# Room acoustic measurement methods in the past, present and future, including the importance of the ISO 3382 series

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The measurement of reverberation time in a room was introduced by W.C. Sabine a few years before 1900 with the purpose to handle acoustic problems in a lecture theatre. The sound source was organ pipes at the seven octave frequencies from 63 Hz to 4000 Hz. Later, the measurements were greatly improved by using interrupted white noise emitted by a loudspeaker and a microphone connected to a level recorder that could display the decay curve. This led to the first international standard on reverberation time measurements in 1963, intended for laboratory measurements of the sound absorption coefficient of materials. In 1975 appeared another international standard intended for reverberation time measurements, primarily in rooms for speech and music. A revision in 1997 introduced the impulse response as a basis for room acoustic measurements. This opened up for derivation of other room acoustic parameters than the reverberation time, and this again led to a better understanding of how to design good rooms for music and speech. Some types of rooms are not sufficiently characterised by the reverberation time, and for that reason a new standard appeared in 2012 with a measurement method specifically intended for open-plan offices. Future development of room acoustic measurements may include faster and more reliable methods, better methods to overcome problems at low frequencies, a method to handle the influence the high-frequency problem of varying temperature and humidity of the air, and new ways to derive three-dimensional information on the sound reflections in a room.

## 1 Introduction

This paper presents a brief overview of room acoustic measurements and how the methods have developed during the last 125 years. The emphasis is on the major milestones that mark significant improvements. During the last 60 years, international standards on measurement methods have played an important role for promoting new and improved methods. The list of references is made with the intention to point at the origin of the measurement methods and the room acoustic parameters.

## 2 The early days of room acoustic measurements

Wallace C. Sabine (1868-1919) is known as founder of room acoustic measurements around 1900. He introduced the concept of reverberation time, defined as the time for the sound intensity in a room to decay to 1/1.000.000 of the initial intensity after a sound source is turned off [1]. The measurements were performed with specially constructed organ pipes as sound sources and a chronograph (stopwatch) to measure the audible decay time. The organ pipes were of the type *gemshorn*, which have a strong fundamental tone and relatively weak overtones. Sabine could calculate the reverberation time related to 60 dB decay by a very clever method. He used four identical sets of organ pipes, and could then measure the audible decay time using one, two, three or all four organ pipes as the sound source. This gave different results because the initial energy was different. For example, the initial sound level is 6 dB higher with four organ pipes compared to one organ pipe; thus, the reverberation time is ten times the difference in audible decay time for the two measurements [1]. The frequencies of the organ pipes were at seven octaves from 64 Hz to 4096 Hz, corresponding to the music tones C. Later, more organ pipes with the tones E and G were included, so measurements could be made in approximately one-third octave intervals. This was meant for laboratory measurements of sound absorption of materials [2].

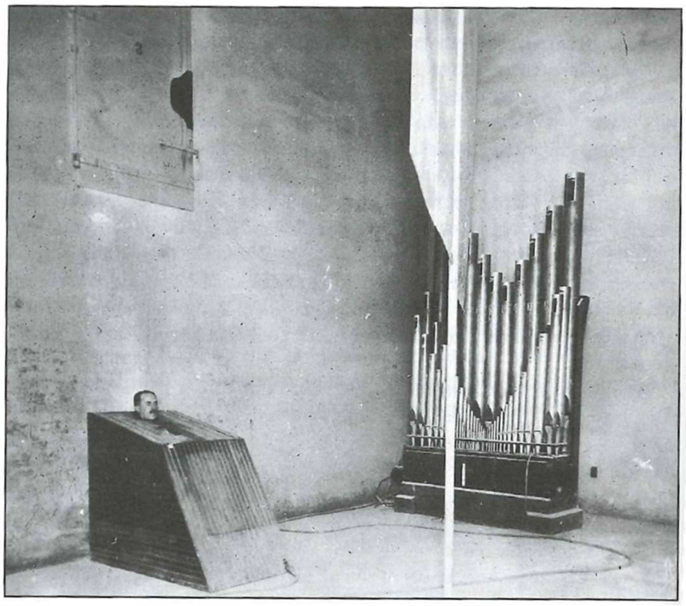

Figure 1: Conducting an absorption test in the reverberation chamber, 1919. From Kopec [2] p. 64.

In Figure 1 is seen the setup for an absorption test in the large reverberation chamber at the Riverbank laboratories. The operator is sitting in a box in order to minimize the absorption from clothing. The rotating fan seen in the photo was used to increase the diffusion. Paul E. Sabine continued the work with acoustic measurements after the death of Wallace C. Sabine. He explains: "*During the 1930s the stop watch and ear method was replaced by relay-controlled chronometers (acoustic clocks) operating in conjunction with frequency oscillators, amplifiers, loudspeakers, attenuators, and microphones*" [3]. The methods using a loudspeaker emitting periodic varying tones, a microphone and oscillograph are described in the book by Vern O. Knudsen [4, Chapter VII]. An example of a warble-tone signal and measured decay curves are seen in Figure 2.

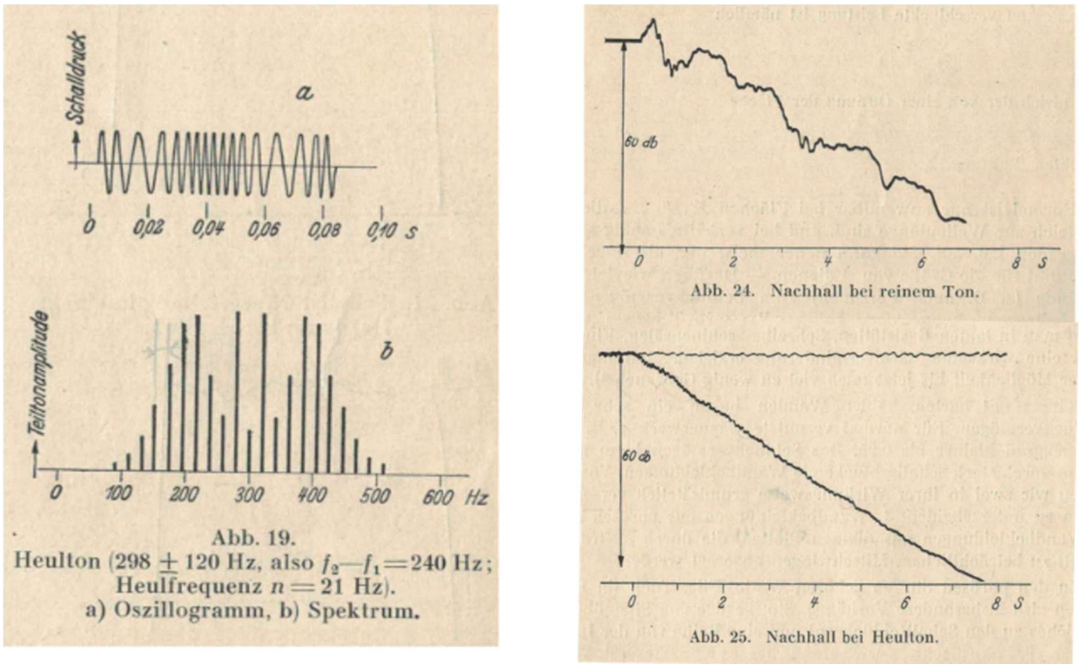


Figure 2: Measurement using a warble-tone. Left: The time- and frequency function of the signal. Right: Decay curves with a single frequency (upper part) or with the warble tone (lower part). From Schoch [5].

Field measurements of reverberation time were also made with (portable) organ pipes and stopwatch until around 1930. However, in 1934 measurements were made in the old Philharmonic Hall of Berlin (destroyed during the second world war) using for the first time a symphony orchestra as the sound source [6]. The music from the very first bars of the Beethoven *Coriolanus* overture was used as the sound signal. This particular music starts with some tutti cords in *fortissimo*, followed by pauses long enough to evaluate the reverberation time, see Figure 3. This implies, that the measurements could be made with the audience present. Reverberation times with and without an audience were reported in (approximate) octave bands from 125 Hz to 2 kHz. The 4 kHz band was measured, but no results were reported due to insufficient signal-to-noise level. Measurements with pistol shots (a start revolver) were also taken into use [6].

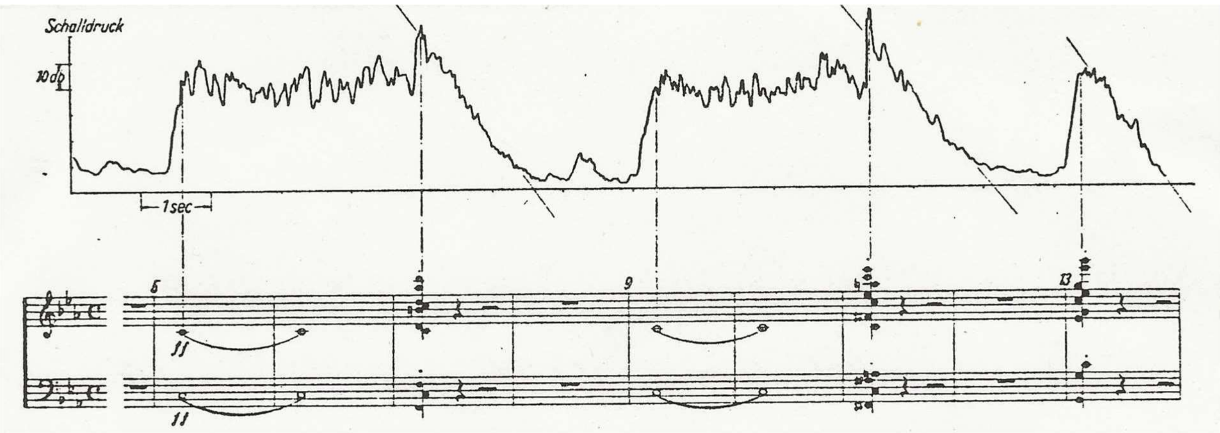


Figure 3: Decay curves in 500 Hz band measured 1934 in the old *Philharmonie*, Berlin, using a symphony orchestra as sound source. The music was Beethoven's *Coriolanus* overture, and the hall was with full audience. From Meyer & Jordan [6].

The registration of the decay curves was very difficult in the 1930s. For the concert hall measurements was used a technique, where the signal from the microphone was sent through a filter and a logarithmic amplifier to a movable mirror. A light beam was directed via the mirror towards a slowly rotating cylinder, which was covered with a phosphorescing layer. The curve that was made by the light beam was visible for long enough time to allow redrawing on paper.

A milestone in room acoustic measurements is the level recorder with a high-speed, logarithmic potentiometer. The first level recorder was made by Neumann around 1940, and from 1943 an improved model by Brüel & Kjær became widespread as an unavoidable part of the acoustic measurement equipment [7].

# 3 First measurement standards

ISO/R 354 recommendation was the first international standard for measuring the absorption coefficient of materials in a reverberation chamber [8]. It was published in 1963, five years after an American ASTM standard with similar contents [9]. A loudspeaker was used to emit the sound, either a *warble tone* or *white noise*. The sound was interrupter to get the decay. A microphone was connected to *cathode ray tube* or a *level recorder*. From this could be derived the decay rate (dB/s) or the reverberation time. The reading was taken from the part of the decay curve between -5 dB and -35 dB (or less) from the start of the decay curve. Measurements were made in octave bands or one-third octave bands from 100 Hz to 4000 Hz.

# 4 Measurement of reverberation time in auditoria

Since the first measurement standard ISO/R 354 was made for laboratory testing of materials, it soon became clear that there was a need for another standard directed towards field measurements, especially for auditoria. Such a standard was published in 1975 as ISO 3382 [10]. It described measurements made with loudspeakers and interrupted noise, and it also opened for other methods using organ pipes, blank pistol shots, or an orchestra as the sound source. The description of source and receiver positions were adapted to typical auditoria or concert halls. The derivation of reverberation time from the decay curve was the same as in ISO/R 354. The frequency range was one-third octave bands from 125 Hz to 4000 Hz. If the decay curve was not close to a straight line, two reverberation times were to be reported for the early and the late part of the decay, respectively.

There are several remarkable matters in this standard. One is the use of one-third octave bands. While this made sense for the measurement of absorption coefficients, it is more problematic for measurements of reverberation time in auditoria. Among acousticians working with concert halls, it was common practice to measure in octave bands and often to look at the average of two or three octave bands. The wider bandwidth was in order to obtain results that were not too sensible to variations in measurement positions.

Another remarkable matter in the standard is the possibility to use a pistol shot. It had become common to measure with pistol shots and derive the reverberation time directly from the squared impulse response, see Figure 4. However, already in 1965, Schroeder had shown how to derive a correct decay curve by backwards integration of the squared impulse response [12]. Without this integration, the results could be wrong, especially if the decay curve deviated much from an exponential decay. The example in Figure 5 shows the squared impulse response and the integrated impulse response measured in a concert hall.

The measurement method with the integrated squared impulse response is a milestone in room acoustic measurements. While the interrupted noise signal is stochastic and has to be repeated several times, the integrated impulse response remains the same if repeated. Schroeder had shown that the decay curve of the latter is the same as the ensemble average of an infinite number of interrupted noise signals [12]. While the interrupted noise method has remained a common method for laboratory measurements, the integrated impulse response has become the preferred method for field measurements because it is time-consuming and accurate.

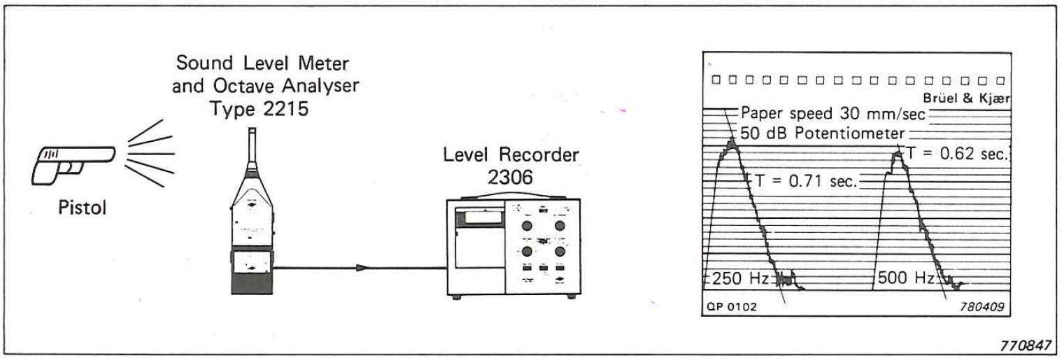


Figure 4: Set-up for measurement of reverberation time with the pistol shot method. From Fig. 6.1 in Ginn [11].

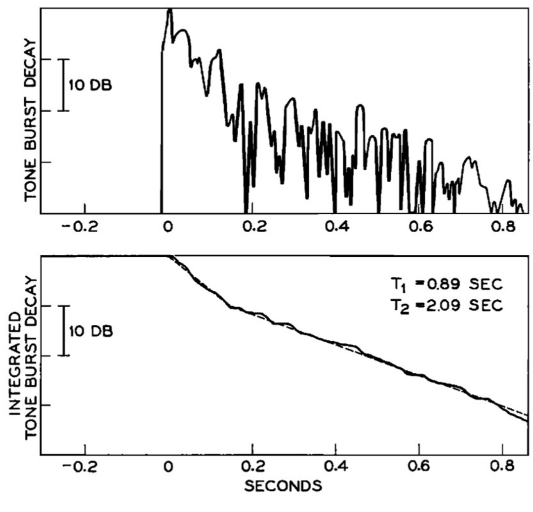


Figure 5: Measured squared impulse response (tone burst decay) and corresponding integrated impulse response (decay curve). A one-third octave band filter centred at 167 Hz was applied. Two different reverberation times have been derived, $T_1$ from the upper 10 dB and $T_2$ from the lower part of the curve. From Schroeder [12].

# 5 Improved measurement methods

## 5.1 Integrated impulse response method

The second edition of ISO 3382 was published in 1997 with several improvements [13]. The introduction states: "*The intention is to make it possible to compare reverberation time measurements with higher certainty, and to promote the use of and consensus in measurement of the newer measures.*" The scope includes this sentence: "*It is not restricted to auditoria or concert halls; it is also applicable to rooms intended for speech and music or where noise protection is a consideration.*"

The standard makes a clear distinction between two alternative methods for measuring the reverberation time: The interrupted noise method or the integrated impulse response method. The decay directly after excitation with a pistol shot or other impulse sources should only be used for survey purposes and is not recommend for accurate evaluation of the reverberation time. Impulse responses can be generated with loudspeakers using signals with Maximum Length Sequence (MLS), chirps or linear sweeps.

The measurement of impulse response opens up for the derivation of several other room acoustic parameters, and such parameters are included in informative annexes of the standard. Most of these new parameters had been developed since the 1950s, especially in relation to the use of scale models for acoustic design of auditoria, see Jordan chapters 4, 9, and 11 in [14]. The room acoustic parameters in this edition of the standard are listed in Table 1. The *lateral energy fraction* (LF) requires a *figure-of-eight* microphone, and the *inter-aural cross correlation* (IACC) requires measurement with a *dummy head*.

Table 1: Auditorium measures derived from impulse responses, ISO 3382 Annex A and B [13].

| Name | Symbol | Unit | Description | Origin |
|---|---|---|---|---|
| Sound strength | $G$ | dB | Total sound level relative to 10 m in free field | Lehmann [15] |
| Early decay time | EDT | s | Reverberation time derived from the first 10 dB | Jordan [16] |
| Early-to-late index | $C_{50}$, $C_{80}$ | dB | Ratio of early to late sound energy in dB (*Clarity*) | Reichard [17] |
| Definition | $D_{50}$ | - | Ratio of early to total sound energy (*Deutlichkeit*) | Thiele [18] |
| Centre time | $T_S$ | ms | Time of gravity of the squared impulse response (*Schwerpunktzeit*) | Kürer [19] |
| Lateral energy fraction | LF | - | Ratio of early lateral energy to early total energy | Barron [20] |
| Inter-aural cross correlation coefficient | IACC | - | Maximum of normalised inter-aural cross correlation function | Damaske [21] |

## 5.2 Linear regression replaces manual estimate of decay rate

The standard of 1997 states that the measurements of reverberation time in concert halls should be made in octave bands from 63 Hz to 4 kHz, while one-third octave bands from 100 Hz to 5 kHz can be used in other kinds of rooms. All reverberation parameters (EDT, $T_{20}$, and $T_{30}$) shall be determined from the slope of linear regression line within the evaluation range. For reverberation time this is a clear improvement from earlier manual methods, but for early decay time (EDT) this is more problematic as shown by Bradley [22]. For nearly 30 years, the EDT had been derived from the two points at 0 dB and -10 dB on the decay curve, neglecting the irregularities that are often seen in the first part of the decay curve, see Jordan [14, page 70]. While the difference between the two evaluation methods for EDT is negligible in long distances from the source, the difference can be very significant in positions close to the source. EDT is known to be a good measure of *perceived reverberance*, but the research behind this was based on the two-point EDT (before 1997).

Due to the fact that the air attenuation can influence the measurement results at frequencies above 500 Hz, the standard requires temperature and relative humidity in the room during the measurements to be included in the test report. These should be measured to an accuracy of ± 1 °C and ± 5 %, respectively.

## 5.3 Speech Transmission Index

In Annex A of the 1997 edition of the standard is mentioned in a note, that the Speech Transmission Index (STI) can also be used to determine the *speech intelligibility*, but this is a special measuring technique not covered in the standard. A simplified version of the method using only signals at 500 Hz and 2000 Hz is the Rapid Speech Transmission Index (RASTI). Brüel & Kjær produced portable equipment for these measurements, consisting of a speech transmitter (Type 4225) and a speech receiver (Type 4419). The method is based on a series of complicated modulation transfer functions, but the measurement result is simple and easy to understand. For many years, the RASTI measurements became quite popular as a supplement to other room acoustic measurements. However, in the 2011 edition of the measurements standard [23], the RASTI method was declared obsolete and was not be used. Also, the STI method has problems in relation to room acoustic measurements, mainly because the method is not sensible to echoes [24].

## 5.4 Sine sweep measurements

An early example of measuring with sine sweep signals was the series of concert hall measurements from 1984 by Gade & Rindel [25]. A linear sine sweep that covered one octave band was used and scaled in time and frequency for the six octave bands from 125 Hz to 4 kHz, see Figure 6. The response measured in the room was converted to an impulse response by *convolution* with the original sine sweep signal.

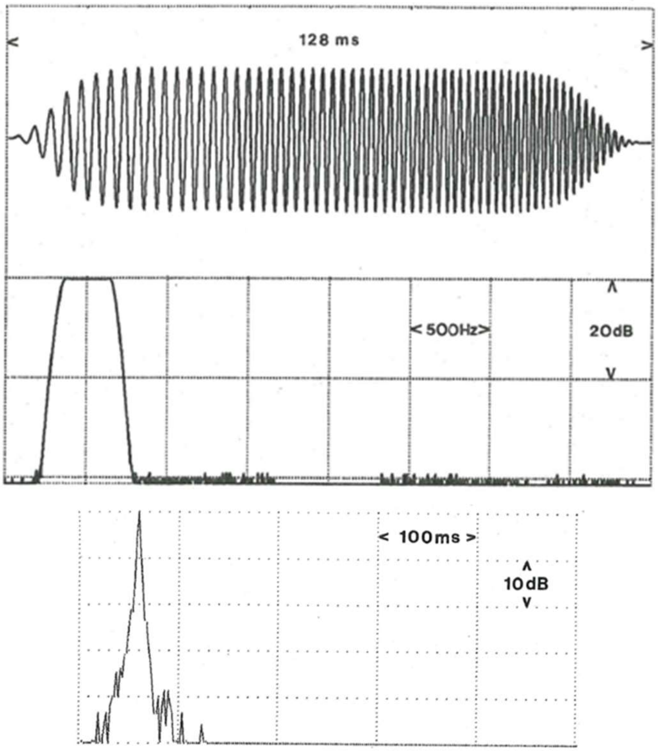


Figure 6: Sine sweep signal covering one octave, here shown for the 500 Hz octave band. Top: Signal in time domain. Middle: Signal in frequency domain. Bottom: Impulse response after convolution. After Gade & Rindel [25].

# 6 Recent developments in room acoustic measurements

## 6.1 Performance spaces in ISO 3382-1

For reasons to be explained in the next section 6.2, it was decided that the room acoustic measurement standard should be divided into two parts (and later three parts). Part 1 from 2009 [26] was in fact a 3rd edition of the previous ISO 3382 standard. This new edition had some minor changes, mainly in the annexes on various room acoustic parameters.

Annex A was extended with information on JND (just noticeable difference) [27] and the *late lateral energy level*, a new parameter related to the *perceived listener envelopment*. It is measured as the lateral energy level after 80 ms using a calibrated *figure-of-eight* microphone and is based on research by Bradley & Soulodre [28].

A new Annex C was added with the parameters *Early Support* ($ST_{Early}$) and *Late Support* ($ST_{Late}$) for the acoustic conditions at the orchestra platform. The former is related to the musicians' ability to *hear each other*, while the latter is related to the musicians' *perceived reverberance*. Both are measured in the distance of 1.0 m from the acoustic centre of an omnidirectional sound source. These parameters are based on research by Gade [29].

## 6.2 Ordinary rooms in ISO 3382-2

In 2001 the technical committee on acoustics ISO/TC 43 received a New Work Item Proposal (ISO/TC 43/SC 2 N 638) that recommend to divide ISO 3382 into two parts. Part 1 should be for performance spaces as the existing standard, while Part 2 should deal with "*the measurement of reverberation time in rooms in general. Examples are living rooms, classrooms, workshops, stairwells, and industrial halls*". ISO 3382-2 [30] is supposed to be a reference standard for building acoustic measurements and other standards where reverberation time is a part of the measurements. The part 2 of the standard deals with reverberation time, only. Both the interrupted noise method and the integrated squared impulse response method are described. The evaluation range for derivation of the reverberation time can be 20 dB or 30 dB, with a preference for 20 dB for various reasons, as explained in the introduction to the standard.

Concerning the number of source and receiver positions and other technical details, the part 2 of the standard distinguishes between three levels of measurement accuracy: *survey*, *engineering*, and *precision*. The precision method is meant for testing laboratories, especially for the measurement of the absorption coefficient of materials. Two annexes are included, one for the measurement uncertainty, and the other one with definition of "*measures that quantify the degree of non-linearity and the degree of curvature of the decay curve. These measures may be used to give warnings when the decay curve is not linear, and consequently the result should be marked as less reliable and not having a unique reverberation*" [30]. The origin of these quality measures is the work of Bodlund in 1984 for a Nordtest method [31]. He elaborated on the possibilities of using a computer for pression measurements in a laboratory with the interrupted noise method. He also introduced *ensemble averaging* as an attractive alternative to arithmetic averaging of reverberation times.

## 6.3 Open plan offices in ISO 3382-3

A second New Work Item Proposal (ISO/TC 43/SC 2 N 889) was proposed in 2007 that recommend establishing a new part 3 to the ISO 3382 series. The reason was acoustical problems in open plan spaces (offices, schools), and the recognition that the reverberation time was not sufficient or useful for characterizing open plan spaces. The proposal stated that "*there is reasonable agreement that other types of measurements such as rate of spatial decay of sound pressure levels, speech transmission index and background noise levels are needed for a more complete evaluation of the performance of open plan spaces*".

The measurement of *spatial decay* in large spaces had already been taken into use in industrial halls, see ISO 14257 [32]. The possibilities of using the speech transmission index (STI) in relation to open plan offices had been suggested by several researchers [33, 34]. Finally, the ISO 3382-3 [35] was published with the title limited to open plan offices.

Several new measures were defined, four of them being mandatory:

- distraction distance $r_D$
- spatial decay rate of A-weighted sound pressure level of speech, $D_{2,S}$
- A-weighted sound pressure level of speech at 4 m, $L_{p,A,S,4\,m}$
- average A-weighted background noise level, $L_{p,A,B}$.

The distraction distance $r_D$ is derived from STI measurements performed on a line of receivers with increasing distances from an omni-directional source. The distance where STI is estimated to decrease below 0,5 is defined as the *distraction distance*. The sound source must emit a noise signal at specified sound power and spectrum that represents speech sound. This new part of the standard did not solve the acoustical problems in open plan offices. However, it did establish a very important common reference for research in the field of acoustics of open plan offices. The acoustical problems in open plan offices are much more complicated than ordinary noise control. It is more like an optimisation problem, and how use the new parameters is still under discussion [36].

A second edition of ISO 3382-3 was published in 2022 [37] with minor changes. Most important is the addition of another parameter, the comfort distance ($r_C$). This is defined as the distance from the omni-directional source, where the A-weighted sound pressure level of speech decreases below 45 dB.

# 7 Future measurement methods

## 7.1 Revision of ISO 3382-1

ISO 3382-1 is currently being revised and some of the ideas for future changes may be unveiled. Most importantly, it will be emphasised that the standard is not only for music rooms, but also includes rooms for speech and open-air performance spaces. It will be made clear which of the room acoustic measures are relevant in rooms for speech, especially classrooms. Some new room acoustic parameters may be suggested, such as an *echo-parameter* and the *acoustic efficiency*, both of them most relevant for open-air performance spaces [38].

A new method for *normalisation* of the measurements to a standard atmosphere (20 °C, 50 % RH) is also being discussed.

## 7.2 Measurement of modal reverberation times

The problem of measuring reverberation time at low frequencies (< 100 Hz) in small rooms (< 200 $m^3$) is still a challenge. One idea is to measure the reverberation time of single modes. Instead of a conventional statistical approach, the source and microphone positions can be chosen strategically in order to separate one low-frequency mode at a time [39]. This is best applied to rectangular rooms, where the modal pattern of the modes is well known.

## 7.3 Application of cepstrum analysis

Flutter echoes and the spectral *colouration* due to periodic sound reflections are easy to hear but difficult to measure objectively. A method that has proven useful, especially for colouration issues, is the application of the so-called *cepstrum* analysis [40]. This is the inverse Fourier transform of the logarithm of the spectrum. The spectrum is derived as the Fourier transform of the impulse response. Peaks in the *cepstrum* indicate a periodicity in the spectrum, which is typical for the colouration.

## 7.4 Measurements with a 3D field microphone

The 3D distribution of the sound reflections in a receiver position can measured by replacing the omnidirectional microphone with a number of cardioid capsules, three orthogonal intensity probes, or some other microphone array. The measured signal can be transformed into *first order ambisonics signals* (B-format) or higher order ambisonics signals with addition of more microphones in the array. This technique can be used to measure the *spatial room impulse response* (SRIR) and to visualise the directions of reflections in the measured impulse response as a *hedgehog pattern* [41-42].

However, the use of 3D field microphones opens up for several other applications. The measured signal can be transferred into a figure-of-eight signal and a simultaneous omni-directional signal for deriving the lateral energy parameters in ISO 3382-1. By application of a *head-related transfer function* (HRTF) the measured signal can also be transferred into a *binaural room impulse response* (BRIR), thus replacing a *dummy head* for the measurement of the IACC parameter.

## 7.5 Application of sound intensity and particle velocity

Further application of the above-mentioned technique is to measure two different impulse responses, the traditional one based on sound pressure and another one based on the 3D sound intensity. Thus, a *dynamic diffusion curve* (DDC) can be derived from the difference between the two decay curves [43]. The DDC is a measure of the amount of non-directional energy as a function of the decay level. This technique is very efficient for analysing the degree of *diffusivity* and for detecting echoes and flutter echoes in a room. It has also been suggested for evaluation of the acoustical quality of reverberation rooms [44].

The simultaneous measurement of sound pressure and *particle velocity* opens up for improvements of measurements in reverberation rooms, that are used for measuring the absorption coefficients of materials. With current technique, it is a significant problem that the *diffusivity* in the room is compromised when the test material is installed. With the possibility to measure both the *potential* energy density and the *kinetic* energy density, the *total energy density* can be achieved. This may offer more accurate and robust measurement results, because the total energy density varies very little throughout the room. This applies to the *steady-state* sound as well as to the *decaying* sound field. This is the basis for a detailed measurement method that has been described in a US patent by Hanyu [45].

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