SOFTWARE DEVELOPMENT FOR ROOM IMPULSE RESPONSE PROCESSING

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This document describes the room impulse response processing of a software developed for calculating the acoustical parameters EDT, T20, T30, C50, C80, IACC and IACCearly, according to ISO3382. In addition, transition time (Tt) is calculated, allowing to calculate EDTt, CTt and IACCt, and giving an approach of early sound field behavior. Calculations can be made for octave or third octave bands, according to IEC-61260 filters specifications. Also multiple RIRs can be processed, allowing the user to analyse the averaged or the individual measurements. The software developed is compared with commercial softwares EASERA, Aurora and AARAE, showing good and consistent results. The code is written in Python language and published online.

Keywords: Reverberation time, Clarity, Interaural Cross Correlation, Transition time, Software

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1. Introduction

There are many acoustical parameters that try to describe different aspects of room acoustic. Most of them are calculated with a fixed procedure, ignoring the existing differences between sound field behavior in rooms. One of these differences is the time limit between early and late sound fields. The classical theory established the time limit to a constant in the range from 50 ms to 80 ms, without further analysis. The same occurs with the limits (expressed in dB) for calculation of reverberation parameters like EDT – T20 – T30. And there's no need of being an expert to notice that rooms with similar reverberation time can sound widely different. And that's because between rooms the sound field evolves differently over time.

With this in mind, the developed software can calculate acoustical parameters EDT, T20, T30, C50, C80, IACC and IACCearly according to ISO3382, with the addition of calculating such parameters considering the transition time (Tt) between early and late sound field of the processed measurement. The developed software (called APC, and so referred to from now on), can manage multiple measurements, allowing to get for each calculated parameter the average, the maximum, the minimum, and the standard deviation, in addition to the calculation made for each individual measurement. As an input, APC software takes impulse response measurements, or sine sweeps measurements and the inverse filter. Also, all plots can be exported as PNG images, and table data can be exported as CSV files. The parameters can be calculated in octave or third octave bands, accomplishing IEC61260 filters specifications.

2. Theoretical framework

2.1 Filter bank

The filtering section is based on the IEC-61260 standard [1], that specifies the nominal center frequencies for the octave and third-octave passband filters using a base 2 system. The filter must be 8th order and the upper and lower band limits are established too, among other specifications. In the software, the filter implementation is done through the Scipy sosfiltfilt function. This method implements a forward-backward digital filter using cascaded second-order sections as shown below in equation 1. The SOS coefficients are produced by Butterworth IIR 8th order filter. The main benefits in contrast to other implementations are less phase delay and ringing at the output [2].

$$H(z) = \prod_{k=1}^{L} H_k(z) = \prod_{k=1}^{L} \frac{b_{0k}+b_{1k}z^{-1}+b_{2k}z^{-2}}{1+a_{1k}z^{-1}+a_{2k}z^{-2}} \tag{1}$$

Traditional band-pass filters can influence the measurement due to the filter ringing, specially at low reverberation times. This increases when a third-octave filtering is used, producing even more ringing. The forward-backward method significantly reduces the error in reverberation time evaluated from the decay curves [3].

2.2 Truncation time

In room impulse response measurements, the noise represents one of the major weaknesses because of influences in the decay curve and thus in the acoustical parameters. The treatment of noise and its compensation varies from one software to another. Different methods for compensation are implemented by the truncation of the RIR through an iterative or non-iterative process.

Lundeby’s method [4] is based on an iterative algorithm that searches for the interpolation between the linear regression of the IR exponential decay and the noise floor. The procedure consists of the steps shown in Figure 1.

The chosen initial interval is a window of 10 ms length, then for the linear regression, a point 6 dB above the noise floor is selected. Later in the iterative process, 6 intervals are used per 10 dB slope decay and again a point 6 dB above the noise floor. It’s decided to use 10 iterations or an error between the Crosspoint tt_i and tt_{i-1} less than 0.001.

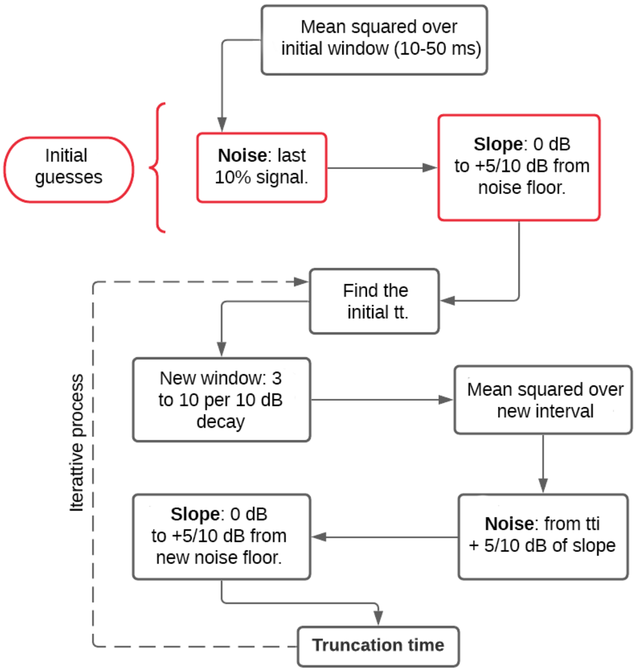

Figure 1. Block diagram of Lundeby's algorithm.

Another method is the Pepino's algorithm [5]. As lundeby's one is also an iterative process: start from a split function made up of a linear function and a constant, and search the best fitting to the impulse response. This function is defined in equation 2.

$$\hat{y}(n) = x_1 t + x_2, \;\; x \leq x_3 \; \hat{y}(x_3), \;\; n > x_3 \quad (2)$$

With n the total samples in the interval time, x_3 the crosspoint, x_2 the signal level on n=0 and x_1 the slope of the exponential decay. Furthermore, the resolution $R = T/N$ where N is the quantity of x_{3i} in the initial vector and T the duration of the impulse response. After realizing the procedure described in figure 2 the final cross-point it's defined 6 dB above the obtained. This is to guarantee that the exponential decay won't be affected in any way by the noise floor.

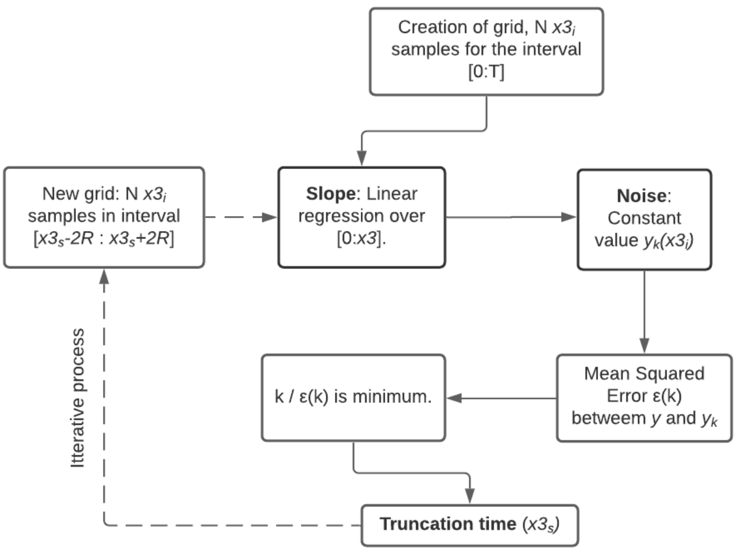

Figure 2. Block diagram of Pepino's algorithm.

The proposed Roge's method for IR truncation is formed by the next steps:

A. Filter the IR with a moving average filter.

B. Add 1 second at the end of the IR with last sample value.

C. Detect the maximum level of the IR [dB FS].

D. Linear interpolation between the *maximum* and the last sample of the IR.

E. Determinate the instant when the maximum difference between the linear function and the IR occurs.

F. Trunc the IR in the maximum difference instant.

G. Repeat from step B for more robustness (one repetition is enough).

2.3 Acoustic parameters

The acoustical parameters calculation follows the ISO 3382-1:2009 standard [6], such as reverberation time based on 20/30 dB evaluation range (T20-T30) and the early decay (EDT), Clarity at 50-80 ms (C50-C80), and Inter Aural Cross Correlation (IACC). Moreover, the software developed introduces the transition time (Tt) calculation, allowing the EDT to be evaluated on the transition time range (EDTt), the Clarity and IACC at transition time (Ct and IACCt).

2.3.1 Transition time

The traditional theory divides the temporal limit for direct and reflected sound with an interval set at 50-80 ms. Transition time of a room impulse response can be interpreted as the time at which all the room reflections become heavily overlapping, and therefore the deterministic behaviour of the sound field turns to stochastic [7]. It is defined based on the cumulative energy over the reflections of the normalized decay cancelled impulse response. The decay cancelled impulse response (The outliers of the IR) is obtained by subtracting the median filter to the IR. Then, the transition time is when the cumulative energy reaches 99%. [17]

$$T_t(t) = t_t \ : \ edf(t) = \frac{cumsum\left(RIR_{out}(t)\right)}{\left(cumsum\left(RIR_{out}(t)\right)\right)} = 0.99 \tag{3}$$

$$RIR_{out} = EDC(t) - RIR_{median}(t) \tag{4}$$

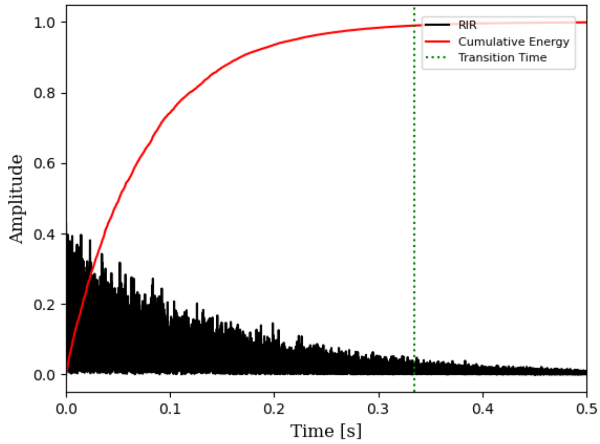

Figure 3. Transition time versus the RIR and the cumulative energy.

Based on these results, the paper presents the EDTt and CTt parameters which are involved with the transition time. For EDTt, a linear fit on the energy decay curve between 0 dB and the transition time is performed and with the slope, the equation (6) is applied. For CTt, the integration limit is determined by the transition time.

2.3.2 Reverberation

To obtain the reverberation time previous a linearization of the exponential decay curve smoothed RIR is required. Three methods are employed: the Schröeder integral, the median filter, and the moving average filter.

Equation 5 describes the Schröeder integral which consists of the backward integration of the squared impulse response [8].

$$E(t) = \int_t^{\infty} h^2(t)dt = \int_0^{\infty} h^2(t)dt - \int_0^{t} h^2(t)dt \quad (5)$$

If the truncation time is not determined the results obtained used (5) could be sensitive to background noise (integration could let the noise be included). [9]

The median filter is a non-linear process that has been effective in reducing certain types of noise and periodic interference patterns without severely degrading the signal [10]. The theory behind the median filter is complicated and it's beyond the scope of the present paper.

The moving average filter operates by averaging a number of points (M) from the input signal (x) to produce each point in the output signal (y). Equation 6 describes this filter.

$$y[i] = \frac{1}{M}\sum_{j=0}^{M-1} x[i + j] \quad (6)$$

In other words, the moving average filter is a convolution of the input signal with a rectangular pulse having an area of one. [11]

The last two filters need a window vector of M values to achieve the output. Thus, a window frequency dependent is proposed in equation (7).

$$w = 2000 * log\left(\frac{f_s}{f_c}\right) \ [samples] \quad (7)$$

Where f_s is the sampling frequency and f_c is the band center frequency. The equation is obtained empirically, showing good results for all bands.

Finally, to obtain the reverberation parameters a linear fit on energy decay curve at certain dynamic ranges according to ISO 3382-2. The limits for the linear regression are:

- EDT (Early Decay Time): The upper limit is 0dB and the lower is -10 dB.
- T20: The upper limit start at -5 dB then the lower limit is -25 dB.
- T30: Upper limit of -5 dB and lower at -35 dB. For this parameter, it's necessary to get at least 45 dB of dynamic range.

Finally with the correspondent slope the EDT, T20, T30 can be obtained with equation 8:

$$EDT,\ T20,\ T30 = -\frac{60}{slope}\ [s] \quad (8)$$

2.3.3 Clarity

Barron asks if it is appropriate to use a single number to characterize the intimacy of an entire concert hall independently on where the listener is seated. The early-to-late signal-to-noise ratio C80, called the clarity factor, is the ratio of the sound energy arriving before, to that arriving after, the first 80 milliseconds from the arrival of the direct sound, expressed as a level. [12]

In the same way, if the first 50 milliseconds are evaluated the clarity factor for 50 ms is obtained.

$$C_{80} = 10 \log log \left(\frac{\int_{0}^{80} p^2(t)dt}{\int_{80}^{\infty} p^2(t)dt} \right) [dB] \tag{9}$$

$$C_{50} = 10 \log log \left(\frac{\int_{0}^{50} p^2(t)dt}{\int_{50}^{\infty} p^2(t)dt} \right) [dB] \tag{10}$$

2.3.4 Interaural Cross Correlation

The interaural Cross Correlation is a measure of the similarity of the sound arriving at two points, the two ears of the listener. Mathematically it is based on the interaural cross-correlation fraction defined as:

$$IACC_f(\tau) = \frac{\int_{t_1}^{t_2} p_L(t)\, p_R(t+\tau)dt}{\sqrt{\int_{t_1}^{t_2} p_L^2(t) \int_{t_1}^{t_2} p_R^2(t)\, dt}} \tag{11}$$

Where L and R are referred to the entrances to the left and right ear canals. After (9) the final IACC value is the maximum possible (it must be between -1 and 1) with τ varied over a range from -1 to +1 ms from the first arrival. [12]

The integration time can be varied with different results. For t_1= 0 and t_2=∞ the term is designated $IACC_{all}$. For t_1= 0 and t_2=80 ms the term is designated $IACC_{early}$.

3. Procedure

The APC software is a Python-based processor of room acoustic responses for acoustical parameters calculation. The process the software follows is shown in Figure 1. The software code and the synthetic IRs are available in: https://github.com/FranciscoRogeVallone/APC

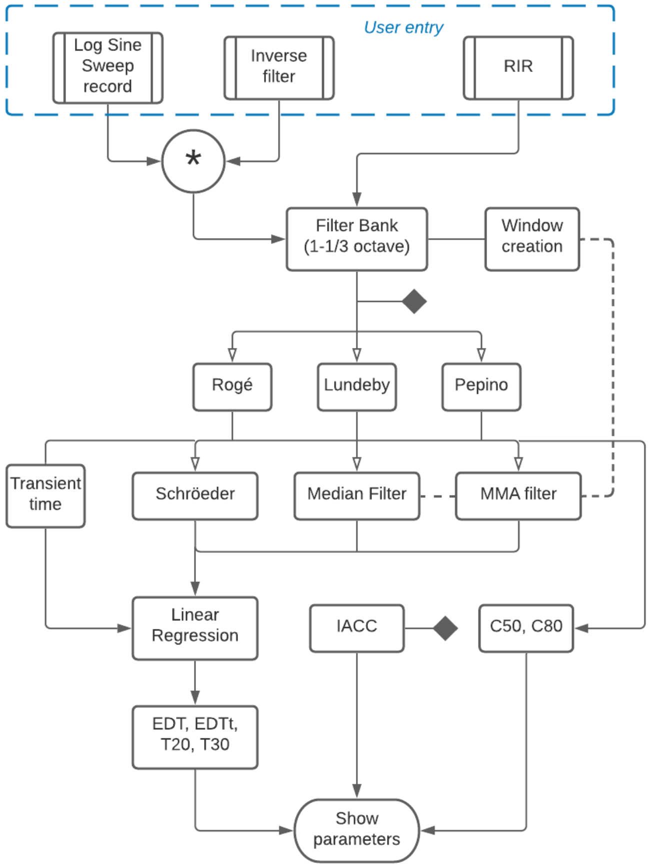

Figure 4. Block diagram of the APC software.

The user inputs are the measurements (mono or stereo). It can be an impulse response, or a sine sweep measurement and the inverse filter. If sine sweep measurement is loaded, it is convoluted with the inverse filter to get the room impulse response. Then, the filter bank is applied corresponding to the setup selected by the user. This setup consists in octave or third octave band selection, and minimum and maximum band selection.

After filtering the signals, truncation time is calculated by the user selected method. The available methods in the software are Lundeby, Pepino and Roge. Then the signals are smoothed by applying the Schoreder inverse integral, a median moving filter, or a mean moving filter, as the user selects.

In this way, the energy decay curve is obtained and then linearized for reverberation parameters calculation. This linearization is applied in different parts of the decay depending on the parameter as is explained in the previous section. The truncated signal is used to calculate IACC and clarity parameters.

After all this process, the calculated parameters are shown in a table, and the impulse response and the energy decay curve are plotted in a graph. The user can select the measurement for which to display the calculated parameters and the plot, and can also select the channel in case of stereo signal. Furthermore the user can select which band to plot. On the other hand, the average of all measurements for each parameter can be shown, allowing the user to select the parameter to display. The average, the minimum, the maximum and the standard deviation are shown in a table, and the average between a double deviation band are plotted in a graph.

4. Troubleshooting and Error control

Error sources are diverse, since the determination of an acoustical parameter is a process with many steps. As a first stage, errors in the measurement process can be present, such as not enough signal to noise ratio. This error drives into an error in the calculation process. At that moment, the software will raise an error message and stop calculation, to avoid the software from crashing. Others errors can be present too, such as microphone position in the near field of the source or spurious noises. These errors may not drive into an error in the calculation process, but users can detect them by RIR plot visualization.

As a second stage, as user inputs and setup are required, it could be an error source. If any of these are missing, the software prevents the user from doing calculations or exporting data, and raises an error message. Also, troubles in the data loaded can be present, such as inputs with more than 2 channels, sample rate mismatch between sine sweep and inverse filter, or non-monophonic signal loaded as inverse filter. For these troubles, the software raises an error message notifying the issue.

Finally, as dealing with computation, errors such as insufficient memory to calculate a set of measurements can take place. In this case, the software will stop calculation and raise an error message indicating the calculation failure, to prevent crashing. Then, the user can continue using the software and try calculations with fewer measurements.

5. Results

For an optimal characterization of the designed software, three pairs of synthetized impulse responses are analyzed. The three RIR's contain a previously stipulated decay slope with

Gaussian white noise. Those slopes are 0.5 s, 1s, and 2s. In this process, three more software are involved: EASERA from afmg, Aurora created by Angelo Farina, and AARAE created by Densil Cabrera [13,14,15]. For all the cases the truncation method used in the comparison is Roge's method

In addition, a comparison between the different truncation methods: the proposed in this document Roge's method, Lundeby's method, and Pepino's. Furthermore, the technique to smooth the impulse response is evaluated.

4.1 Software comparison

The parameters in this section are only evaluated on 1 second synthetic impulse response. The evaluation for the other synthetic impulse response are shown figures in Appendix B. Also, the Tables in Appendix B show the normalization error to APC for each software for more precise comparison.

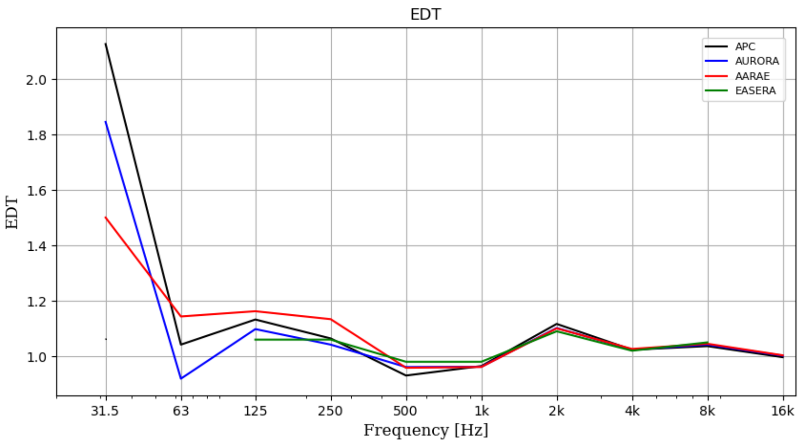

Figure 5. EDT comparison for 1 s synthetic impulse response.

Figure 5 for the 1 s synthetic impulse response reveals that for 31.5 Hz band the results are greater than other software. For the range between 63 Hz and 250 Hz the APC values are in the middle of AARAE and Aurora ones. In the case of 500 Hz the result appears to be slightly less than the media and beyond 500 Hz these are visually undetectable.

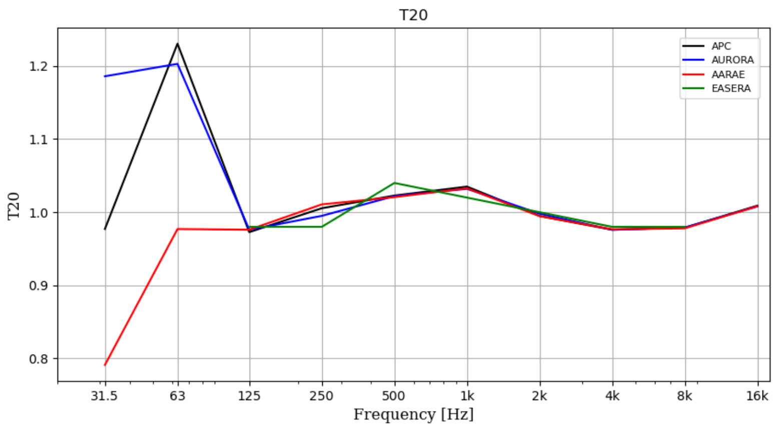

Figure 6. T20 comparison for 1 sec. synthetic impulse response.

Figure 6 reveals that the values beyond 125 Hz are pretty similar to the others softwares. For 63 Hz the result is most close to the aurora ones and for 31.5 Hz it is in the middle of Aurora and AARAE (which have a difference of almost 0.4 seconds).

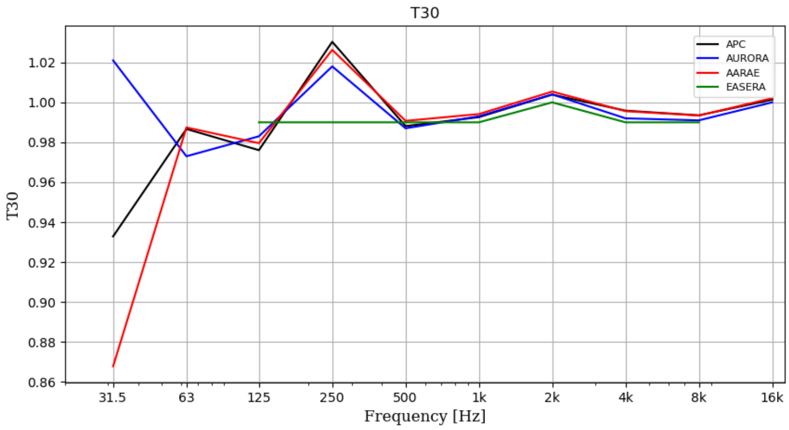

Figure 7. T30 comparison for 1 sec. synthetic impulse response.

The T30 comparison gives similar results from 500 Hz to 16 kHz. In the range of low frequencies, the APC values follow the AARAE tendencies except from 31.5 Hz when the APC result is in the middle of Aurora and AARAE.

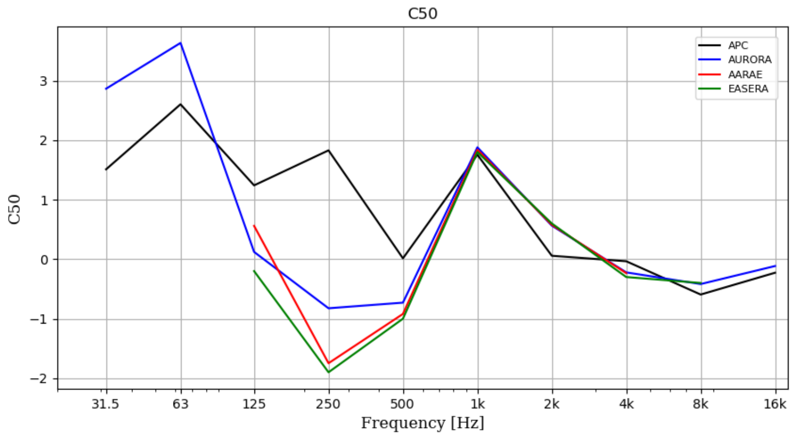

Figure 8. C50 comparison for 1 sec. synthetic impulse response.

C50 for 1 second synthetic impulse response shows atypical differences in the range of 125 Hz and 500 Hz. The figures in Appendix B for 0.5 sec and 2 sec are more in concordance with the software. Even the Aurora software shows a huge deviation in 63 Hz for the 2 seconds RIR.

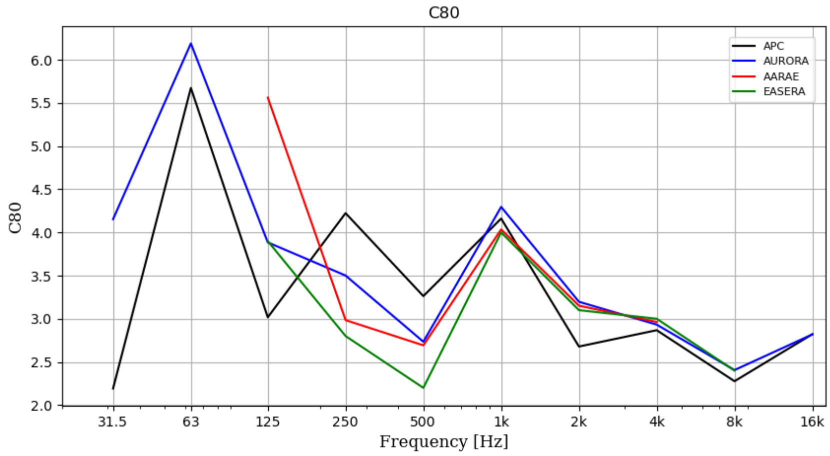

Figure 9. C80 comparison for the 1 sec. synthetic impulse response.

Figure 9 reveals a greater deviation for low frequencies. In high frequencies, less difference is noted. Nevertheless, the differences between the software are significant in the range of 31.5 Hz to 1 kHz.

IACC comparison is done according to the ISO 3382 standard. For this purpose, the impulse response was taken with a dummy head in La usina del arte Symphony hall. [16]

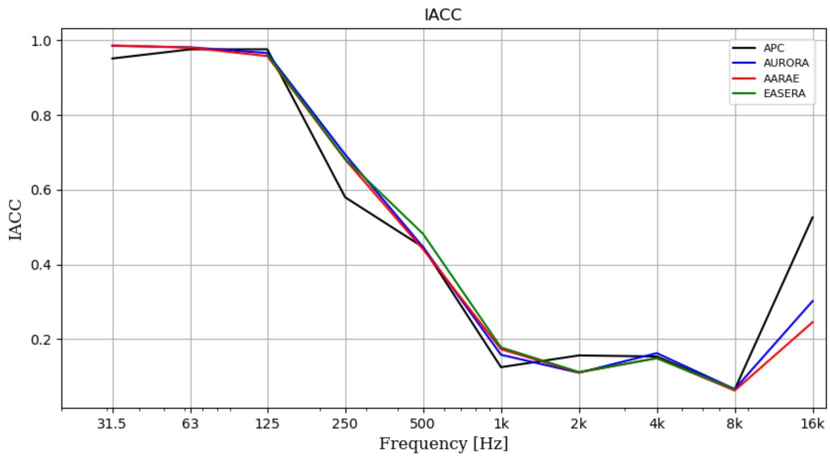

Figure 10. IACC comparison for a real impulse response from a dummy head.

Figure 10 remarks some local points where the difference is notable, these are 250 Hz, 2 kHz and 26 kHz. In the other cases, the values are really close to each other even between the different software.

4.2 Truncation method

The different truncation time methods are evaluated with a 1 second synthetic impulse response. In Appendix C the percentage deviation to Lundeby's method results is given.

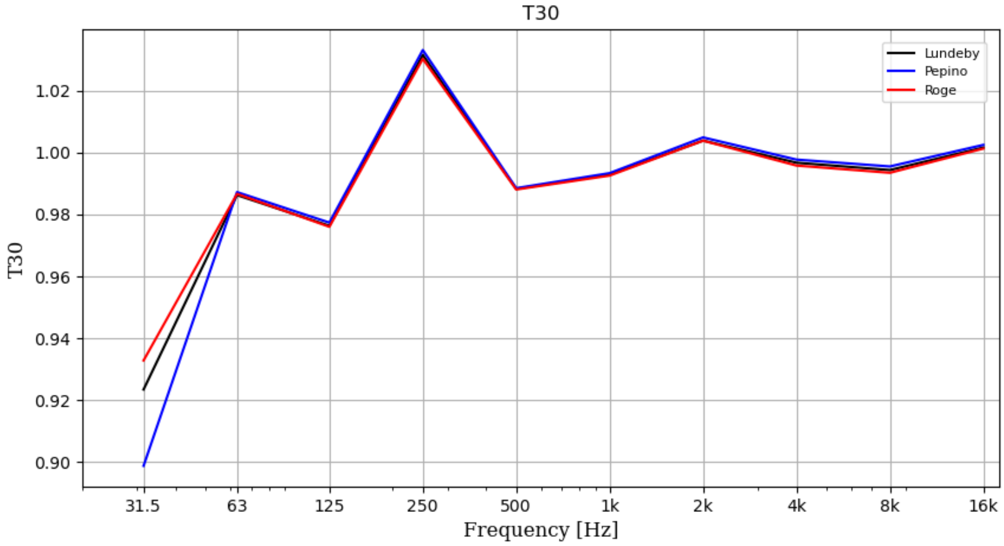

Figure 11. T30 comparison for different truncation methods.

The bigger difference for all cases is the T30 parameter in the 31.5 frequency band where the Roge's method is less than 10 msec to Lundeby's one and 30 msec to Pepino's.

4.3 Smooth method

As explained in section 2 three different methods for smooth the impulse response are employed. To test the Schröeder integration, Median filter and MMA filter a synthetic impulse response of 1 second is used with the Roge's truncation method.

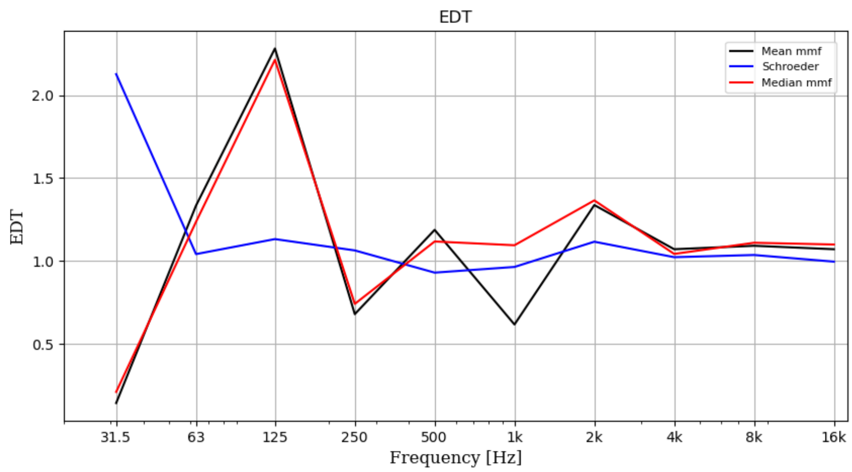

Figure 12. EDT comparison for different smooth methods.

EDT shows the bigger difference in 31.5 Hz band when the difference reaches almost 2 seconds of difference between methods. Then the Schröeder integration is more stable around 1 second and median and MMA filters are more unstable.

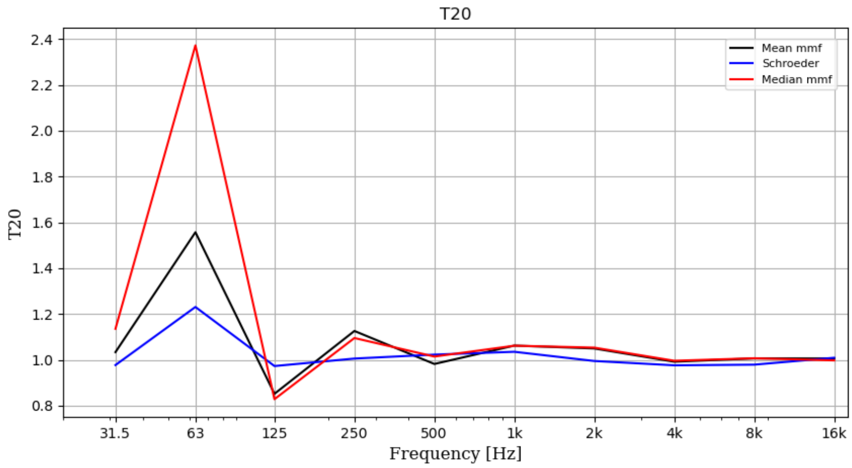

Figure 13. T20 comparison for different smooth methods.

Figure 13 reveals the same tendency: Schröder most stable than others. The biggest difference is founded at 63 Hz when the median filter has a maximum of 2.37 s, MMA filter 1.56 s and Schröeder 1.23 s.

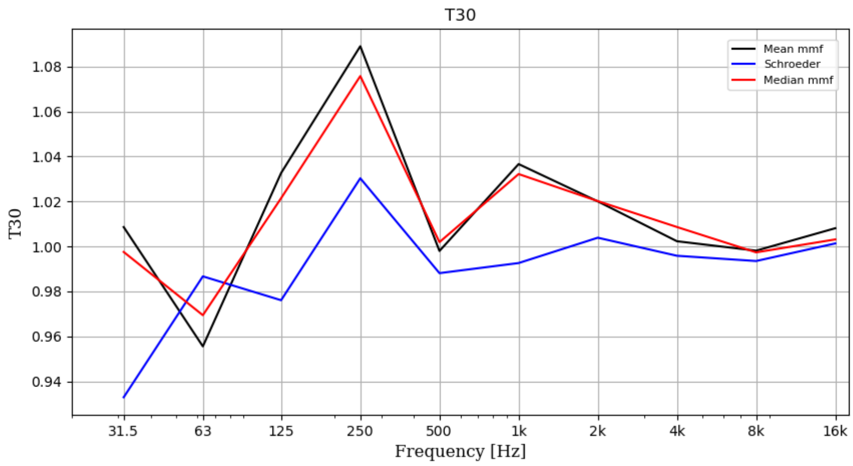

Figure 14. T30 comparison for different smooth methods.

T30 is the parameter with less deviation between the methods (note the scale of x axis in comparison with EDT-T20). Again, a more stable Schöeder method. Median filter and MMA filter with a more unstable tendency and greater values.

5. Conclusions

Section 3.1 clearly shows good and consistent results from APC reverberation parameters (EDT-T20-T30) in comparison to other software. The energy parameters reveal that is not a unique way to approach the problem and it is for that the great deviation that presents C50 and C80 specially at low frequencies.

In our particular case all the tables and figures show that for 250 Hz band is when the results are more distant from the EASERA, AARAE and Aurora results. This is an indication to debug the code and find the cause of this problem in order to present more consistent results.

Section 3.2 reveals that Roge's method proposed in this report is a good alternative to find the truncation time of the RIR's. The difference between Lundeby's and Pepino's method is close to 0%. It is important to remark that the proposed method is not an iterative algorithm so the speed of calculation is way greater.

The smooth method section clearly shows that the Schröeder inverse filtering method is the best solution in terms of stability results and calculation velocity. Median filter and MMA filter need more computer processing and takes a bit more time to do.

The last section reveals that the transient time is not really a constant value for all frequencies and that the method proposed gives reasonable values. In addition, the EDTt would be a good way to estimate the reverberation time of the direct sound.

A set of future implementations are proposed. The possibility to record audio with the corresponding Log-Sine sweep and inverse filter, do a calibration with an input value or a calibration file, and the integration with a 3D RIR's project to build a versatile and strong software for the RIR's analysis.

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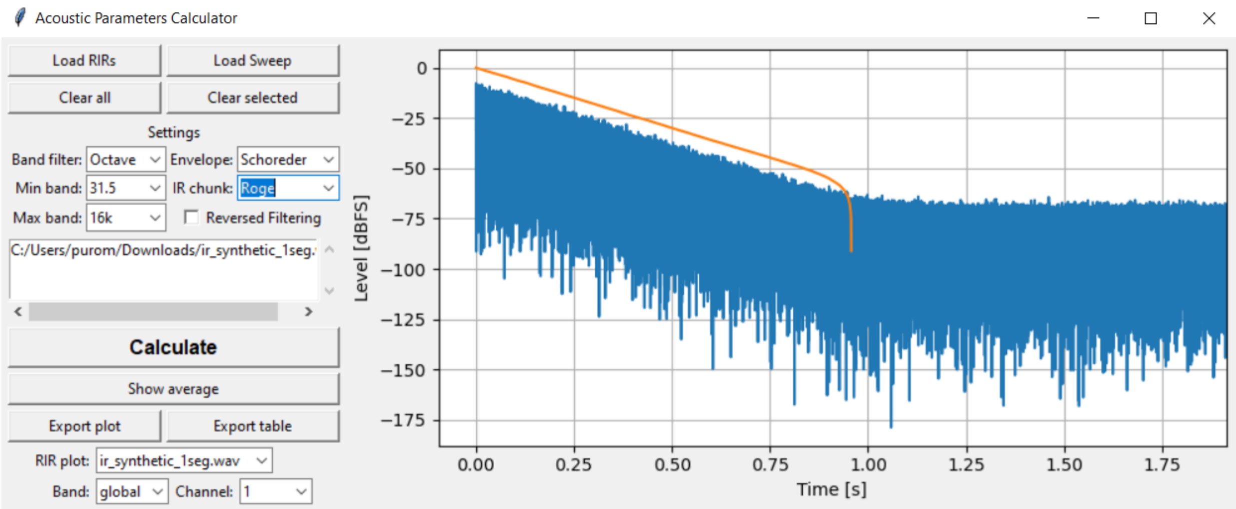
7. Appendix A. GUI

The software code and the synthetic IRs are available in:
https://github.com/FranciscoRogeVallone/APC.



	global	31.5	63	125	250	500	1k	2k	4k	8k	16k
EDT	1.02	2.13	1.04	1.13	1.06	0.93	0.96	1.12	1.02	1.04	1.0
T20	1.0	0.98	1.23	0.97	1.01	1.02	1.04	0.99	0.98	0.98	1.01
T30	1.0	0.93	0.99	0.98	1.03	0.99	0.99	1.0	1.0	0.99	1.0
C50	-0.14	1.51	2.6	1.24	1.83	0.01	1.76	0.06	-0.03	-0.59	-0.23
C80	2.78	2.19	5.67	3.02	4.22	3.26	4.16	2.68	2.87	2.28	2.82
Tt	0.33	0.48	0.37	0.32	0.34	0.33	0.33	0.35	0.33	0.34	0.34
EDTt	1.0	1.26	1.2	0.95	0.96	0.99	1.02	1.02	0.99	1.0	1.01
CTt	19.96	23.81	23.47	20.59	20.39	20.25	20.31	20.09	20.14	19.99	20.01
IACC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IACC early	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 15. Guide User Interface of APC software.

8. Appendix B. Parameters comparison.

Table 2. APC results.

0.5 s.	**31.5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**16000**	**Global**
EDT	0.875	0.385	0.499	0.658	0.504	0.492	0.519	0.481	0.531	0.490	0.506
T20	0.663	0.476	0.512	0.442	0.522	0.509	0.506	0.506	0.493	0.510	0.502
T30	0.552	0.431	0.537	0.491	0.489	0.509	0.505	0.499	0.494	0.503	0.499
C50	4.331	8.115	5.978	5.203	6.587	3.954	4.055	4.761	3.826	5.024	4.554
C80	6.659	14.954	11.897	6.857	9.463	10.052	8.995	8.976	8.470	9.310	8.978
1 s.	**31.5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**16000**	**Global**
EDT	2.127	1.042	1.133	1.064	0.930	0.965	1.117	1.023	1.037	0.997	1.018
T20	0.977	1.231	0.973	1.005	1.023	1.035	0.995	0.976	0.979	1.009	0.996
T30	0.933	0.987	0.976	1.030	0.988	0.993	1.004	0.996	0.994	1.001	0.998
C50	1.510	2.602	1.240	1.828	0.014	1.755	0.057	-0.035	-0.594	-0.228	-0.144
C80	2.192	5.674	3.018	4.224	3.263	4.161	2.678	2.868	2.277	2.821	2.779
2 s.	**31.5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**16000**	**Global**
EDT	1.638	2.468	2.056	2.088	2.021	2.019	1.945	1.984	1.995	1.976	1.976
T20	2.280	2.085	1.977	2.061	2.156	2.111	1.991	2.008	2.030	2.007	2.019
T30	2.463	2.184	1.826	2.003	2.080	2.044	2.004	1.993	2.024	2.013	2.014
C50	-2.163	-2.039	-3.132	-2.798	-4.112	-2.932	-3.918	-3.756	-4.042	-3.398	-3.804
C80	-1.130	-0.382	0.123	-0.885	-1.438	-0.305	-1.182	-1.418	-1.449	-0.878	-1.286

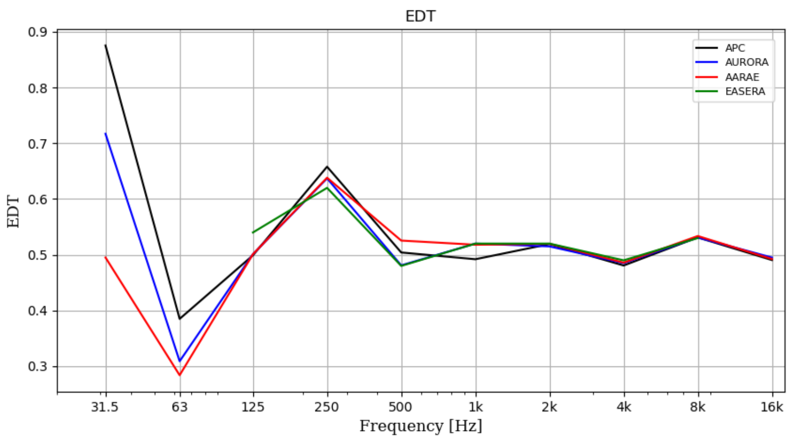


Figure 16. EDT comparison for 0.5 s synthetic impulse response.

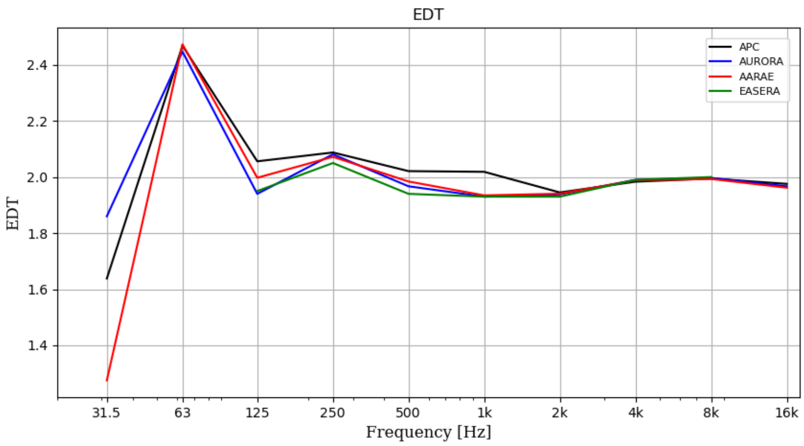


Figure 17. EDT comparison for 2 s synthetic impulse response.

Table 3. Percentage deviation to APC EDT results.

EDT 0.5s	**31.5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**16000**	**Global**
AURORA	-22.08%	-24.59%	0.41%	-3.28%	-4.80%	5.39%	-0.81%	0.88%	-0.01%	0.91%	0.75%
AARAE	-76.81%	-35.59%	0.41%	-3.09%	4.07%	5.01%	0.10%	1.06%	0.48%	0.37%	2.66%
EASERA	-	-	7.60%	-6.12%	-5.02%	5.39%	0.16%	1.89%	-0.20%	-	4.74%
EDT 1s	**31.5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**16000**	**Global**
AURORA	-15.23%	-13.39%	-3.15%	-2.13%	3.19%	-0.27%	-1.34%	0.06%	0.52%	0.55%	-1.44%
AARAE	-41.73%	8.88%	2.57%	6.14%	2.92%	-0.33%	-1.47%	0.29%	0.81%	0.69%	3.67%
EASERA	-	-	-6.85%	-0.40%	5.07%	1.57%	-2.46%	-0.34%	1.28%	-	0.15%
EDT 2s	**31.5**	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**16k**	**Global**
AURORA	11.92%	-0.87%	-5.98%	-0.32%	-2.75%	-4.59%	-0.36%	0.32%	0.11%	-0.44%	0.75%
AARAE	-28.50%	0.19%	-2.94%	-0.75%	-1.86%	-4.35%	-0.23%	0.25%	-0.08%	-0.70%	2.66%
EASERA	-	-	-5.44%	-1.83%	-4.18%	-4.59%	-0.77%	0.32%	0.26%	-	4.74%

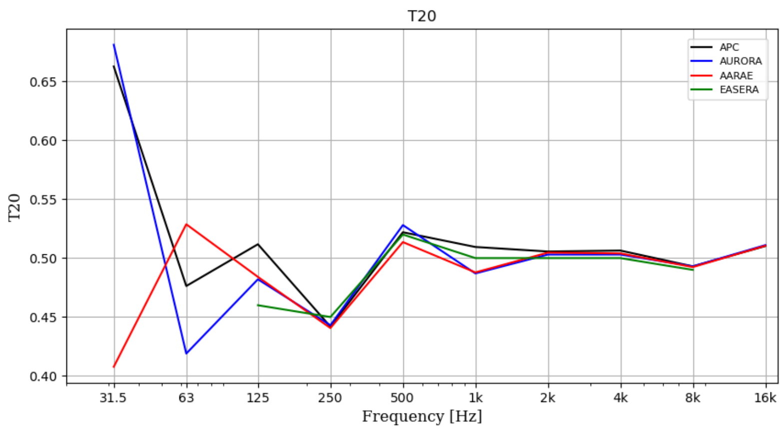


Figure 18. T20 comparison for 0.5 sec. synthetic impulse response.

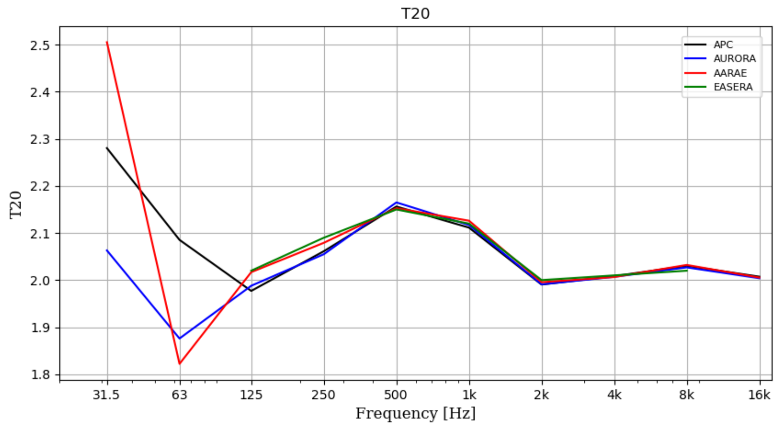


Figure 19. T20 comparison for 2 sec. synthetic impulse response.

Table 4. Percentage deviation to APC T20 values.

T20 - 0.5 s	**31.5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**16000**	**Global**
AURORA	2.70%	-13.68%	-6.17%	0.26%	1.15%	-4.60%	-0.52%	-0.68%	0.00%	0.16%	-0.47%
AARAE	-67.01%	20.75%	0.42%	-0.53%	-2.81%	0.18%	0.32%	0.19%	-0.12%	-0.11%	-2.22%
EASERA	-	-	-11.25 %	1.81%	-0.37%	-1.89%	-1.12%	-1.28%	-0.61%	-	-0.47%
T20 - 0.5 s	**31.5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**16000**	**Global**
AURORA	17.62%	-2.30%	0.34%	-1.05%	-0.07%	-0.30%	0.32%	0.00%	0.02%	-0.09%	0.63%
AARAE	-49.94%	-23.14%	0.01%	1.55%	-0.13%	0.07%	-0.34%	0.06%	-0.11%	0.00%	-0.01%
EASERA	-	-	0.74%	-2.60%	1.66%	-1.48%	0.52%	0.41%	0.12%	-	1.41%
T20 - 0.5 s	**31.5**	**63**	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**16000**	**Global**
AURORA	-10.53%	-11.16%	0.55%	-0.31%	0.40%	0.26%	0.02%	-0.07%	-0.17%	-0.17%	-0.47%
AARAE	17.65%	-2.96%	1.43%	1.16%	-0.57%	0.43%	0.23%	-0.02%	0.26%	0.07%	-2.22%
EASERA	-	-	2.13%	1.37%	-0.29%	0.40%	0.47%	0.08%	-0.51%	-	-0.47%

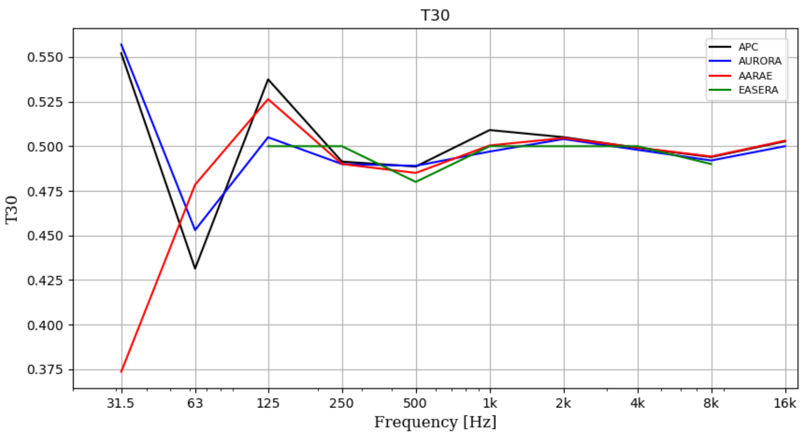


Figure 20. T30 comparison for 0.5 sec. synthetic impulse response.

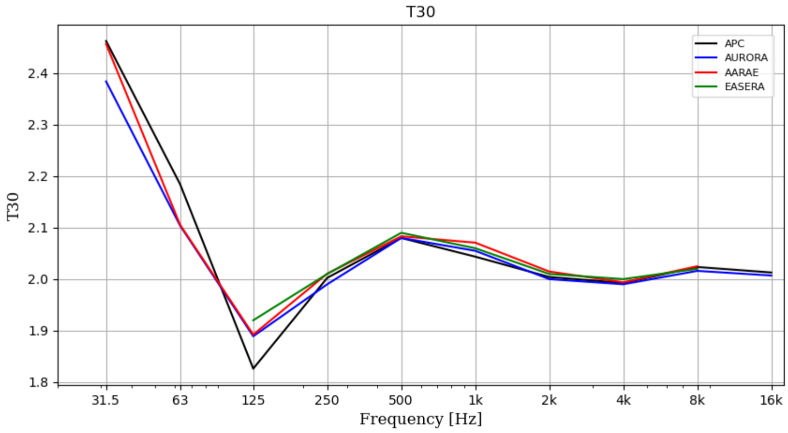


Figure 21. T30 comparison for 2 sec. synthetic impulse response.

Table 5. Percentage deviation for APC T30 values.

T30 - 0.5s	**31.5**	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**16k**	**Global**
AURORA	0.88%	4.76%	-6.43%	-0.28%	0.08%	-2.42%	-0.21%	-0.23%	-0.39%	-0.55%	0.22%
AARAE	-47.75%	9.82%	-2.10%	-0.28%	-0.74%	-1.72%	-0.10%	0.02%	0.06%	0.07%	0.40%
EASERA	-	-	-7.49%	1.72%	-1.79%	-1.81%	-1.01%	0.17%	-0.80%	-	0.22%
T30 - 1s	**31.5**	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**16k**	**Global**
AURORA	8.63%	-1.41%	0.71%	-1.21%	-0.11%	0.04%	0.01%	-0.39%	-0.25%	-0.13%	0.25%
AARAE	-7.50%	0.08%	0.36%	-0.39%	0.27%	0.15%	0.15%	-0.03%	-0.01%	0.08%	0.11%
EASERA	-	-	1.41%	-4.07%	0.19%	-0.26%	-0.39%	-0.59%	-0.35%	-	-0.76%
T30 - 2s	**31.5**	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**16000**	**Global**
AURORA	-3.29%	-3.82%	3.33%	-0.63%	0.00%	0.55%	-0.20%	-0.13%	-0.37%	-0.29%	0.22%
AARAE	-0.23%	-3.75%	3.49%	0.41%	0.16%	1.31%	0.53%	0.07%	0.07%	-	0.40%
EASERA	-	-	4.89%	0.37%	0.48%	0.80%	0.29%	0.37%	-0.18%	-	0.22%

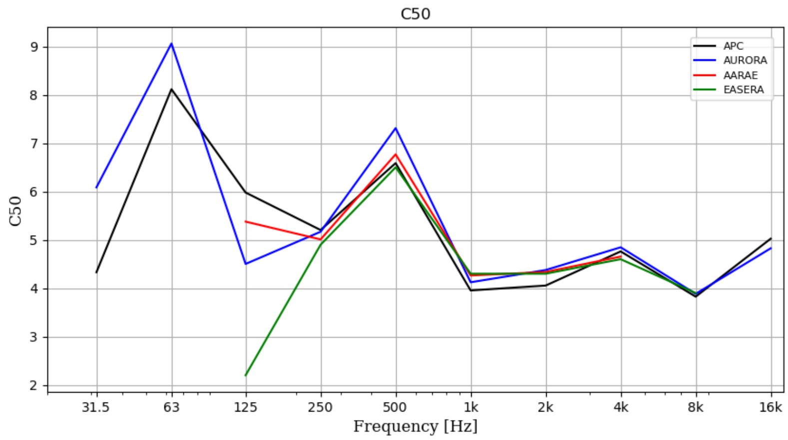


Figure 22. C50 comparison for 0.5 sec. synthetic impulse response.

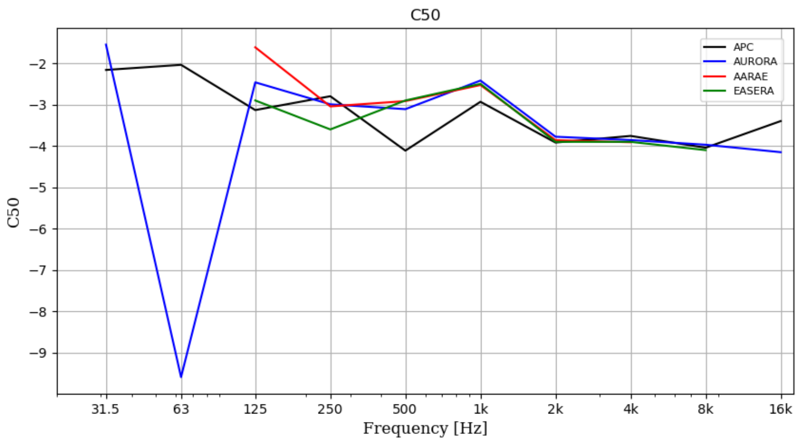


Figure 23. C50 comparison for 2 sec. synthetic impulse response.

Table 6. Percentage deviation from APC C50 values.

C50 - 0.5s	**31.5**	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**16k**	**Global**
AURORA	28.83%	10.43%	-32.79%	-0.68%	9.90%	4.10%	7.34%	1.76%	1.50%	-4.12%	-2.56%
AARAE	-	-	-11.19%	-3.87%	2.68%	7.26%	6.47%	-2.28%	-	-	-
EASERA	-	-	-171.74%	-6.19%	-1.33%	8.05%	5.70%	-3.50%	1.91%	-	5.13%
C50 - 1s	**31.5**	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**16k**	**Global**
AURORA	47.29%	28.38%	-916.40%	321.60%	101.94%	6.58%	89.81%	84.33%	-42.12%	-97.93%	14.73%
AARAE	-	-	-121.58%	204.60%	101.54%	4.52%	90.04%	85.18%	-	-	-
EASERA	-	-	720.01%	196.22%	101.42%	2.48%	90.42%	88.41%	-48.51%	-	27.95%
C50 - 2s	**31.5**	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**16k**	**Global**
AURORA	-39.52%	78.73%	-27.22%	6.52%	-32.23%	-21.20%	-3.75%	2.58%	-1.82%	18.12%	-2.56%
AARAE	-	-	-93.78%	8.07%	-41.08%	-16.00%	-1.52%	3.93%	-	-	-
EASERA	-	-	-8.00%	22.28%	-41.81%	-17.27%	-0.45%	3.68%	1.41%	-	5.13%

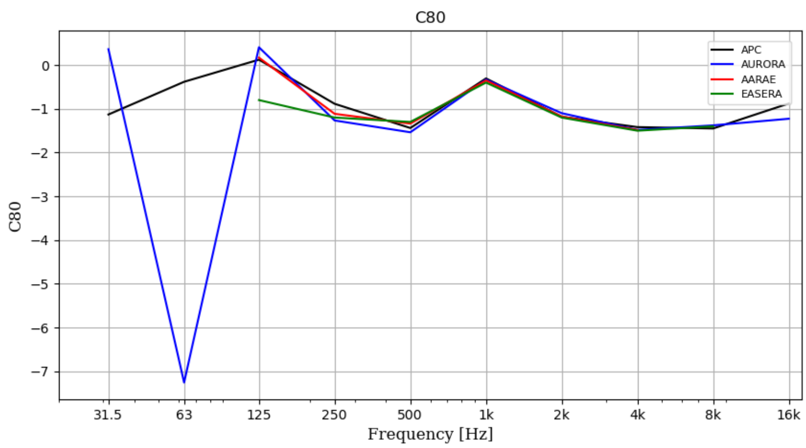


Figure 24. C80 comparison for 0.5 sec. synthetic impulse response.

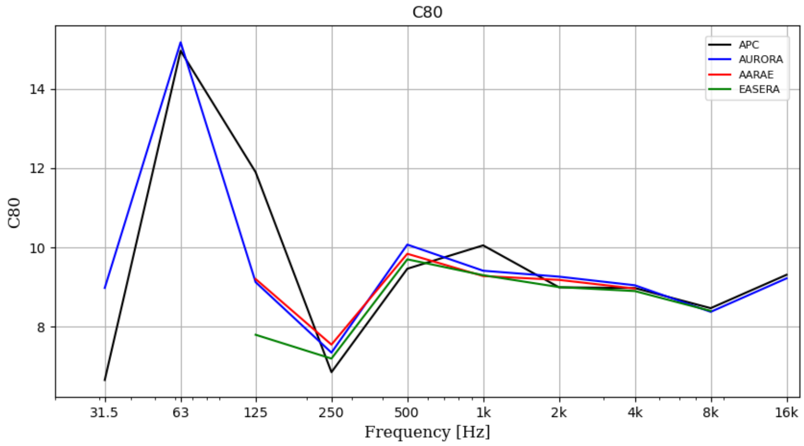


Figure 25. C80 comparison for 2 sec. synthetic impulse response.

C80 - 0.5s	31.5	63	125	250	500	1k	2k	4k	8k	16k	Global
AURORA	25.83%	1.41%	-30.37%	6.70%	6.04%	-6.79%	2.90%	0.78%	-1.11%	-0.97%	-1.11%
AARAE	-	-	-29.25%	9.20%	3.83%	-8.33%	2.04%	-0.15 %	-	-	-
EASERA	-	-	-52.52%	4.76%	2.45%	-8.08%	0.06%	-0.85 %	-0.83%	-	1.34%
C80 - 1s	**31.5**	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**16k**	**Global**
AURORA	47.23%	8.33%	22.33%	-20.65 %	-19.34 %	3.14%	16.22%	2.20%	5.37%	-0.08%	5.05%
AARAE	-	-	45.75%	-41.55 %	-21.19 %	-3.13%	15.01%	3.20%	-	-	-
EASERA	-	-	22.63%	-50.85 %	-48.31 %	-4.03%	13.60%	4.41%	5.13%	-	4.17%
C80 - 2s	**31.5**	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**16k**	**Global**
AURORA	411.33%	94.73%	69.67%	30.08%	6.35%	8.03%	-7.48%	4.33%	-5.18%	28.40%	-1.11%
AARAE	-	-	27.14%	20.58%	-7.48%	13.28%	-0.44%	4.54%	-	-	-
EASERA	-	-	115.43%	26.24%	-10.65 %	23.66%	1.48%	5.48%	-3.53%	-	1.34%

9. Appendix C. Truncation methods.

EDT	**31.5**	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**16k**
Lundeby	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Pepino	-0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Roge	0.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
T20	**31.5**	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**16k**
Lundeby	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Pepino	-0.15%	0.01%	0.02%	0.02%	0.01%	0.01%	0.02%	0.02%	0.02%	0.02%
Roge	0.23%	0.00%	-0.03%	-0.04%	-0.01%	-0.01%	-0.02%	-0.04%	-0.04%	-0.02%
T30	**31.5**	**63**	**125**	**250**	**500**	**1k**	**2k**	**4k**	**8k**	**16k**
Lundeby	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Pepino	-2.74%	0.10%	0.11%	0.15%	0.02%	0.05%	0.10%	0.10%	0.12%	0.09%
Roge	1.01%	0.04%	-0.03%	-0.12%	-0.02%	-0.03%	0.00%	-0.09%	-0.09%	-0.03%