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# COMPARISON OF BLIND REVERBERATION TIME ESTIMATION IN AN ENCLOSED SPACE BY ANALYSING ENERGY DECAY CURVE

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## ABSTRACT

This paper presents a novel method for estimating reverberation time in an enclosed space by analyzing the energy decay curve. Reverberation time (RT) is a key parameter to determine the acoustic of a room and it provides an information about the quality and intelligibility of sound in an enclosure. RT can be determine directly from room acoustics, but in case where this is difficult to determine, it is estimated blindly from the reverberation speech. Blind reverberation time (BRT) is a method of measuring the reverberation time of a room without the use of any external equipment. It is based on the human auditory system's ability to detect and measure the decay of sound and acoustic properties of a room, which can be used to determine how suitable it is for certain activities, such as music or speech. In this study, we provide a study/comparison of two methods for BRT estimation. Data were collected from relevant papers as cited. Comparison of the two methods are carried out in terms of estimation error and effect on signal-to-noise ratio (SNR). The methods were able to estimates the RT within 0.2sec for RT ≤ 0.8sec and SNR ≥ 10dB. Thus, the key effect of additive noise on all methods is a positive bias of the estimation error which results in estimation error of e ≥ 0.2sec, which is an over-estimation. The results obtained shows that the methods can be used to accurately compare the reverberation time in an enclosed space with minimal effort.

**Keywords**: Reverbation Time, signal-to-noise-ratio, estimation error, decay curve, blind estimation

## INTRODUCTION

The reverberation time (RT) is usually obtained by analyzing the decay rate of the energy decay curve that is observed when a noise source is switched off, and the energy curve of the room impulse response (RIR). Reverberation time of an enclosed space can be estimated by analyzing the energy decay curve. The energy decay curve is a graph that shows the decrease in sound energy over time (Lollman et al., 2019). RT is calculated by measuring the time it takes for the sound energy to drop by 60 dB from its initial level. This can be done by measuring the time between two points on the graph, one at 0 dB and one at -60 dB. RT is then calculated as the difference between these two points.

Blind reverberation time (BRT) is a method of measuring the reverberation time of a room without the use of any external equipment. It is based on the human auditory system's ability to detect and measure the decay of sound in a room. BRT is typically used to measure the acoustic properties of a room, such as its reverberation time, which can be used to determine how suitable it is for certain activities, such as music or speech (Chen & Hsu, 2012).

Blind estimation is estimating the reverberation time using the observed reverberant speech signal. An estimation of the reverberation time of a room or enclosed space can serve as an indicator of the quality and intelligibility of speech observed in that room or enclosed space. Acoustics is an important concern of enclosures in buildings such as concert halls, auditoria, lecture theatres and meeting rooms (Sridhar, 1996). It is well established in architectural acoustics that spaces for diverse purposes require different acoustic specifications typically described by room acoustics parameters (Schulte, 2002). Reverberation time is the most important and commonly used objective parameter for acoustics in enclosures. From a functional design point of view, multi-purpose spaces are often desirable, especially when resources are limited (Everest et al., 2001).. Typically a space is designed to have a short reverberation time, but artificial reverberation is added via an electro-acoustic system when a longer reverberation time is needed. If the use of electro-acoustic or sound reinforcement systems is acceptable, this solution to some extent can often achieve reasonably satisfactory results. On the other hand, the settings and the number of audience/occupants can vary for diverse uses and on different occasions in a multi-purpose hall or other dedicated spaces. The change of absorption alters natural reverberation. A more advantageous electro-acoustic system can be one with some intelligence and the ability to adapt itself to natural reverberation (Vary & Raina, 2006).From an architectural acoustics perspective multi-purpose enclosures or room with variable and adaptive acoustics are difficult to analyze and they are highly sensitive to additive noise. However, such spaces may become more feasible using amplified sound with the aid of signal processing and blind room acoustic parameter estimation techniques (Sridhar et al., 2007).

### Review of the related Literature

There are basically two types of approach for automatic RT estimation mentioned in literature. Some approaches use some sort of segmentation procedure to find the interesting sounds from a continuous signal, and perform the RT analysis on those parts of the signal only. Another class of methods performs calculations on the signal continuously, regardless of the signal content. These methods are termed Blind estimation methods.

Van Walstijn et al., (2005) provide an empirical formula to predict the RT in an enclosure environment. The formula is based solely on the geometry and the surface material of an environment. The formula provided is given by:

$$RT = RT_{60} = \frac{0.49V}{\Sigma A} \qquad (1)$$

Where 'v' is the volume and A is total area.

In (Chu, 1998), a Schroeder techniques was developed to calculate the average of the decay curves directly using backwards integration of the related RIR. The practical formula for applying the method is:

$$D(t) = N \int_{t}^{T} h^2(\tau)d\tau \quad (2)$$

Where N is taken as one and the decay curve is scaled so that the maximum value, i.e., the value of the decay curve at $T_i$ is zero decibels. Schroeder backward integration method is coupled with linear regression using line of best fits to its slope. The RT is then computed based on the slope of the line. Although this provides accurate estimates of the RT, it may not always be practical or even possible to measure RIR in the room (Schulte, 2002). Tsai & Hsu, (2014) proposed a method that blindly estimates the RT by analyzing the distribution decay rates of the observed reverberant speech signal. The authors show that the negative-side variance of the distribution can be related to RT. The method requires a training phase to obtain the relation between the negative-side variance and the RT. In (Falk et al., 2010), the author develops a truly blind method for estimating RT using maximum like hood procedure. The estimates are obtained continuously and an ordered statistics filters is used to extract the most likely RT from the accumulated estimates. Additional article by (Prates et al., 2019) proposed a neural network to determine reverberation time of the room. The author used mean square and cross entropy error. However, only comparative result were presented in his research. Directional energy decay curve was presented in (Berzborn, et al., 2019). The author present a model that sound decay analysis measurement contain clear inconsistencies. Assessment review based on single channel algorithm to determine blind reverberation time estimation and estimation by chosen algorithms at different data base was proposed by (Löllmann, et al., 2019).The author present different conditions based on signal to noise ratio (SNR) and direct to noise reverberation ratio (DDR), much signal response was not considered in the result. BRT can be compared to other methods of measuring reverberation time, such as using an impulse response measurement system or using an acoustic analyzer. The main advantage of BRT is that it does not require any external equipment and can be done quickly and easily by anyone with basic knowledge of acoustics.

**Room Acoustic**

Room Acoustics concern the way sound is created, propagated, perceived, measured and modelled inside enclosures. Enclosures can be dwellings, offices, workshops, factory halls, lecture rooms, auditoria, concert halls, transportation terminals, etc. Room acoustics is the broad term that describes how sound waves interact with a room. Each room, and all the objects in it, will react differently to different frequencies of sound. Every speaker will sound different in different rooms. A room acoustics may significantly affect the overall intelligibility of the produced speech (Everest et al., 2001). The problem is degradation of the desired signal caused by the acoustics channel within and enclosed space. Because the sound source cannot always be located near the producer of desired sound signal, the received signal is commonly affected by reverberation introduced by multi-path propagation of the sound. The received signal generally consists of direct sound, reflections that arrive shortly after the direct sound (early reverberation), and reflections that arrive after the early reverberation (commonly called late reverberation). Room acoustics can be improved by adding acoustic treatments such as sound-absorbing panels, diffusers, and bass traps. These treatments help to reduce reverberation and improve clarity in the room.

**Listening Room Acoustics**

The single most important and influential link in the audio reproduction chain is also the least understood and most neglected - the listening room itself. Unfortunately, this is also the most difficult or costly "component" to change. What follows will be a brief overview of the immensely complex and multi-faceted topic of room acoustics and listening room design. There are many factors that influence the "sonic signature" of a given space. To try and illuminate them all would require and in-depth course on acoustics. The more conservative goal of this treatise is to explore a few of the topics most germane to the Audiophiles listening room environment. Three that stand out as important considerations are: room size, rigidity and mass, and reflectivity. Professionals prefer the term *reverb time or Rt-60,* is the amount of time (in seconds) it takes for a pulsed tone to decay to a level 60 dB below the original intensity (Limet al., 2015). A live room has a great deal of reflectivity, and hence a long Rt-60. A dead room has little reflectivity and a short Rt-60. RT-60 measurements are most useful in determining the acoustic properties of larger spaces such as mosques, auditoria (Scharrer & Vorlander, 2010). In smaller environs the Rt-60 measurements become as short as to be useless. In these confined spaces, individual reflections from nearby surfaces dominate the sonic picture and are the primary focus for the audiophile. Reflections can be both desirable and detrimental. Reflections arriving approximately 30-50 ms or more after the original will be perceived as separate sounds (Falk et al., 2010). This phenomenon is known as the Haas effect. It is these initial reflections that are most important to the brain in determining the apparent size of the listening room. By manipulating the ratio of direct vs. reflected sound, we can fool the brain into thinking we are listening in a larger room than actually exists (Vary & Raina, 2006).

**Metrics of room acoustics**

The room metrics are parameters that specify the acoustic quality of a room. In order to quantify the quality of sound in a room, several parameters are involved; which include early decay time, clarity and intelligibility. All these parameters are derived directly from, or with the help of, the Room Impulse Response (RIR). It is the acoustical footprint of a room.

However, a room does not have just one single room impulse response. The RIR is the combination of the direct and reflected sound at one position in a room caused by an impulse emitted from a source at another position in the same room. Thus different receiver and source positions will lead to different RIR in the same room. These many reflected sound field components together become reverberation.

**Reverberation time**

The time that it takes for sound pressure level (SPL) to drop by 60dB is taken as a measure of the damping characteristic of the room and is called reverberation time (RT) of the room. The greater the volume of the room in proportion to its surface, the more sound energy can be stored in the room's air. The approximate RT is given by Sabine's equation shown (Tsai & Hsu, 2014).

$$RT = RT_{60} = \frac{0.49V}{\sum A} \quad (3)$$

**Reverberation curve**

The RT can be measured using the reverberation curve, as shown figure 1, which shows the decay of SPL in a room after the sound sources have become quiet or turned off. Rooms with different geometry may have parts with different RT. This effect will make the reverberation curve have double or more slopes.

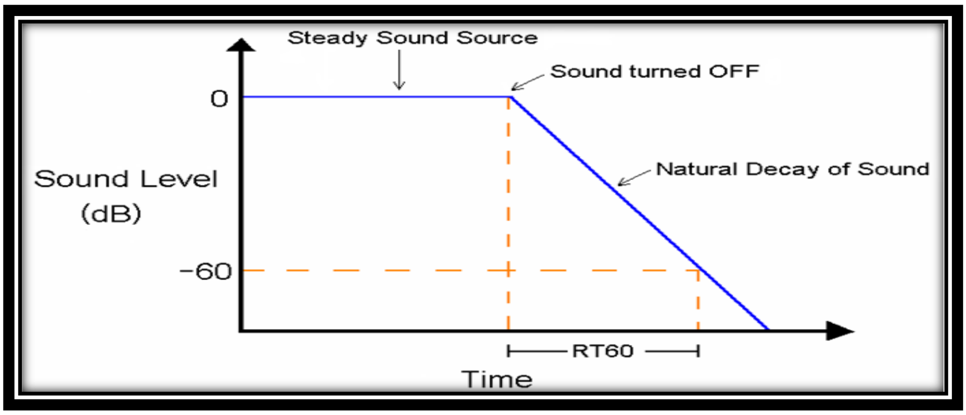


Figure 1: Reverberation time curves

**METHODOLOGY**

In this section, the methodology followed for comparing blind RT estimation in a room is described. For optimum acoustic room design, six steps are followed as shown in figure 2. The first step is to decide the room usage; multipurpose hall, lecture hall or conference room, afterward to compute the volume of the room. At this stage, the RT for the room can be obtained using graph shown in figure 3. This value is term as optimum value and is kept aside which shall be used for comparison with calculated value. The total surface area of the room is then determined.

Here, the room is divided into three parts which are: floor, walls and ceiling. To determine the finishes of the room, the room is categorized according to the material and items in the room, for instance carpet in the floor, concrete and wood panels for the walls, and banners and ceiling plaster for the ceiling. with known total surface area and finishes in the room, the total effective absorption area for the room is determine using relevant absorption coefficient according equation (4). The RT is calculated using Sabine's equation. This is the simple methods for computing the RT of a room. After the calculating using Sabine's equation, the value obtained is then compared with value obtained using graph. If the values are the same, the design is good. The room is overly treated if the RT is lower than the optimum value. Hence, the audience may experience fewer sound reflections from the room.

$A_e = \propto_1 A_1 + \propto_2 A_2 + \propto_3 A_3 + \propto_4 A_4 (5) +$ (4)

**RESULT AND DISCUSSION**

Blind Reverberation Time Estimation Using the Kurtosis of the Energy Decay Curve by (Ma et al. 2018) proposes a blind RT estimation method based on the kurtosis of the EDC. The method was tested on simulated and real-world impulse responses and compared with other methods. The results showed that the kurtosis-based method outperformed other methods in terms of accuracy and robustness. Xie et al. (2011) proposes a blind RT estimation method based on the slopes of the EDC. The method was tested on simulated and real-world impulse responses and compared with other methods. The results showed that the slope-based method was more accurate and robust than other methods. In addition, Blind Reverberation Time Estimation Using the Interquartile Range of the Energy Decay Curve by (Wang et al. 2015) proposes a blind RT estimation method based on the interquartile range (IQR) of the EDC. The method was tested on simulated and real-world impulse responses and compared with other methods. The results showed that the IQR-based method was more accurate and robust than other methods.

In this work, two methods for blind estimation of RT using decay rate are compared. The methods are compared based on different additive noise level, i.e. SNR at 10dB and 20dB.

The two methods are spectral decay distribution and maximum like-hood distribution as described in literature review. In (Wen et al., 2008) and (Lollman et al., 2010), where we collected the data, an experiment was conducted and an algorithm was run on Matlab for each of the methods using T I C and T O C operation. The measurement was carried out in an enclosed and occupied room. Anechoic speech from TIMIT corpus (Gaubitch et al., 2012) was used for all the experiment. TIMIT contains ten sentences spoken by each of the 438 male and 192 females' talkers, giving a total of 6300 sentences.

Estimation error is the difference between estimated RT and optimum RT.

$Error, e = RT_{est} - RT_{opt}$ (5)

To determine the optimum value of RT, the graph of figure 4 was used from the known volume of the room. The volume of the room under consideration is 1200m3, therefore, the optimum RT for speech from the graph will be 0.8sec. The estimated RT for the room without additive noise is 0.6sec. Thus, the estimated error is 0.2sec. Positive and negative estimation error indicates over and under estimation respectively. Table 1 is the table for RT, error estimation and decay rate using two methods of blindly estimating RT for SNR 20dB. It describes the room acoustics impulse response. The errors are obtained from experiment measurements while the decay rate is calculated using the formula describe in equation (5). Figure 3 is the plot from table 1. It can be observed that both methods provide accurate estimate with ± 2secs for all cases of RT ≤ 0.8 secs. Table 2 shows the room acoustic response for SNR 10dB. From the table, figure 4(a) is plotted. It can be observed that with SNR of 10dB, estimation error has increase within RT ≤ 0.8sec for instance at RT 0.2sec and 0.4sec, estimated error is ≥0.2. Figure 4(b) is the decay rate curve for the RT. It can be observed that the as RT increases the decay rate is decrease, that is an inverse relation. This indicates that the sound is dying out with time.

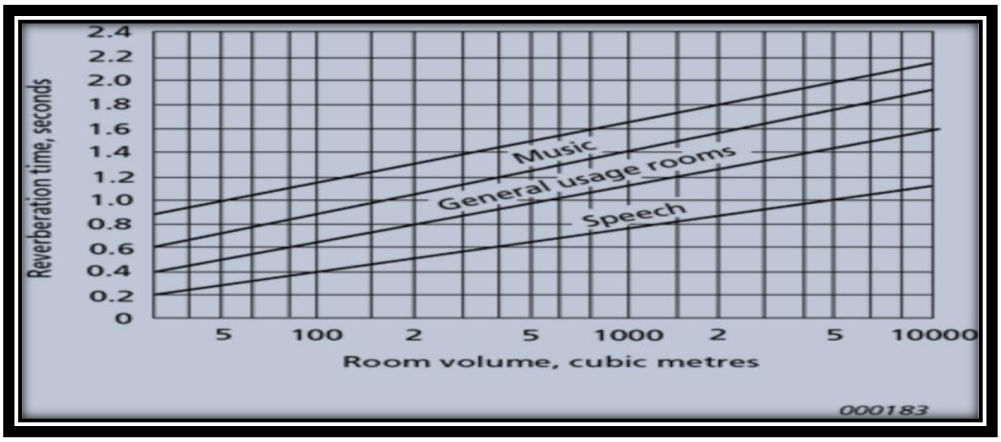


Figure 2**:** Reverberation time plot

**Table 1: Reverberation time estimation for SNR 20dB**

| For SNR 20dB | | | |
|---|---|---|---|
| RT (s) | Error $_{SDD}$ | Error $_{ML}$ | Decay rate |
| 0.20 | 0.12 | 0.19 | 34.54 |
| 0.30 | 0.11 | 0.02 | 23.03 |
| 0.35 | 0.05 | 0.08 | 19.79 |
| 0.40 | 0.08 | 0.00 | 17.27 |
| 0.50 | 0.10 | -0.10 | 13.82 |
| 0.54 | 0.04 | 0.08 | 12.82 |
| 0.60 | 0.15 | -0.16 | 11.52 |
| 0.70 | 0.20 | -0.15 | 9.87 |
| 0.80 | 0.18 | -0.13 | 8.64 |
| 0.86 | -0.18 | 0.01 | 8.08 |
| 0.90 | 0.18 | 0.00 | 7.68 |
| 1.00 | 0.80 | 0.19 | 6.91 |

**Table 2: Reverberation time estimation for SNR 10dB**

| **For SNR 10dB** | | | |
|---|---|---|---|
| **RT (s)** | **Error $_{SDD}$** | **Error $_{ML}$** | **decay rate** |
| 0.20 | 0.32 | 0.32 | 34.54 |
| 0.30 | 0.28 | 0.18 | 23.03 |
| 0.35 | 0.22 | 0.17 | 19.79 |
| 0.40 | 0.34 | 0.80 | 17.27 |
| 0.50 | 0.48 | 0.00 | 13.82 |
| 0.54 | 0.45 | 0.20 | 12.82 |
| 0.60 | 0.78 | -0.10 | 11.51 |
| 0.70 | 1.00 | -0.08 | 9.87 |
| 0.80 | 0.58 | 0.30 | 8.64 |
| 0.86 | 0.00 | 0.32 | 8.08 |
| 0.90 | 0.00 | 0.30 | 7.68 |
| 1.00 | 0.00 | 0.20 | 6.91 |

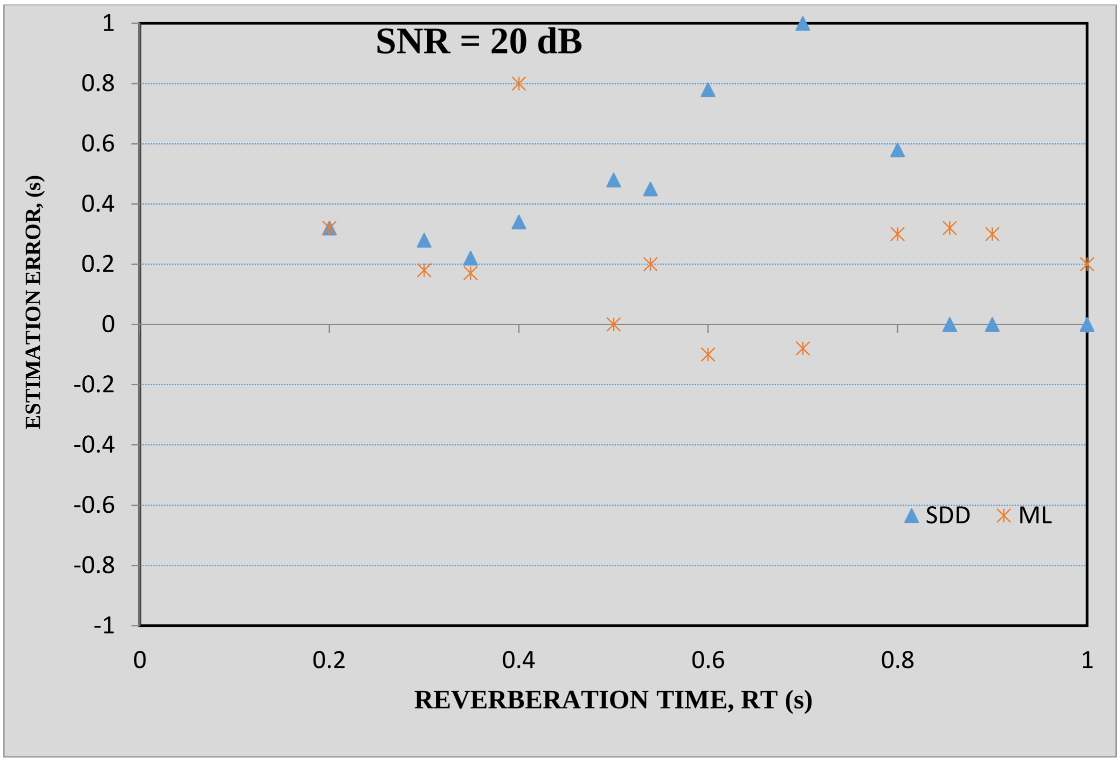


Figure 3: Reverberation time estimation with 20dB

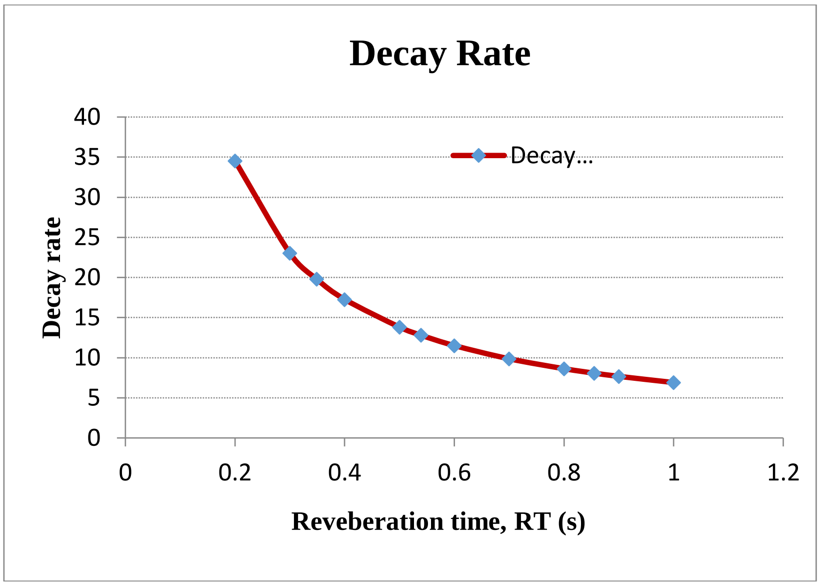


Figure 4: (a) Decay rate curve

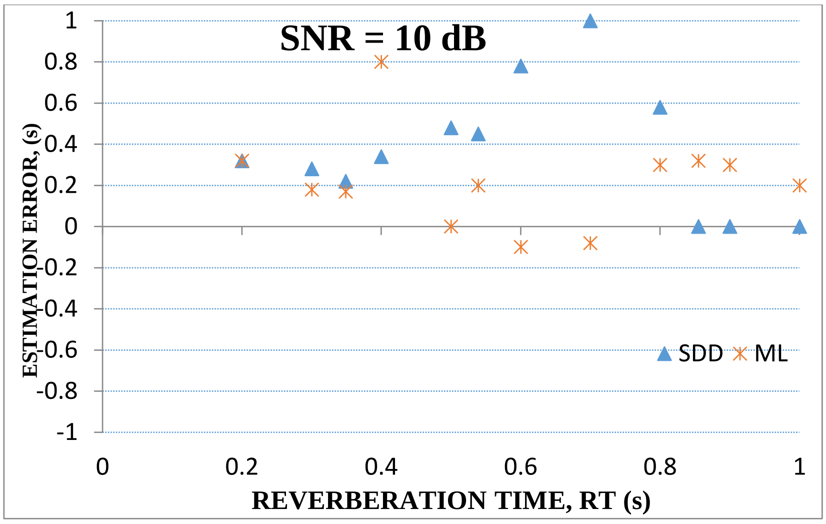


Figure 4: **(b)** Reverberation time estimation with 10dB

## CONCLUSION

This paper compare two methods of estimating RT blindly by observing the decay rate of the speech slope distribution (SDD) and maximum like-hood (ML). The effect of SNR on the analyzed data was discussed. It can be concluded from the results that the compared methods provide accurate estimates within ±0.2sec for RT≤ 0.8sec for SNR > 10dB. The key effect of additive noise on all methods is a positive bias of the estimation error which results in estimation error of e ≥ 0.2sec

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