



## METHODS OF MEASURING THE REVERBERATION TIME

Marko Horvat, Kristian Jambrosic, Hrvoje Domitrovic

Faculty of EE and Computing, University of Zagreb, Unska 3, Zagreb, Croatia

**Abstract:** *The goal of this paper is to compare the results of reverberation time measurements obtained with different well-established methods used for this type of measurements, as well as some additional ones which could serve as in situ tool when standard methods are not available. The methods compared in this paper include integrated impulse response measured with pink noise, exponential sweep and MLS, balloon bursts, interrupted pink noise and the B&K filtered burst method. In order to make the comparison, the measurements were performed in two acoustically very different spaces - a damped listening room and a rather reverberant hallway. The results were evaluated according to dynamic range criterion as well.*

Key words: reverberation time, measurement method

### 1. INTRODUCTION

Although a large number of parameters have been defined over the years in order to describe and evaluate the acoustical properties of a certain space, the reverberation time has always been the basic indicator of acoustical behavior [1]. Furthermore, in our professional work up to date it was required to measure the reverberation time in a large number of spaces with very different properties, regarding their size, shape and intended purpose. Therefore, it was decided that an extensive research shall be made in an attempt to determine the best possible measurement setup to be used in reverberation time measurements which will provide the most reliable results.

As a part of this large-scale research on the measurements of reverberation time, this paper gives an overview of the most common methods used in this kind of measurements by comparing the results obtained with each method and discussing the advantages and disadvantages of these methods.

Over the years, a number of different methods for measuring the reverberation time has been developed and implemented, the most common being: the interrupted noise method, the integrated impulse response method, the method of recording the room response to an impulsive source, the burst method. These methods have been investigated and the results obtained using them were compared in order to ascertain the most suitable one to be used in field measurements.

In order to remove a degree of uncertainty, all measurements were made using the same sound source, except when an impulsive source was used instead, namely, a balloon. Furthermore, all responses were recorded with the same microphone, except when the burst method was investigated.

The measurements were taken in two small, but acoustically very different spaces. The future research shall include the measurements in large spaces, which were not available at the time the measurements were conducted.

### 2. THE REQUIREMENTS AND PARAMETERS IN REVERBERATION TIME MEASUREMENTS

The requirements that have to be met when performing a reverberation time measurement are stated in [1] and can be summarized as:

- the source, either a loudspeaker or, if nothing else is available, an impulsive source of some kind, should have an omni-directional radiation pattern (or as close to it as possible)
- the sound pressure level must be high enough to provide a minimum required dynamic range to perform a reverberation time measurement, to be more precise, at least 45 dB for methods that do not apply synchronous averaging

It is quite clear that an omni-directional source has to be used in order to excite the measured space uniformly, in all directions. All our measurements have been performed using the omni-directional loudspeaker and a balloon, for both of which it was assumed that their radiation pattern approaches the ideal one, thereby fulfilling the requirement on omni-directivity.

The minimum required dynamic range is 45 dB if no synchronous averaging is used, as stated earlier.

Several parameters [1] can actually be measured and calculated from the energy decay curve obtained from reverberation time measurements: the Early Decay Time (*EDT*) as the 10 dB difference between 0 and -10 dB on the decay curve, the  $RT_{20}$  as the 20 dB difference between -5 and -25 dB on the decay curve and, finally, the  $RT_{30}$  as the 30 dB difference between -5 and -35 dB on the decay curve. The noise level has to be at least 10 dB lower than the lowest point of interest on the decay curve in order not to degrade the decay of the measurement signal.

The  $RT_{30}$  parameter is considered to be the most accurate and the goal is to be able to measure it whenever possible. If this is not the case, the  $RT_{20}$  parameter is used as the indicator of reverberation time. The *EDT* is only used when all else fails, however, it should be noted that it is not a true measure of reverberation time because it can and often does differ a lot from  $RT_{20}$  and  $RT_{30}$ . If the  $RT_{20}$  or *EDT* is measured instead of  $RT_{30}$ , it should be noted with the results.

Since the loudspeaker, as well as the whole measurement system used in the measurements, was always the same one, the main goal was to investigate which method would behave best under the given conditions and make the most of the equipment at hand.

### 3. METHODS OF MEASUREMENT

As already stated in the introduction, the following methods were investigated in this paper:

- the integrated impulse response method
- the interrupted noise method
- the method of recording the room response to an impulsive source
- the filtered burst method implemented by Bruel&Kjaer

The integrated impulse response method has been implemented in a number of computer applications. The application chosen to be investigated here is the ARTA Software [2], designed specifically for impulse response measurements and parameters derived from it. The available test signals in ARTA for impulse response measurements are pink noise, swept sine and MLS and the decision has been made to investigate all of them to determine the best one to be used in reverberation time measurements. This method has the inherent advantages of a) ensuring the repeatability of the measurements and b) allowing for synchronous averaging, thereby adding a

few decibels to the required dynamic range and lowering the demands on the sound source at the same time.

The interrupted noise method basically uses a portion of pink noise with a duration of several seconds which ends abruptly. The response of the room to this noise signal, i.e. the reverberation, is recorded as a wav. file and then imported in ARTA for further analysis. This method is shown to our students as a standard laboratory exercise in one of the courses, so the desire was to examine its usefulness in real field conditions.

The method which utilizes an impulsive source of some kind by recording the response of the room to it is actually quite similar to the interrupted noise method. The procedure is described above, while the only difference is the source of excitation. Unlike the interrupted noise method, which uses a loudspeaker, this method allows for a wide variety of impulsive-like sources [3], like air-filled balloons, firecrackers, pistol shots, hand clap, two pieces of board clapped together, etc. Unfortunately, most of the sources mentioned above (with the exception of large-sized balloons) have a very poor spectral content when it comes to low frequencies. They are, therefore, not suitable for reverberation time measurements at low frequencies because they cannot provide the required dynamic range even in small spaces, let alone the large ones. As a result, the idea for future research was born of utilizing a new category of impulsive sources. Some kind of explosive device would be used to provide sufficient excitation at low frequencies, such as small caliber cannon, a balloon filled with explosive mixture of acetylene and oxygen and then set off, a can containing a chunk of calcium carbide reacting with water and producing acetylene as a result, etc. This ideas have not yet been realized, though, mostly due to financial and safety reasons.

Since we were able to acquire a Bruel&Kjaer 2231 Sound Level Meter with the Reverberation Processor module, the decision has been made that the filtered burst method of measuring the reverberation time implemented by B&K should also be investigated in order to determine whether the results obtained in this manner are comparable to other methods. The B&K 2231 Sound Level Meter equipped with the Reverberation Processor module acts as a self-sufficient measurement system, requiring only a power amplifier and a loudspeaker to be complete. A number of bandwidth-limited bursts are used in the frequency range of choice in order to measure the reverberation time.

### 4. MEASURED SPACES AND MEASUREMENT SETUP

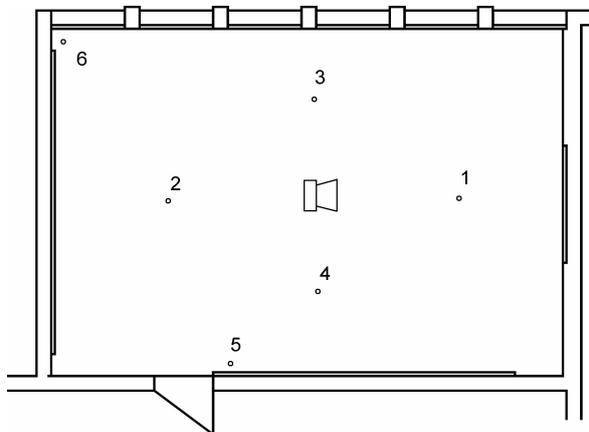
As one of the goals of this research is to perform measurements in spaces with different acoustical properties, given their size, shape and acoustic treatment, the first step was to conduct the initial measurements in two spaces which could be considered as small, given

their room volume. Future research will extend these measurements to large spaces.

The first room is actually a listening room located at the Department of Electroacoustics of the Faculty of EE and Computing in Zagreb. The room itself is 10.2 m long, 7.1 m wide and 3.2 m high and has a room volume of 230 m<sup>3</sup>. Since all the acoustic elements used for acoustic treatment can easily be removed from the walls and put back on (a concept of changeable acoustics), the room acts as a constant test room for different acoustic setups. The current one brings the room very close to a good listening room, although additional work needs to be done. The current interior of the room is shown in Fig.1 and the floor plan of the room with indicated source and microphone positions is shown in Fig.2.



**Fig.1.** Current interior of room 1



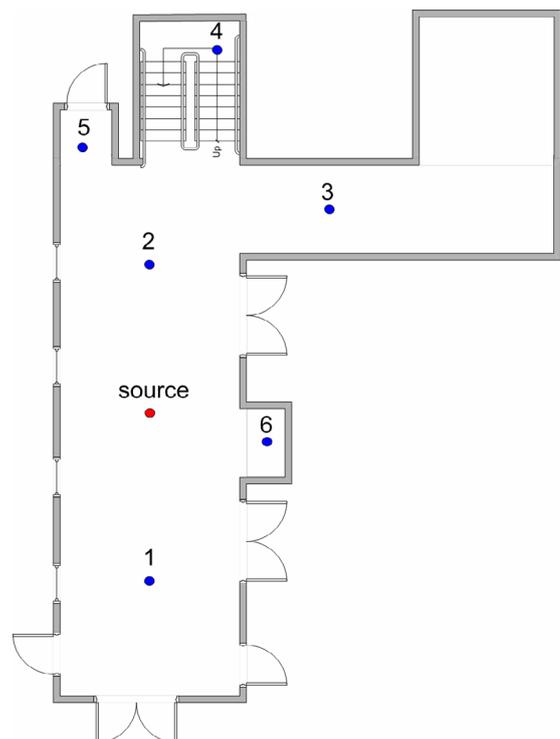
**Fig.2.** The floor plan of room 1

The second room is a rather reverberant hallway also located in one of the buildings of the Faculty of EE and computing. The room acts as a multipurpose space with the primary function of providing access to several lecture halls, but it also serves as an art gallery and sometimes as a bar, if required. It is an elongated, rather tight L-shaped space with a staircase leading to a lower level hall, thereby forming a coupled room system. The room itself was chosen because of its availability and proximity. Furthermore, its room volume of

approximately 800 m<sup>3</sup> is not significantly larger than the volume of the first room, but the acoustic finishing differs a lot, consisting mostly of marble. The interior of the room is shown in Fig.3 and the floor plan indicated source and microphone positions is shown in Fig.4.



**Fig.3.** The interior of room 2



**Fig.4.** The floor plan of room 2

In order to provide equal conditions for all investigated methods that require a loudspeaker as a source, namely, the integrated impulse response, the interrupted pink noise and the B&K filtered burst method, measurements were done using the same omni-directional loudspeaker of our own design, shown in Fig.5, powered with TOA P300D power amplifier. The source of the test signal was either a laptop computer connected to the power amplifier via TASCAM US-144 audio interface or the B&K 2231 Sound Level Meter with the Reverberation Processor

module acting as a self-sufficient system. In the investigation of the method of recording the room response to an impulsive source, balloons of 80, 120 and 160 cm in circumference were used as the sources of excitation, as shown in Fig.6. Furthermore, a Behringer ECM-8000 omni-directional microphone was used in all the measurements except the ones conducted with B&K equipment, which used its own microphone.



**Fig.5.** The omni-directional loudspeaker



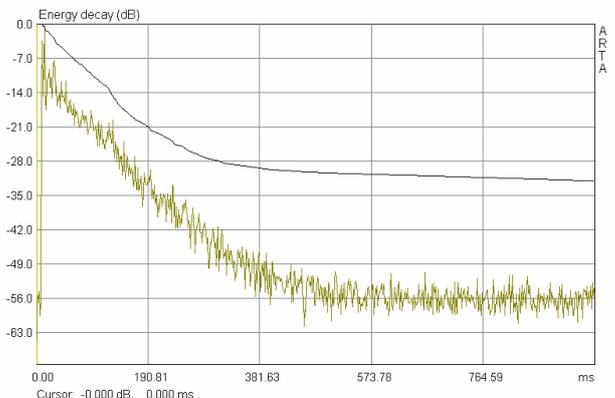
**Fig.6.** A balloon as an impulsive source

Although common practice requires the reverberation time measurements to be performed in octave frequency bands with center frequencies from 125 Hz to 4 kHz, the decision has been made to extend the frequency range of interest to octave bands with center frequencies of 63 Hz and 8 kHz as well, in order to address the problem in a proper manner.

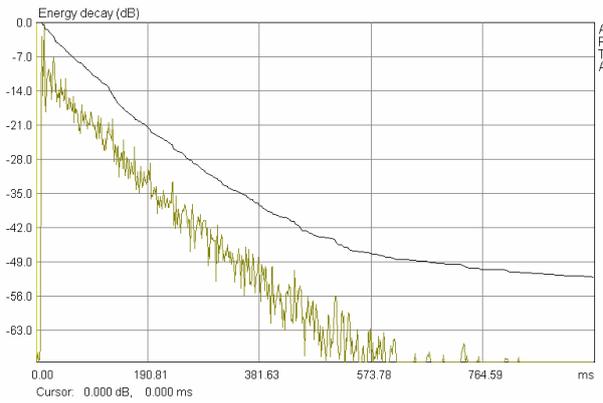
## 5. THE RESULTS

In order to yield the results of the measurements in an efficient manner, all the data obtained during the measurement process was analyzed with ARTA software. The integrated impulse response method implemented in ARTA enables direct analysis of the obtained data, while the interrupted noise method and the method of recording the response to an impulsive source require making a recording of room response to stated test signals in a form of a wav. file, which is then imported in ARTA and analyzed. B&K filtered burst method implemented in their equipment is, however, a self-sufficient measurement system which yields final results and does not allow for further investigation of what it does and how it really works. Therefore, the final results obtained with B&K were just compared to the final results obtained with other methods.

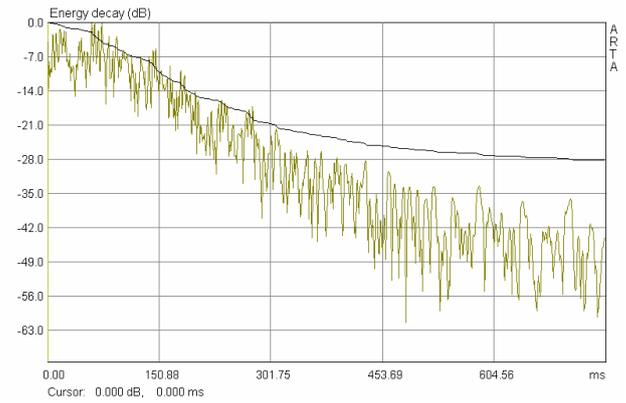
The first question that comes to mind is the question of available dynamic range each method is able to provide, given that the measurement setup is always the same. Figs.7-11 show wideband energy decay curves recorded in room 1 at microphone position 2 for a) integrated impulse response (IIR) method implemented in ARTA using the pink noise, swept sine and MLS signal and implementing the synchronous averaging in order to increase the dynamic range, b) the recorded response to a small balloon burst and c) the interrupted noise method.



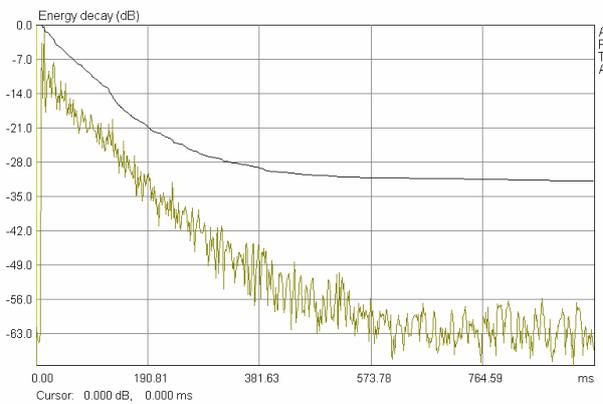
**Fig.7.** Wideband energy decay curve recorded in room 1 at position 2 for IIR measured with pink noise



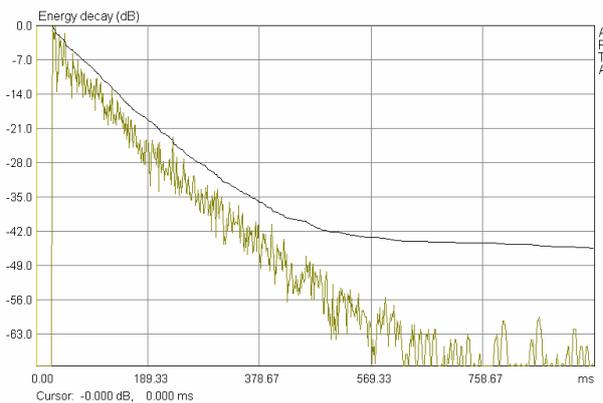
**Fig.8.** Wideband energy decay curve recorded in room 1 at position 2 for IIR measured with swept sine



**Fig.11.** Wideband energy decay curve recorded in room 1 at position 2 for interrupted pink noise



**Fig.9.** Wideband energy decay curve recorded in room 1 at position 2 for IIR measured with MLS



**Fig.10.** Wideband energy decay curve recorded in room 1 at position 2 for small-size balloon burst

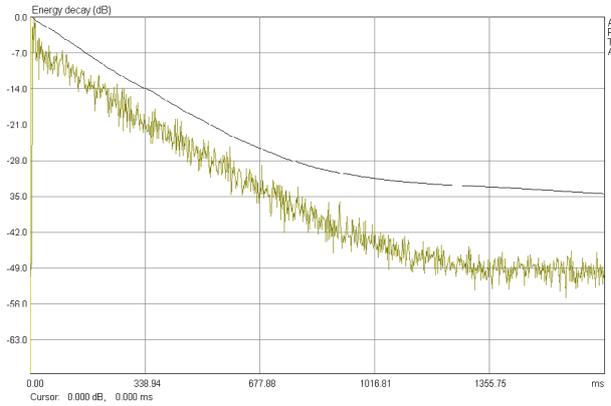
The energy decay curves presented above clearly indicate that the integrated impulse response measured using the swept sine signal and a balloon burst provide by far the greatest available dynamic range, thereby ensuring the maximum commodity in the process of calculation of reverberation time. On the other hand, the integrated impulse response measured using the pink noise and the MLS signal are not able to provide the required dynamic range, but they can still be utilized if certain precautions are taken. Finally, the interrupted noise method provides a dynamic range so narrow, compared to other methods, that the results obtained from it cannot be considered as reliable.

There are several reasons that could explain the results obtained above. First of all, a balloon burst, as well as a burst of any kind of impulsive source, can provide a very high peak sound pressure level. The measurements we have made using balloons show that these levels can easily reach 140 dB in rooms with room volumes mentioned above. Therefore, the peak signal level is high above the noise level, thereby providing a rather wide dynamic range to work within. Furthermore, it is a well known fact that loudspeakers that are fed with a sine-like signal will provide sound pressure level that is a few decibels higher than the one they would provide if fed with a noise-like signal of the same amplitude. In addition, if the averaging process is utilized in measuring the integrated impulse response, it will provide a few additional decibels in the useful dynamic range.

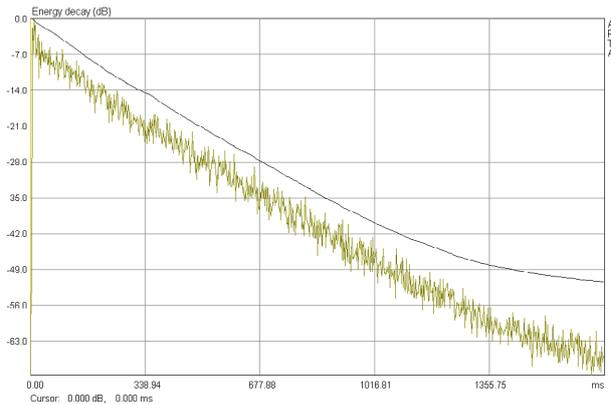
Having all this in mind, it becomes quite clear why balloon bursts and IIR measured with swept sine are the best choice, in our opinion. As stated before, the IIR measured with pink noise and MLS can still be used, although they do not provide enough comfort, while the interrupted noise method has proved to be practically useless.

The energy decay curves recorded in room 2 at microphone position 1 for a) integrated impulse response (IIR) method implemented in ARTA using the pink noise, swept sine and MLS signal and implementing the synchronous averaging in order to increase the dynamic range, b) the recorded responses to a small, medium and

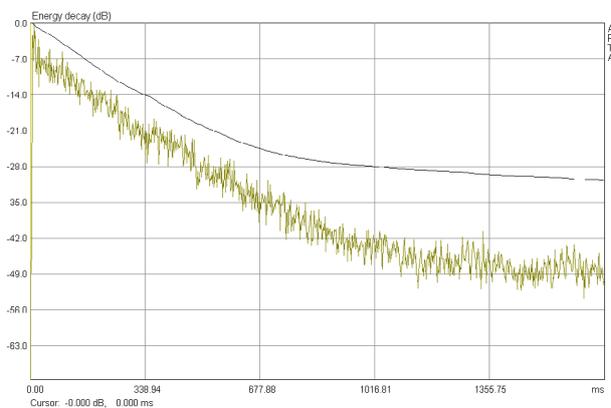
large balloon bursts and c) the interrupted noise method confirm our conclusions. These energy decay curves are shown in Figs.12-18.



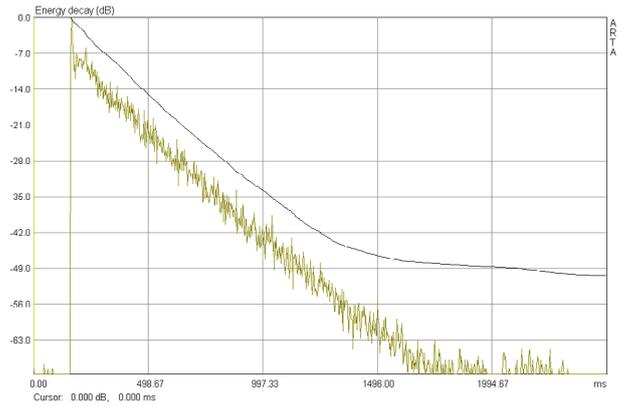
**Fig.12.** Wideband energy decay curve recorded in room 2 at position 1 for IIR measured with pink noise



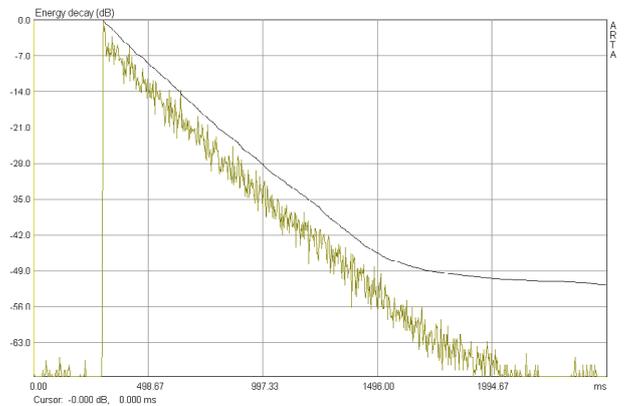
**Fig.13.** Wideband energy decay curve recorded in room 2 at position 1 for IIR measured with swept sine



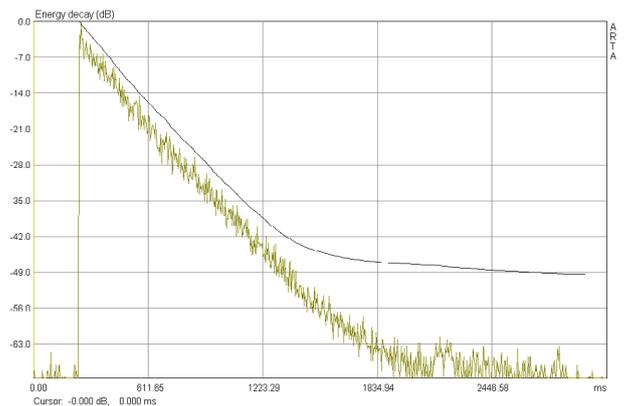
**Fig.14.** Wideband energy decay curve recorded in room 2 at position 1 for IIR measured with MLS



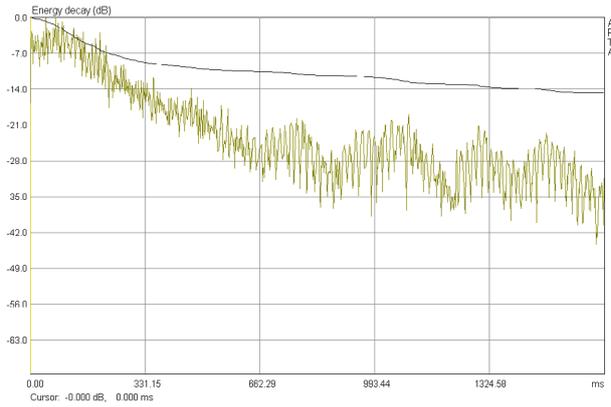
**Fig.15.** Wideband energy decay curve recorded in room 2 at position 1 for small-size balloon burst



**Fig.16.** Wideband energy decay curve recorded in room 2 at position 1 for medium-size balloon burst

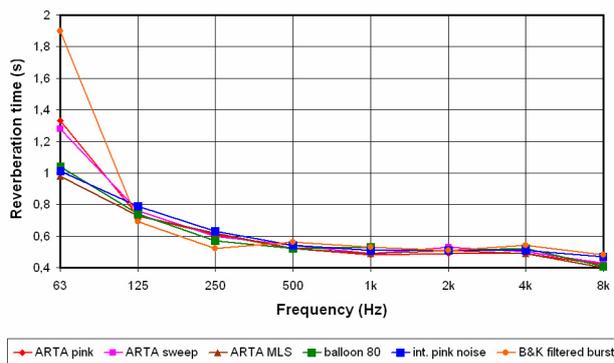


**Fig.17.** Wideband energy decay curve recorded in room 2 at position 1 for large-size balloon burst

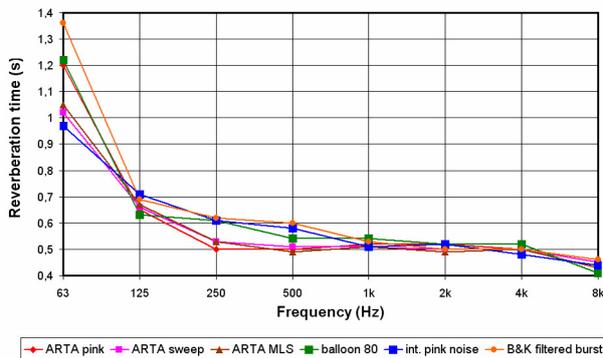


**Fig.18.** Wideband energy decay curve recorded in room 2 at position 1 for interrupted pink noise

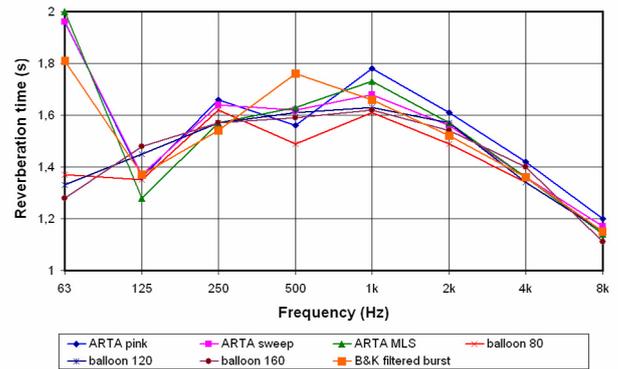
Since it is not possible to present all the results obtained from the measurements made in this part of the research, only a couple of charts are shown for each room in Figs.19-22.



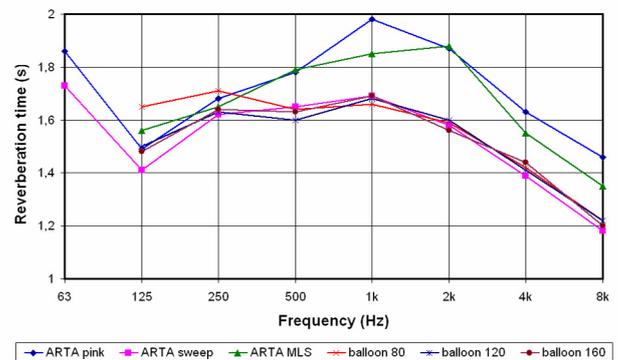
**Fig.19.** Reverberation times measured in room 1 at position 1



**Fig.20.** Reverberation times measured in room 1 at position 2



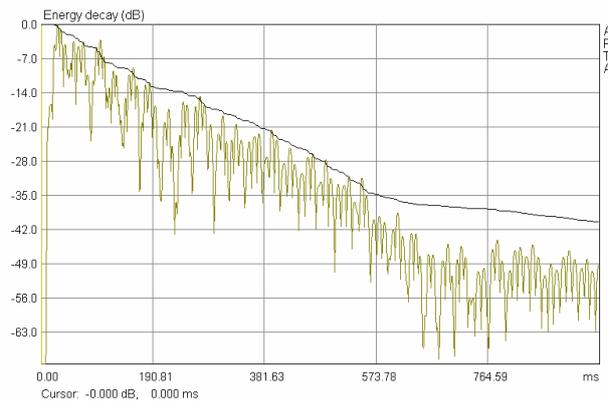
**Fig.21.** Reverberation times measured in room 2 at position 1



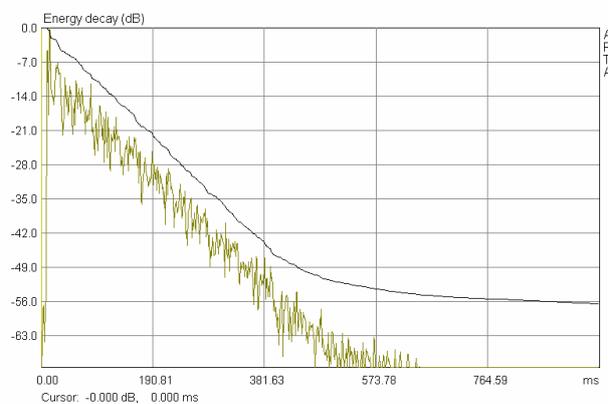
**Fig.22.** Reverberation times measured in room 2 at position 3

Figs.19 and 20 show that in room 1 all methods provide results that are in very good agreement, unlike in room 2, as shown in Figs.21 and 22. One possible explanation could be the very acoustical properties of both rooms. On one hand, room 1 is acoustically dampened space with a quite ordinary shape, while room 2 is quite the opposite, a space with highly reflective surfaces and an exceptionally irregular shape. Of course, it is a little premature to draw such conclusions; more measurements have to be done in several other spaces in order to observe a possible pattern in the results.

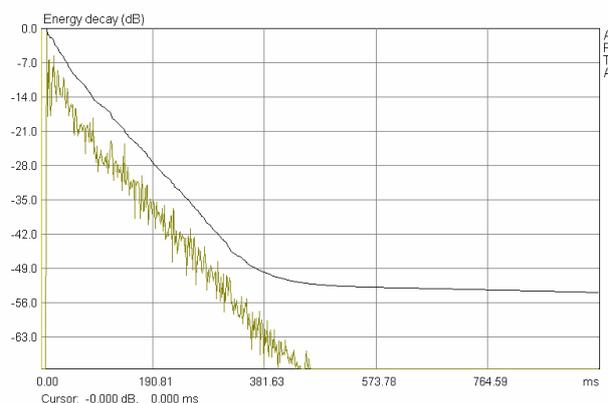
The results also show the best agreement at high frequency octave bands, while the dispersion of results becomes evident as the frequency decreases. The probable reason for this is that the energy decay curve in higher octave bands is quite smooth and linear, so the process of taking two points on it (in this case done by a living human being, except for B&K, which is automated) in order to determine the rate of decay, i.e. the reverberation time is quite straightforward. At low octave bands, however, the decay curve loses its smoothness and usually has more than one slope, so it can be difficult to determine and choose the right one. An example of the phenomenon described above is shown in Figs.23-25 for a decay curve recorded in room 1 at position 2 for IIR measured with swept sine.



**Fig.23.** Energy decay curve filtered for the octave band around 63 Hz



**Fig.24.** Energy decay curve filtered for the octave band around 1 kHz

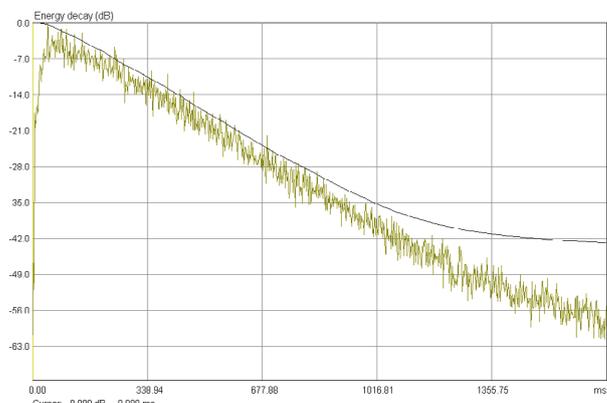


**Fig.25.** Energy decay curve filtered for the octave band around 8 kHz

Reverberation time measurements at low frequencies are limited with lack of sources able to excite the space properly. In our case, neither the omni-directional source was constructed to work below 80 Hz, nor does a balloon

excitation have a rich enough spectral content in the frequency band of interest to ensure the required dynamic range. Furthermore, the octave band around 63 Hz contains the 50 (60) Hz frequency of power grids, which can significantly raise the noise level in this particular band, inherently destroying any possibility of making a reliable reverberation time measurement.

The results shown in Fig.22 for room 2 at position 3 show one other interesting observation. It can clearly be seen that reverberation times measured with IIR using pink noise and MLS differs significantly from the results obtained by other methods. Furthermore, the results for octave band around 63 Hz could either not be obtained at all or be obtained with questionable accuracy. Following the discussion on dynamic range and the problems at low frequencies, the only conclusion was that the dynamic range was reduced at this particular position and became so narrow that viable results could not be obtained. The floor plan of the room, shown in Fig.4 offers an explanation. As there is no line of sight between the source and the microphone located at position 3, there is no direct sound at that position and its absence reduces the dynamic range by several decibels. This does not represent a problem for methods capable to provide enough dynamics and in octave bands where the source is able to excite the room properly. However, if the dynamic range is already narrow for any of the reasons stated above, then this additional reduction is in most cases fatal, again destroying any possibility of obtaining any, let alone viable results. The reduction of dynamic range can clearly be seen in Fig.26 when compared to Fig.13.



**Fig.26.** Wideband energy decay curve recorded in room 2 at position 3 for IIR measured with swept sine

## 6. CONCLUSION

The primary goal of this paper was to ascertain the best method to be used for reverberation time measurements in accordance with the basic criterion on the dynamic range. The results show that the integrated impulse response method using the swept sine signal provides the best results, given that the measurement setup is always the same, because in these conditions it is able to provide the

widest dynamic range. Although it is not recommended to measure the reverberation time by recording room response to excitation with impulsive sources due to non-repeatability of such measurements, we have found that this method can actually be used because the results are in most cases in very good agreement with the results obtained using other methods.

The fact is, any of the methods investigated in this paper will provide reliable results if the excitation is powerful enough to ensure a sufficient dynamic range and if the noise level in the investigated space is reasonably low. As this is not always the case, the solution may be to look for more powerful sources of excitation, especially when it

comes to measurements in large spaces, as a topic of future work.

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