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A Practical Approach to Assessing Reverberation Time Measurement Uncertainty

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ABSTRACT

An experimental assessment of the uncertainty in reverberation time is performed. The obtained statistics allow for extraction of measurement precision and uncertainties due to the use of different equipment by different operators for the living quarters on board ships. The results of these measurements are compared against the theoretical concepts, which are also reviewed in this paper.

1. Introduction

In line with an increasing demand for higher comfort levels on board of ships Damen Shipyards is faced with contractual demands on acoustical comfort as well. One of the key elements of acoustical comfort is the lack of interference from the other inhabitants for which there are strict requirements in statutory regulation and additional comfort class notations. These requirements are all based on the concept of R'_w as described in ISO717-1:2013 [1] which is determined based on measuring the difference in sound pressure levels in the 'source' room and the 'receiver' room and applying corrections for amongst others the amount of absorption of the receiver room. This amount is measured in terms of reverberation time.

For operators responsible for performing reliable measurements of reverberation time it is of practical value to have a basic understanding of the uncertainties in reverberation time measurements. In this paper an overview is presented of the relevant technical challenges in reverberation time measurements, in the hope that this will contribute to a broader understanding of the uncertainties involved in carrying out these measurements and the possible consequences this has for the contractual obligations regarding R'_w measurements. Based on this overview a practical exercise has been carried out to quantify the accuracy and reliability of reverberation time measurements in real-life conditions.

2. Theoretical background

The following is not intended to be a complete mathematical analysis of the measurement of reverberation time but rather an overview of the practical difficulties encountered during the measurement of reverberation time in small spaces and some of

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their theoretical backgrounds. Additionally, where possible or relevant, suggestions will be presented for the mitigation of some of these issues.

2.1. Logarithmic scale of human perception

As is well know the human perception of the frequency of sound and especially frequency intervals operates on a mostly logarithmic scale as is evidenced by the concept of critical bandwidth and the associated phenomenon of masking [6]. Acoustic measurements which are intended to produce results matching human perception are therefore commonly carried out on a logarithmic scale, achieved by the division of the frequency-axis into one-third octave bands (which closely approximate critical bandwidth) or octave bands. Other bandwidths exist but are not dealt with here.

2.2. Measurement of reverberation time

Many fundamentally different techniques exist for the determination of reverberation time in a space. The reverberation time may be mathematically derived from the transfer function (and corresponding impulse response) between two points in space. The excitation signal used can be a continuous pseudo-noise signal or any other signal which excites all relevant frequencies. Alternatively, a time-reversed and band-limited impulse response signal of a one-third octave bandpass filter may be fed to a loudspeaker and the room response sampled and processed accordingly.

More commonly, the decay of sound pressure levels in a space after the abrupt switch-off of a narrow-band or broadband noise signal, or a single impulsive signal, may be directly measured by equipment capable of rapid logging, storage and processing. Suitable mathematical post-processing (such as integration or backwards integration) exists to bring all these measurement results into one single coordinate system, thus allowing practical comparisons.

When performed with care, these widely differing strategies produce results which are in close agreement with each other and may therefore be assumed to be representative. It is customary to present the resulting reverberation time T_{60} for a 60 dB decay, even if, due to practical limitations a smaller interval such as 20 dB or 30 dB is actually determined. The results are accordingly identified as T_{20} or T_{30}, but always scaled to represent a 60 dB decay.

2.3. Noise signal

A commonly used test signal for the determination of reverberation time is broadband noise. Generally speaking, a simple generator will produce a noise signal with equal energy per frequency, known universally as white noise. Although in theory the nature of the noise signal would not affect the correct measurement of sound decay in a space, in practice this produces constraints.

On investigating the frequency scale, moving downwards from the highest frequencies, the bandwidth of octave and one-third octave filters becomes narrower in each lower band. For octaves this is a halving of energy in each lower band, which amounts to -3dB per octave.

In one-third octave analysis the bandwidth is 23% of the centre frequency. So a 10 kHz third octave band filter will have a bandwidth of 2300 Hz but the 100 Hz filter a bandwidth of only 23 Hz. Thus, a 100 Hz one-third octave band will only measure one hundredth of the energy of a 10 kHz band.

When white noise is used as a test signal for analyses performed with one-third octave filters, the lowest frequencies will have the least energy. And as we shall see later, determination of reverberation time meets the severest challenges at the lowest frequencies. For these and other reasons the choice has been made to alter the character of the white noise (equal energy for each frequency), by boosting the low frequencies and reducing the high frequencies, by 3dB per octave. This produces the characteristic signal known as pink noise (equal energy per octave band), which is precisely optimised to match the behaviour of both octave bands and one-third octave bands.

It is acknowledged that broadband signals with other spectral shapes (optimised by graphic equalizers) can also be used, but these are not under consideration here.

2.4. Loudspeaker

This noise signal must be produced at a high sound level in order to determine the reverberation time in a space. Commonly a decay of at least 40 dB should be obtained. When high background noise levels are present this presents a challenge. Additionally, loudspeakers have a low radiation efficiency at low frequencies. Consequently, a powerful amplifier and loudspeaker combination is required to produce signals of Background Noise.

Many spaces where the determination of reverberation time is required, suffer from background noise. This is most often due to all manner of machinery such as heating, air-conditioning, or in the case of the shipbuilding industry, power generators (unless shore power is used). This background noise is often dominant at low frequencies. Consequently, a new challenge is faced in the performance of reliable measurements. At low frequencies the one-third octave bands are narrower, sound sources produce less sound energy and the background noise is higher.

2.5. Room modes

A room mode is a frequency at which a standing wave can be formed in the room. In rectangular rooms these frequencies may be predicted by relatively straightforward calculations [7]. For the correct determination of reverberation time there is a requirement that there shall be a sufficient number of room modes in each investigated frequency band such that the sound field can be considered to be diffuse in each frequency band. In smaller rooms the number of room modes is insufficient at low frequencies with the result that the reverberation time measured in one of the lower bands might be determined by the behaviour of a single mode.

Additionally, the occurrence of room modes results in the reverberation time being position-dependent, since the room response at a specific location will depend on the most dominant modes at that location. A single measurement at a single point will therefore not give a representative reverberation time for the room. Measurements at many different places must be averaged.

2.6. Averaging

A noise signal, whether white or pink, is stochastic in nature with the result that its instantaneous spectrum will have a different shape every time it is switched off for the measurement of reverberation time. Consequently, each determination will produce a different result, depending on which modes are excited most. Moreover, the spread of results will increase mathematically with reducing bandwidth and correspondingly reducing frequency, since narrower bands are more susceptible to changes in the character of the noise due to their smaller bandwidth. The greatest spread occurs at the lowest frequencies. The solution is to perform the same measurement at the same point in space a few times and average the results. Several averaging strategies exist. The actual decay shapes may be averaged, sometimes referred to as ensemble averaging, and the result computed from this. Alternatively, the reverberation times may be determined from each decay and these times averaged.

2.7. Use of impulses

To avoid the requirement of averaging several measurements at each spatial position, a deterministic signal is required. A single impulse fills this need in principle. Commonly used sources of a single impulse may be the shot from a starters pistol (used in sports) or a bursting balloon. In [3] Schroeder showed why an impulse response requires integration to achieve results comparable to the average of many noise-based measurements. Despite the benefits of an impulse, the downside is that an impulse by its nature contains less energy at lower frequencies or narrower frequency bands, just as with white noise.

2.8. Ringing of band filters

Octave bands and one-third octave band filters, whether implemented in the analogue or digital domains, display the undesirable property of ringing. This ringing places constraints on the minimum measurable reverberation times. This has been explained in [2] which also explains one useful improvement strategy which is to reverse the time direction of the filter. Several instruments exist or existed which implement this strategy by first recording the reverberation decay, reversing the time axis, and then presenting the resulting signal to the filters. In this way it has been shown that there is a fourfold reduction in minimum measurable reverberation time. In [2] it is also explained, based on earlier work, that the minimum measurable reverberation times for normal forward analysis may be predicted by:

$$BT_{60} > 16$$

Where B is the bandwidth of the filter in Hertz and T_{60} is the reverberation time in seconds. In common language it is then said that the BT product should be greater than 16. If this condition is not met, the measured decay time include the dynamics of the filter, resulting in unpredictable errors. Figure 1 summarizes the minimum measurable reverberation times for one-third octaves and both forward and reverse analysis. The orange line shows the minimum times for noise-cut-off based measurements and the blue line shows the fourfold reduction attainable if time-reversed integration of the impulse is used.

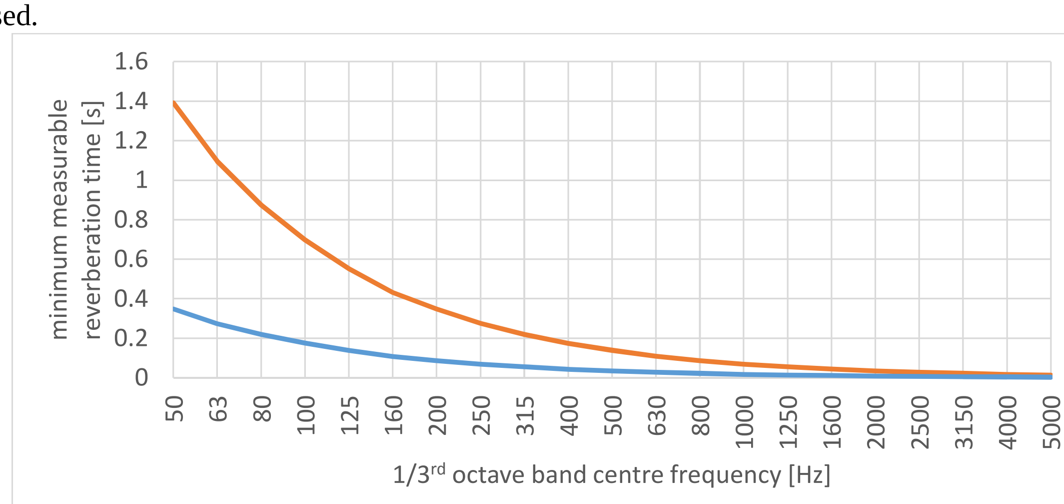

Figure 1 Minimum measurable T_{60} reverberation times in one-third octave bands, orange= forward analysis, blue= time reversed analysis

3. Measurement approach

The measurements carried out for this paper are focused on providing a good indication of the measurement uncertainties for reverberation time measurements to be used for the assessment of R'_W values of separation walls. Since the measurements are focused on carrying out R'$_W$ measurements according ISO717 [1] the frequency range under consideration is from the 100 Hz one-third octave band and higher.

With the advent of small, light, but nevertheless very powerful amplifiers, the weight of the amplifier is no longer a problem. However, it will still be necessary to use a heavy, powerful loudspeaker for these measurements to ensure sufficient power in the lower frequency bands. Most commercial solutions are available in two configurations, one with a single powerful loudspeaker in a cabinet, and the other a dodecahedron-shaped structure with a loudspeaker mounted in each of the twelve facets. For this study both are used.

The method applied throughout this paper is based on the interrupted noise method. Pink noise signal is used throughout this investigation in combination with sound sources that are powerful enough to at least excite the 100 Hz band sufficiently. Since the decay is measured from a stochastic signal rather than a deterministic signal averaging is required. In the procedure applied the individual reverberation times are averaged per one-third octave band.

3.1. Variations

Based on the considerations in chapter 2 and some earlier experimentation it was found that the largest sources of uncertainties in both R'$_W$ and reverberation time measurements are related to the size of the rooms (and thus the number of room modes per one-third octave band) and the operator carrying out the measurements. These two aspects are investigated in this paper, while all other aspects are kept the same for the measurements carried out for this investigation.

The variation in room modes is realised by selecting spaces to carry out the measurements of significant size difference. Since spaces on board vessels are usually relatively constrained in size, a large conference room inside the Damen main office is used and as representative space on board of ships a crew cabin has been selected. Typical dimensions and a short type description are presented in Table 1 and the number of room modes per one-third octave band is presented, indicative, in Figure 2.

Table 1 Space dimensions and description

	Dimensions LxBxH [m]	Volume [m^3]	Type
Conference Room	13.6x10.4x4	566	Large meeting room
4 Personnel Cabin	3.1x2.35x2.1	15	Cabin for 4 crew members on board of a ship

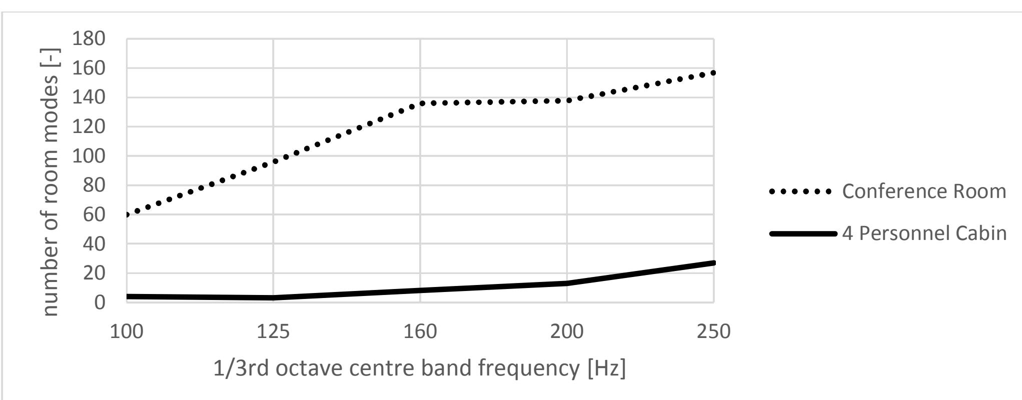

Figure 2 Number of room modes per one-third octave band, indicative since in the calculations a rectangular room shape has been assumed

A key element in these measurements is that they are carried out by individuals, that despite the prescriptive guidelines and relevant training may have different ways of carrying out the measurements and interpreting the guidelines. There is no published work available, to the authors belief, that properly quantifies this effect, but it was found out in the process of developing the internal routines that the precise way of measuring does make a significant difference in the end result, and most of the deviations related to R'w measurements related to the inaccuracies in the reverberation time measurements. The operators carrying out the measurements that are presented in this paper have all received identical training on the physical and mathematical aspects of the measurements and were provided with a detailed guideline on how to carry out the measurements with the specific equipment that is in use at Damen Shipyards. The measurements that are used for this paper are part of the training to enable the operators to independently and correctly carry out these measurements. For that purpose there were at all measurement locations instructors available that would point out deviations to the procedure and that at the same time ensured that the data for this paper is collected in a correct and consistent manner.

4. Measurement execution

Reverberation time measurements are performed according ISO3382:2:2008 [5].
The reverberation times in the Conference Room are measured using a dodecahedron (CESVA FP122 with a sound power level of 112 dB at 1/3rd octave band of 100 Hz) and on board the vessel with a single speaker cabinet (B&K type 4224 with a sound power level of 103 dB at 1/3rd octave band of 100 Hz). For the Conference Room the operators are asked to measure the reverberation time for two source locations and three (fixed) operator positions. In total 24 operators measured the reverberation time with the same sound pressure level measurement device and the same sound source (CESVA) each time The location of the sound source is in one of the four corners, such that each corner of the Conference Room is measured twelve times in total. Also for the 4 Personnel Cabin the operators are asked to measure the reverberation time for two source locations and three (fixed) operator positions. In total 22 operators measured the reverberation time with the same sound pressure level measurement device and the same sound source (B&K) each time. In figure 3, a schematic overview of the rooms, sound source positions and sound level measurement positions are indicated.

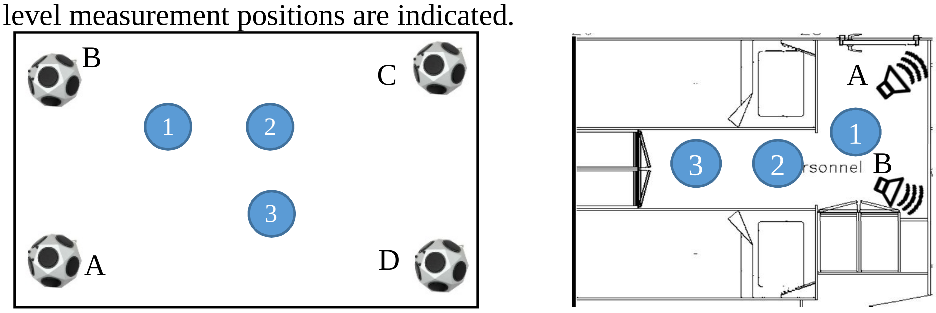

Figure 3 Schematic overview of Conference Room (left), 4 Personnel Cabin (right) and sound source positions (A-D) and sound level measurement positions (1-3)

5. Measurement results

In the following graphs, Figure 4 to Figure 6 some typical results of the measurements of the reverberation time for a certain position in the conference room and the crew cabin in a number of frequency bands are presented. The source level is calculated as the average sound pressure level between second 1 and 4. At approximately 6.8 seconds the sound source is switched off and the decay of the sound level can be seen. The decay of

20 dB is marked with dots, starting at a level of 5 dB below the obtained source level. The background level of the measurement is calculated as the average sound pressure level between 8 and 10 seconds.

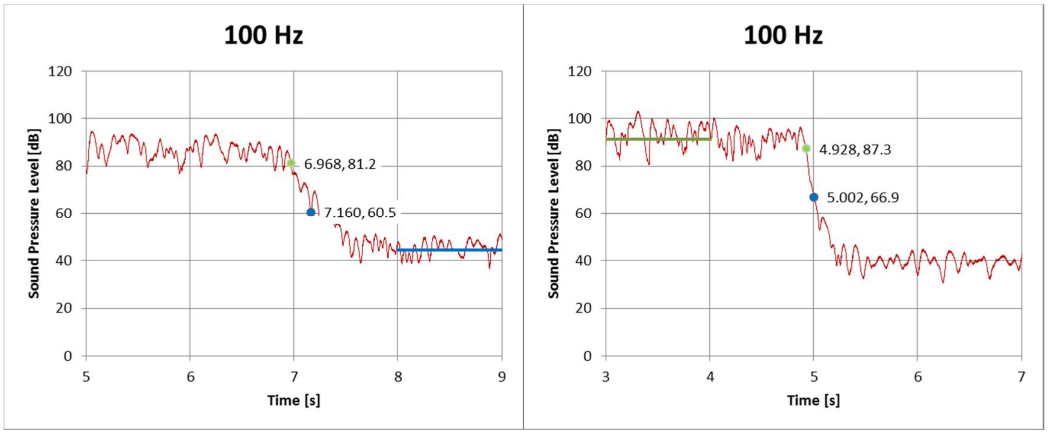

Figure 4 Example of the level over time in the 100 Hz band in the Conference Room (left) and 4 Personnel Cabin (right) with indication of the calculation parameters for T_{60}

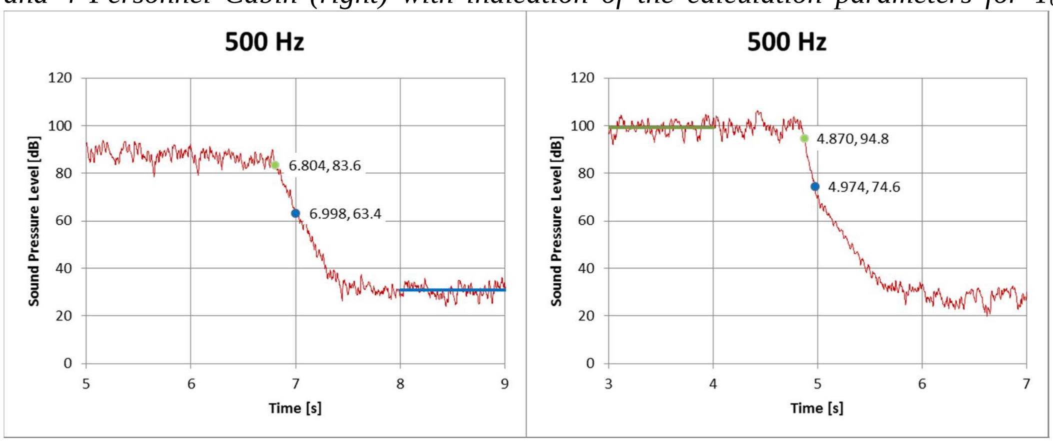

Figure 5 Example of the level over time in the 500 Hz band in the Conference Room (left) and 4 Personnel Cabin (right) with indication of the calculation parameters for T_{60}

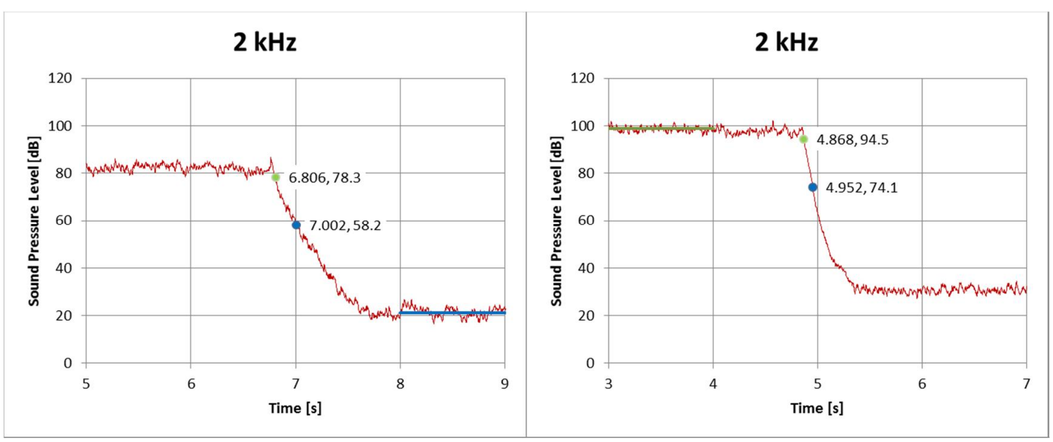

Figure 6 Example of the level over time in the 2000 Hz band in the Conference Room (left) and 4 Personnel Cabin (right) with indication of the calculation parameters for T_{60}

The final reverberation times are achieved by averaging the successful measurements per one-third octave band over the two source positions (indicated with capitals A to D) with each three measurements (indicated with numbers 1 to 3). The reverberation time T_{60} is an average of the measured T_{20}, T_{30} and T_{40} per individual measurement per frequency band. For the two rooms that have been measured the resulting reverberation times T_{60} have been presented in the graphs below, Figure 7 and Figure 8. In each of the graphs there are three quantities plotted:

- Reverberation time T_{60} (the number in the center of the grey bar).
- 95% confidence interval of T_{60} (indicated by the grey bar) to indicate how accurate T_{60} is measured in that frequency band.
- Twice the standard deviation of T_{60} (indicated by the error bars) to indicate how large the spread between individual measurements is.

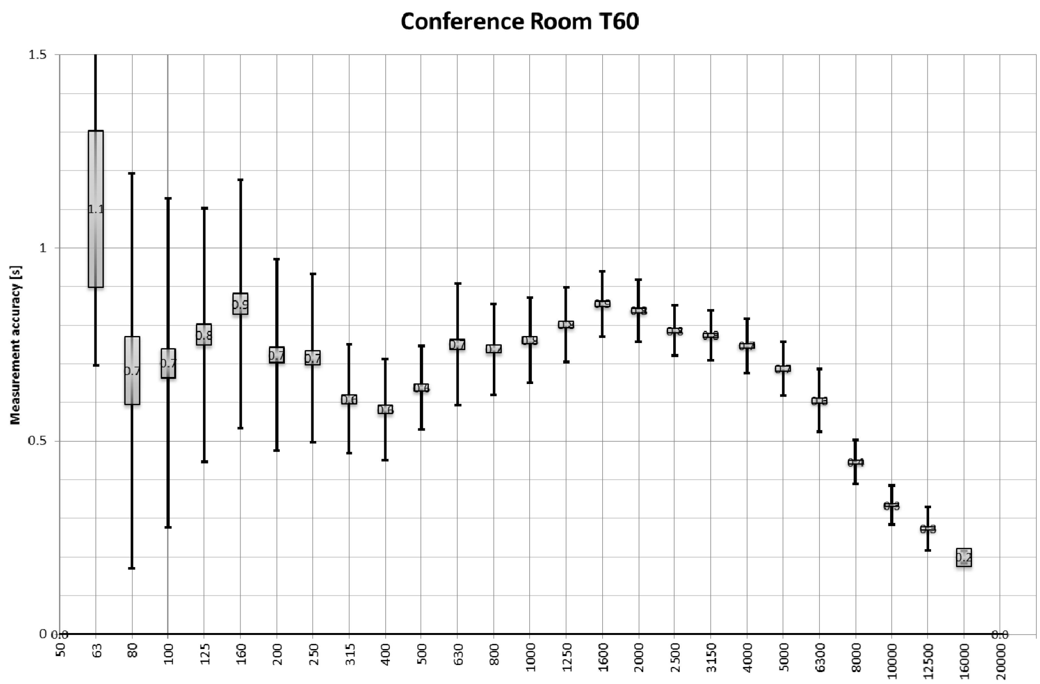

Figure 7 Measured reverberation time T60 in the Conference Room, including 95% confidence interval and two times the standard deviation of measurements

The reverberation time of the Conference Room shows that for low frequencies the standard deviation of the measurements are large, however because sufficient measurements are performed, the confidence interval for the average is relatively small.

In Figure 8 of the 4 Personnel Cabin a clear peak in the value and spread of the reverberation time is found at 250 Hz, a similar effect can be seen in figure 10 which shows $T_{20,}$ T_{30} and T_{40} as presented in Figure 9.

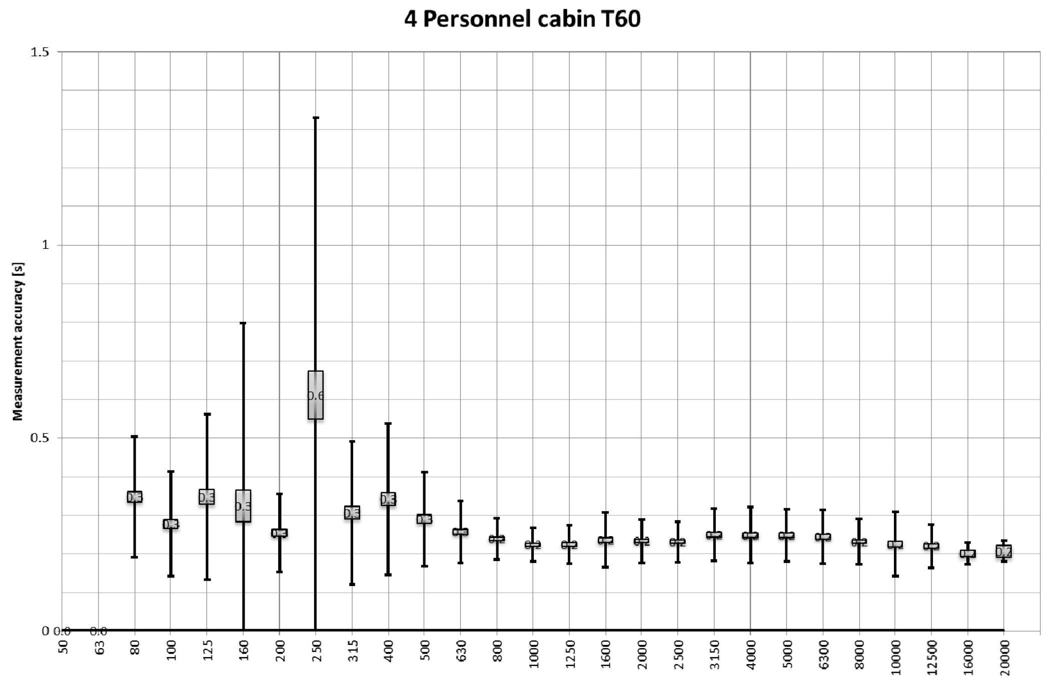

Figure 8 Measured reverberation time T_{60} in the 4 Personnel Cabin, including 95% confidence interval and two times the standard deviation of measurements

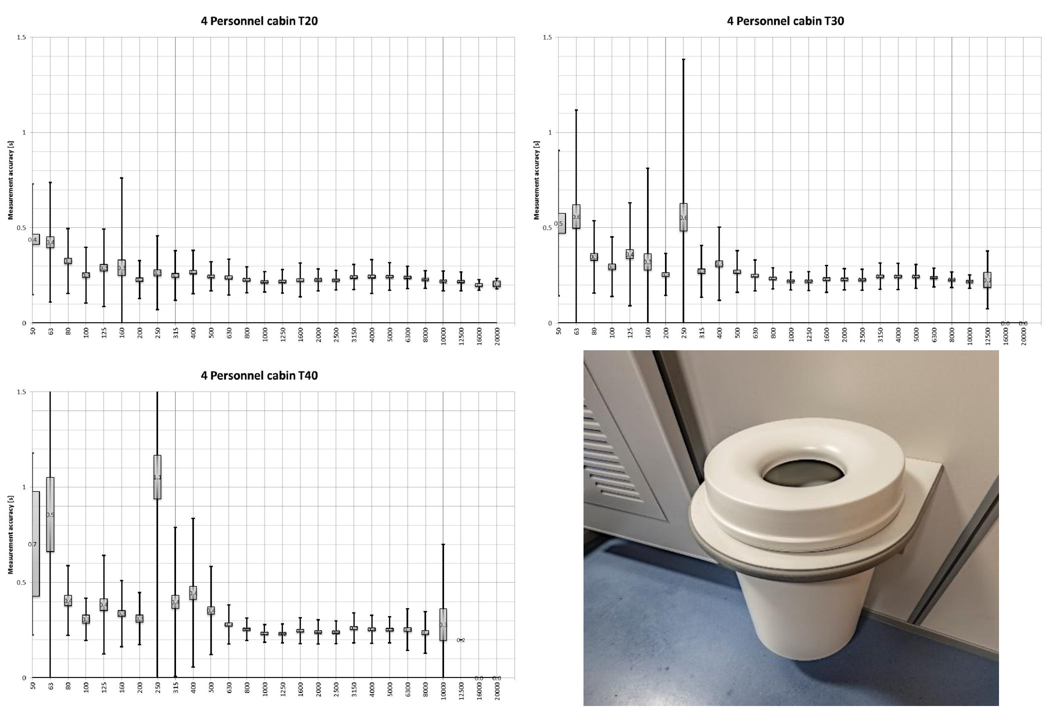

Figure 9 Reverberation time for 4 Personnel Cabin based on 20, 30 and 40dB decay clearly indicating that in the 1/3rd octave band centre frequency of 250 Hz the measured decay is not correctly measured

The cause could be heard by the ears of the well observant operator, but it is also clearly visible in the obtained time signal given in Figure 10. The two dots indicate the decay for 20 dB (T_{20}), but the room decay cannot be measured further as it is obscured by the decay of the litterbin.

In this example it is still possible to estimate the correct value of the reverberation time based on T_{20}, but in most other measurements also T_{20} was already influenced by the resonance of the litter bin and therefore the spread in measurements in this frequency band is high for all measurements.

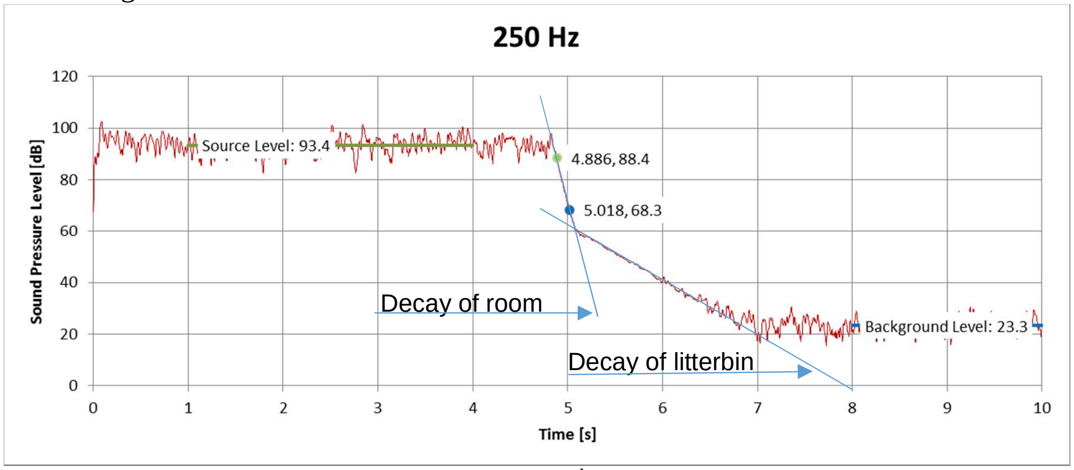

Figure 10 Measured level of the 250 Hz 1/3rd octave band over time in the 4 Personnel Cabin

6. Discussion

Comparison of the decay graphs, Figure 4 to Figure 6, of the 100 Hz band with the 500 Hz and 2000 Hz band illustrates as explained in chapter 2 that for the higher frequency bands the accuracy of determination of the decay time is higher, due to smaller variations of the sound pressure level over time. During the decay of the sound level in the 100 Hz band there are significant changes in instantaneous sound levels that make it challenging to define a single instant of 20 dB decay, and due to the small difference between source level and background level larger decays, 30 dB or 40 dB, cannot be determined at all. This issue cannot be mitigated by modifying the measurement procedure for a given room, as it is related to the physical constraints of the room (room modes) and the sound source (low radiation efficiency at low frequencies). Since the measured signals are random and stochastic in nature it is possible to mitigate this effect by repeating the measurements multiple times, which results in acceptable small confidence intervals.

In Figure 11 the 95% confidence Interval in seconds for the 4 Personnel Cabin and the Conference Room is given for the measured standard deviations of 1/3rd octave band center frequency of 100 Hz, 500 Hz and 2000 Hz. As a result of the higher standard deviation in the 100 Hz 1/3rd octave band center frequency more measurements are required to achieve a similar confidence interval. Since the reverberation time is typically measured in values in the order of magnitude of 0.1 s. it is reasonable to expect a confidence interval of $\leq$ 0.1 s. over all frequency bands; To achieve this at least 4 measurements are required in the 4 Personnel Cabin and approximately 11 measurements in the Conference Room.

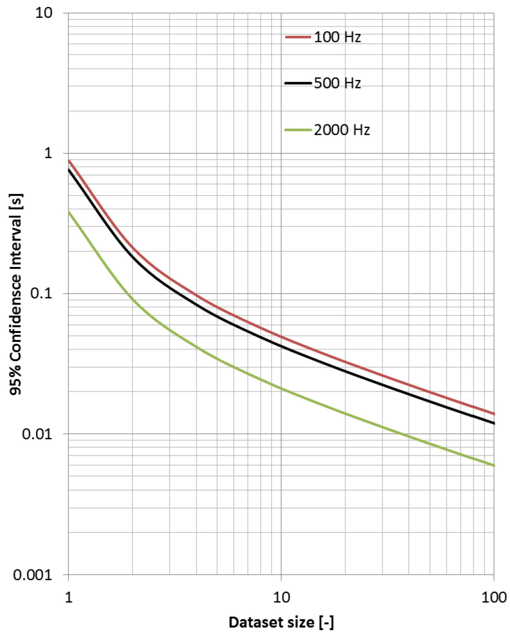

Figure 11 95% Confidence Interval in seconds for a certain size of dataset for the found standard deviations in the 1/3rd octave bands of 100, 500 and 2000 Hz in the 4 Personnel Cabin (left) and Conference Room (right)

As was explained in the overview in §2.8 it is mathematically challenging to measure reverberation times less than 0.7 s. in the 100 Hz band with the applied forward analysis method. This was not observed in the measurement results where both the confidence interval and the standard deviations show acceptable behavior in that range, especially in the 4 Personnel Cabin.

Based on experience at Damen a guideline is used for assessing the quality of the individual reverberation times that is based on the relative difference between T_{20}, T_{30} and T_{40}. A large deviation between T_{20}, T_{30} and T_{40} indicates that there may other factors influencing the measurement than the room decay itself, in this example, Figure 10, it turns out that this is caused by a lightly damped mode of the litterbin in that room.

7. Conclusions

Due to the many aspects mentioned in chapter 2, the uncertainty of reverberation time measurements at low frequencies is the largest. This is confirmed in practice by measurements of reverberation time of a Conference Room and a ship cabin.

A single measurement at a single point will therefore not give a representative reverberation time for the room, especially in the lower frequencies due to the smaller bandwidth at low frequencies. Measurements at different places must be averaged to get accurate results. For the 1/3rd octave band center frequency of 100 Hz minimally 4 measurements are needed at different locations to have a 95% Confidence Interval below 0.1 s. in the 4 Personnel Cabin.

Care should be taken for determining the reverberation time of a room, calculated out of the T_{20}, T_{30} and/or T_{40}. The behavior of a room can be influenced by elements inside that room, which can resonate and can affect the reverberation time, as was shown with the example of the cabin with the litterbin. There is no properly described method in the referenced guidelines for assessing the quality of the measurement of individual reverberation times. Our suggestion is to define a maximum allowable ratio between consecutive decay times.

8. References

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