amount of time it will take to acquire and process these data as a routine chore for production loudspeaker design and manufacturing.

F.3 Comments of M. Gander, 1996-10-23

F.3.1 Comments offered based on participation in working group

a) There is no recommendation or discussion of the need for differences in angle and bandwidth over different frequency ranges. It would seem that less resolution is required as frequency decreases, for multiple sources of a given source size and separation.

b) No psychoacoustic criteria. "How does it sound?" Just because fingering is visible in measurement data, it may or may not mean it is psychoacoustically relevant.

c) Practical viability. The requirements of twelfth-octave-bandwidth resolution and 1° angular resolution require massive data gathering and storage capability. The signal-to-noise requirements of such narrow resolution can also demand prohibitively expensive, and hence potentially exclusionary, synthetic anechoic environments and instrumentation. Even if the above-listed items (a) and (b) were fully explored, and ultimately indicated the desirability of that level of data collection, it would present a barrier to entry to most practitioners and manufacturers, many of whom could not afford to make or utilize the measurements.

In the event that this degree of detail is ultimately determined to be necessary, I would propose that a two-tiered system be employed, where level 1 measurement detail would represent twelfth-octave-bandwidth and 1° angular resolution, and level 2 measurement detail would represent third-octave and 5° resolution.

F.3.2 Reply by working group chairs, 1997-06-30

F.3.2.1 Comment a

Given the tremendous variety of existing loudspeaker configurations, from a single non-enclosed device to multi-way enclosed systems, it would require many measurements on many systems to determine whether or not recommendations could be made as to decreasing the frequency or angular resolution of measurement for different types of systems over different frequency ranges. Even if such recommendations could be made, the recommendation would include a number of preliminary measurements necessary to determine if a device or a system of devices is qualified for lower resolution measurements. There is no certainty that all this would result in a simpler measuring process.

However, this point is addressed to some extent in annex A. Figures A.4 and A.5 indicate that the smaller the amount of level variation in a frequency response, which tends to be the case at lower frequencies, the smaller the amplitude smoothing error is, and therefore a lower frequency resolution of measurement is possible.

Annex A has been amended to better assist the user in the selection of the right measurement resolution.

### F.3.2.2 Comment b

AES-5id-1997 is based on objective criteria only and this will be clarified by the addition of the following sentence in the abstract and scope.

The information presented here is based on objective measurements and does not take subjective or psychoacoustic criteria into account.

### F.3.2.3 Comment c

The purpose of an information document is to make information available. The information available in it should not be limited due to possible costs of implementation. This is not a standard recommended practice, it is an information document.

Further research is needed to determine what should distinguish a level 1 from a level 2 in a two-tiered system. Having two levels implies we know the resolution that should be given for all the criteria including psychoacoustic criteria, but that is not yet the case. As the document is written now, it simply states the possible errors or deviations associated with different measurement, presentation and prediction resolutions in the direct field of sound sources. It is intended at this time only to say that if you measure, present, or predict in the direct field with such and such a resolution, you can see errors or differences from high resolution data as high as such and such.

We are not currently prepared to say more than that, but it is noted that this is a direction in which the document could evolve with more research.

## F.4 Comments of S. Berkow, 1996-11-05

### F.4.1 Comments submitted in response to published call

The work regarding the resolution of polar measurements of loudspeakers published by Seidel and Staffeldt (annex D) provides valuable insight into the need for accurate measurements of loudspeakers. However, a careful reading of the paper reveals a significant oversight in the development of the conclusions presented.

To review: The goals outlined in the paper were to explore and define the resolution required when acquiring polar data for a loudspeaker or array of loudspeakers. It is indicated that a major use of these data is electro-acoustic modeling programs. The research done was based solely on objective measures. Subjective issues will hopefully be raised separately.

It is my opinion that an important objective measure was overlooked when defining the conclusions presented in the paper: the acoustical environment in which the system is to be modeled. I believe this is a substantial oversight. It is my opinion that consideration of the acoustical environment will NOT invalidate the work done to date. Rather it will act to help further refine the conclusions presented in the proposed standard.

Consider the following: If a user makes high-resolution measurements (consider third-octave frequency, 5° angular), the paper suggests that it is possible to know or limit the expected errors with regard to even higher resolution measurements. The implicit assumption is that the measurements made are made in an anechoic acoustical environment! A legitimate question to ask is, will the errors encountered by reducing either angular or frequency resolution be measurable in a room with a real (non-anechoic) acoustical environment? This is a particularly important question in light of the fact that this standard will strongly influence data with which electroacoustical modeling programs calculate the complex performance of large arrays of loudspeakers in rooms.

This discussion raised three important objective questions:

a) what measurement resolution is sufficient to limit errors in a target acoustical environment;
b) what data must be collected and presented by loudspeaker manufacturers;
c) what resolution data must be used in calculations by electroacoustic modeling programs for the calculations to be measurable?

While I do not offer a solution to these questions in this note, in light of the published results there are several well-known acoustical models which could be used to determine (or approximate) the errors encountered when using polar data of a given resolution (both angular and frequency) in a specified acoustical environment. In practice the acoustical environment could be included by specification of such objective parameters as the direct-to-reverberant ratio of the target acoustical environment, or the distance from the measurement point or plane to the closest acoustically reflective surface. Such values could be used to indicate the maximum resolution required for modeling within a selected expected error range.

Please note that the work of this committee will influence the actions of both loudspeaker manufactures and contractors/consultants. In each case, I believe it is the intent of all parties to provide data and models which use the maximum resolution required to achieve accuracy without having to spend undue amounts of time, computer power, or dollars measuring polar data or calculating simulation values to a resolution which cannot be measured in the field.

F.4.2 Reply by working group chairs, 1997-07-09

The foreword and scope are modified to better reflect the fact that the acoustical environment and the modeling of sound sources in reverberant spaces are not subjects within the scope of AES-5id-1997.

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