EVALUATION OF GEOMETRY-BASED PARAMETRIC AURALIZATION

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This paper presents evaluation results of parametric auralization system. The auralization method, based on image-source and edge diffraction modeling, is briefly overviewed and evaluation of the auralization quality is performed both subjectively and objectively. As a case study the auralization of a lecture room is considered with three different musical stimuli. The evaluation results show that with sound of a clarinet the auralizations are almost identical than obtained with recording the anechoic signal in a real space. However, the auralizations slightly differ from the recorded ones with transient-like signals, especially at low frequencies below 600 Hz. Despite, the evaluation results proved that plausible and natural sounding monophonic or binaural auralization is possible with the current auralization algorithms.

INTRODUCTION

In this paper we report the results of a study in which a high quality auralization system is developed. In this paper the term auralization [1] is defined to encompass both room acoustic modeling and sound reproduction. The auralization system, the Digital Interactive Virtual Acoustics (DIVA) system, has been developed since 1994 at the Helsinki University of Technology [2]. Our goal has been to make as plausible auralization as possible based on the room geometry and material data.

In the DIVA auralization system the room acoustic modeling is divided into two main parts. First, the direct sound and early reflections are modeled with the image-source method [3, 4] that enables spatial and parametric representation of the early reflections. Second, late reverberation is modeled with an efficient late reverberation algorithm [5]. The detailed descriptions of the implementation of the applied image-source method and DSP structure of auralization have been presented earlier [6, 7, 8].

The design of an auralization system is an iterative process where one step by step approach the ultimate goal, an authentic auralization. The preliminary evaluation results with the same geometry, a lecture room, has been reported earlier [9, 10]. In this paper the evaluation of auralization quality has been carried out both objectively with a time-frequency analysis of ear canal signals, motivated by auditory perception [11], and subjectively with listening tests. As a novelty, we have included edge diffraction modeling [12, 13, 8] to the designed auralization system. In addition, some auralization parameters are redefined and tuned.

1. EVALUATION PROCESS

The evaluation of auralization quality is conducted by comparing recorded soundtracks (considered as reference signals) and auralized soundtracks (see Fig. 1). The reference signals have been recorded both with real-head recording technique [14, 15, 16] and using an omnidirectional measurement microphone. The preliminary evaluation consists of both static and dynamic auralizations. In this context dynamic auralization means that the listening position can change during the auralization process. However, in this article only results of evaluation of static auralizations are presented because in previous studies it has been found that dynamic movements of the listener do not help in the evaluation of auralization quality.

1.1. Recording of the reference signals

The real-head recordings were performed by playing anechoic stimuli with a small active loudspeaker (Genelec 1029A) in the studied space which was a lecture room (dimensions 12 m x 7.3 m x 2.6 m) presented in Fig. 2. Two recording positions r1 and r2 are also shown. To capture the binaural cues to the reference soundtracks small electret microphones (Sennheiser KE 4-211-2) were placed at the entrances of the blocked ear canals and connected to a DAT recorder. In addition, in the same positions (r1 and r2) monophonic recordings were made with an omnidirectional microphone (B&K 4192). Additionally, the background noise without any stimulus was recorded with both monophonic and binaural techniques, to be added to the auralizations.

To find out different aspects of auralization quality we used three different stimuli; clarinet (cla), guitar (gui), and drumming with a snare drum (dru). These signals were chosen because they have different spectral and

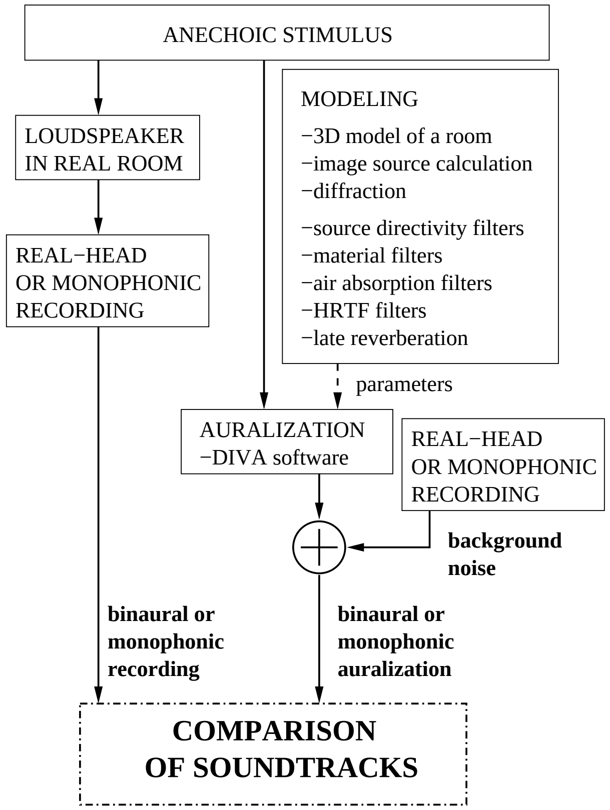

Figure 1: The framework of the evaluation is based on the comparison of recorded and auralized soundtracks. Both monophonic and binaural soundtracks are compared.

temporal content. The drum is a transient-like wideband signal while clarinet is a tonal signal containing hardly any transients. The acoustic guitar has both of them, a sharp attack and sustained tones.

1.2. Auralized soundtracks

The auralized soundtracks were prepared with the DIVA auralization system [2, 6] in which direct sound and early reflections are modeled with the image-source method, that enables separate auralization of them. The traditional image-source method is enhanced by computing edge diffractions which are included as diffraction image sources [7, 8]. Late reverberation is modeled with a recursive algorithm and the spectrum of the reverberant tail is shaped to include air and material absorption as well as diffuse field radiation characteristics of sound source. The parametric representation of the direct sound and early reflections define sound source directivity, air and material absorption, binaural computing as well as edge diffraction parameters. The auralization process is carried out in the time domain using digital signal processing. This auralization structure is flexible, it can be used for both static and dynamic rendering.

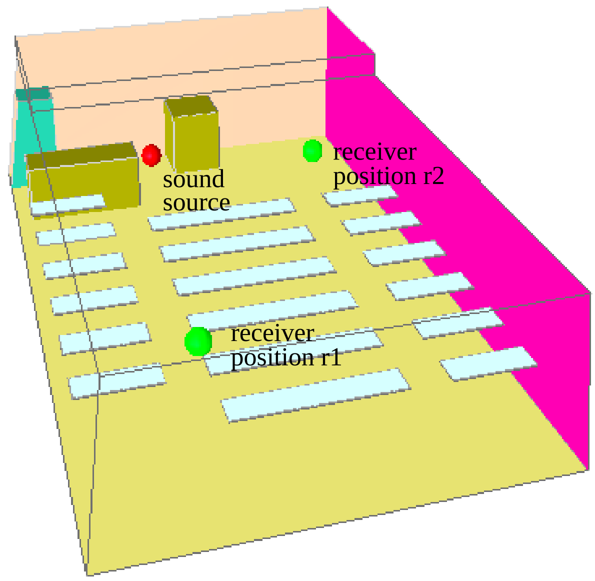

Figure 2: The 3D model of the studied lecture room. While recording binaural soundtracks the head was pointed to forward direction in recording positions r1 and r2. The height of the sound source was 1.2 m and the height of the recording positions were 1.7 m.

For this study we calculated two binaural and two monophonic sets of soundtracks with three stimuli. In both the binaural and monophonic sets, specular image sources up to fourth order were searched. In this geometry that means about 65 visible ones. For two sets (one binaural and one monophonic), in addition to specular reflections, first order diffraction components[1] were searched, resulting ca. 20,000 visible image sources. In both listening positions (r1 and r2), all except a few image sources were closer than 20 meters from the listening position corresponding in time less than 50 ms delay after the direct sound.

After sound rendering the recorded background noise was added to the auralized soundtracks and finally the levels of the soundtracks were adjusted to be the same than in reference recordings. In this study, we did not equalize the headphone response to avoid possible compensation problems [6].

1.3. Comments about the soundtracks

It can be argued that a binaural recording is not an optimal reference soundtrack. Real-head recordings perform optimally only when the size and the shape of the recording head corresponds the size and the shape of the lis-

[1] In this study, we considered as first order diffraction components sound paths in which one of the four reflections can be a diffraction. For example, such sound path as diffraction-specular-specular-specular or specular-specular-diffraction-specular can occur.

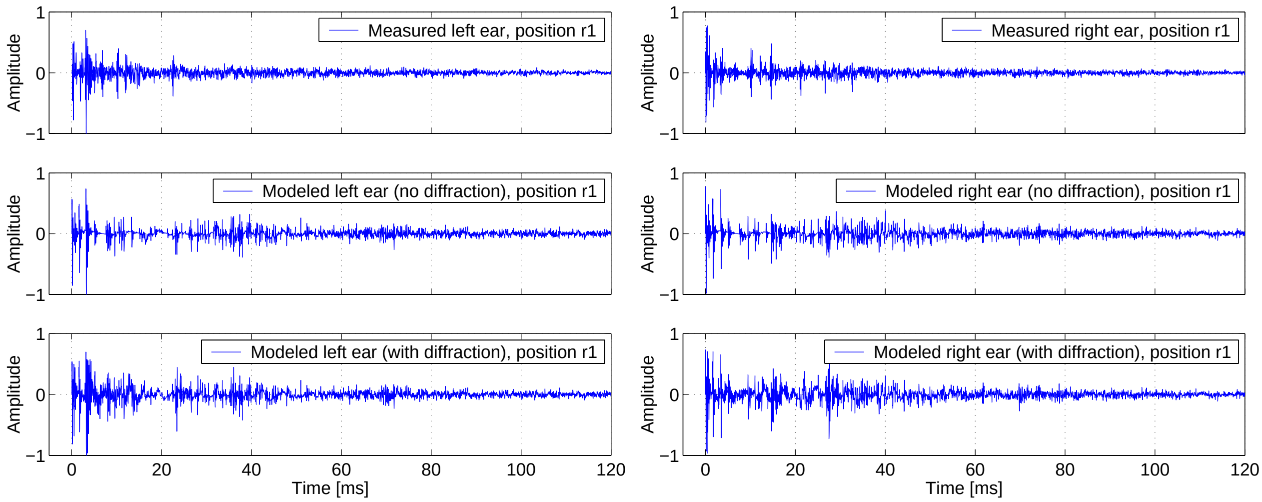

Figure 3: Modeled and measured binaural impulse responses at the listening position r1.

tener's head. In addition, binaural recordings as well as HRTF measurements have been found very critical to microphone placement in the entrance of ear canals at high frequencies [17, 18]. However, it is the best practical way to capture spatial information of a sound field and it enables fairly reliable reproduction method (headphones). The applied HRTFs were measured from the same person who did the real-head recordings. This way we can assume that the recorded and auralized soundtracks should contain the same binaural spatial information. Besides, a high quality omnidirectional microphone was used to record monophonic soundtracks, to verify the validity of the real-head recordings.

In addition to the recorded soundtracks, impulse responses were measured from the lecture room. These responses are useful in parametrization of the auralization system. As an example, the measured and modeled binaural impulse responses are illustrated in Fig. 3. It can be seen that such broadband responses look quite similar despite the fact that the modeled responses without diffraction have lower reflection densities within the first 50 ms. However, visual comparison of broadband impulse responses do not tell much about the audible differences of these responses or the rendered soundtracks.

2. EVALUATION OF AURALIZATION QUALITY

Traditionally, the acoustics of a room is evaluated by measuring impulse responses and calculating room acoustical attributes (e.g., reverberation time and clarity) at different frequency bands [19]. On the other hand, listening tests have been utilized to find out perceptual quality metrics [20, 21].

The auralization quality has many different aspects that can be evaluated with different methods. Bech has found that people can reliably discriminate between spatial and timbre cues when evaluating room acoustics [22]. Based on this and our previous studies [9, 10] we have concentrated to two main aspects, namely the spatial properties and the timbral quality (or coloration). The spatial properties consists of, e.g., localization of sound source and the perceived size of the studied space. The timbral quality might be considered as the overall quality or tone color.

To find out audible differences between recorded and auralized soundtracks both subjective and objective evaluation have been considered. First, subjective evaluation results are presented and then objective evaluation is performed to possibly explain subjective results.

2.1. Subjective evaluation

To find out subjective perceptual differences between recorded and auralized soundtracks a listening test was carried out. Unfortunately, there exists no recommended listening test methodology for testing the auralization quality. However, as we are trying to look into the subjective assessment of small differences, similar methodology as in evaluation of audio codecs are used. One good comparison method is ABX paradigm [23], or its standardized extension to include interval scales (ITU-R.BS1116 [24]). This *double-blind triple stimulus with hidden reference* method [24] is intended for use in the assessment of systems which introduce impairments (or differences) so small as to be undetectable without rigorous control of the experimental conditions. In preliminary tests it was found that the auralizations are so close to recorded soundtracks that the ABX method with interval scale was chosen.

2.1.1. Test method and subjects

The listening test was conducted using the GuineaPig2 software [25] and the answering window is illustrated in Fig. 4. Thirteen subjects (two females and eleven males) participated in the listening test. All of them reported normal hearing although this was not verified with audiometric tests. The test was done in a standard listening room and the headphone (Sennheiser HD-580) reproduction method was applied.

The listening task was to compare *spatial* and *timbral differences* between recorded and auralized soundtracks. Subjects were told to quantify sound source location, size of space, and reverberation when considering spatial differences and in case of timbral differences such attributes as sound color and frequency content was advised to be judged. The answering scale was from “very annoying” to “imperceptible” (see Fig. 4) as recommended in the BS.1116. Each answer corresponded to a decimal value from 1.0 to 5.0, score 1.0 being for “very annoying”.

Both recorded and auralized soundtracks, with durations from 2 to 3 seconds, were played in parallel to a listener who could switch between them (crossfading time was 40 ms). In the applied double-blind triple-stimulus hidden-reference method the reference signal was either signal A or signal B and subjects were forced to grade this hidden reference to be “imperceptible”. Then the other signal (A or B) was judged against the reference. By this way subjects reliability was controlled all the time.

All subjects were trained with four triplets which were listened before the test under surveillance of the test supervisor. During the training session subjects learned to utilize the GUI and they also familiarized themselves with the tasks and the answering scales. In other words, training session ensured that subjects understood the tasks.

2.1.2. Tested variables and hypotheses

The whole listening test contained 36 tasks which were listened in two groups (first 24 binaural and then 12 monophonic tasks). The playing order of these tasks inside a group was randomized. The tested variables, which we considered to be relevant, were the following:

- three stimuli (cla, gui, and dru),
- two listening positions (r1 and r2),
- two modeling methods (with and without diffraction).

Twelve binaural tasks were lowpass filtered to contain only frequencies below 5 kHz, while the other 12 binaural and 12 monophonic tasks contained the whole audible frequency range (fs = 48 kHz). The total number of different tasks was obtained by combining all the variables (3x2x2x3 = 36 tasks).

Based on previous evaluations the following hypotheses were considered:

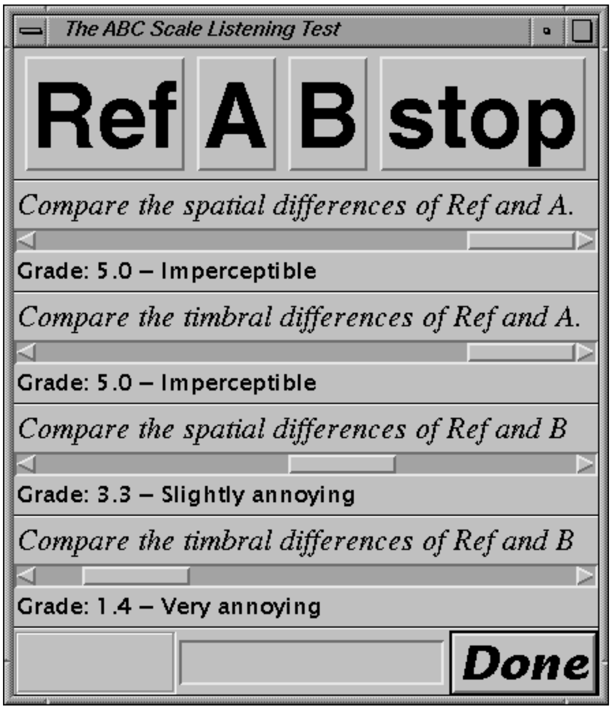

Figure 4: The graphical user interface utilized in listening test

- the full bandwidth recordings have defects at frequencies above 5 kHz,
- there is no audible differences between auralized and recorded soundtracks,
- the inclusion of diffraction modeling is needed in auralization even when the sound source is not in the shadow.

In the following, the results of the listening test are presented to find out the validity of these hypotheses. In addition, these hypotheses are explained in more detail.

2.1.3. Results

The results of the listening test were analyzed with the SPSS V7.5 software. First the correctness of data unrolling was assessed by tabulating the data by independent variables. Data was unrolled correctly, but one minor mistake in the test procedure was detected. One task has been judged twice and the corresponding pair for this task has not been included to the test. However, this defect in test procedure did not affect severely to the results. The BS.1116 [24] recommends to use difference grades in the analysis and they were calculated by subtracting the test signal grades from the hidden reference grades for both the *spatial difference* and the *timbral difference*. Positive difference grades show directly if a subject has not found the hidden reference. The different grades allow as well the analysis of the reliability of subjects with

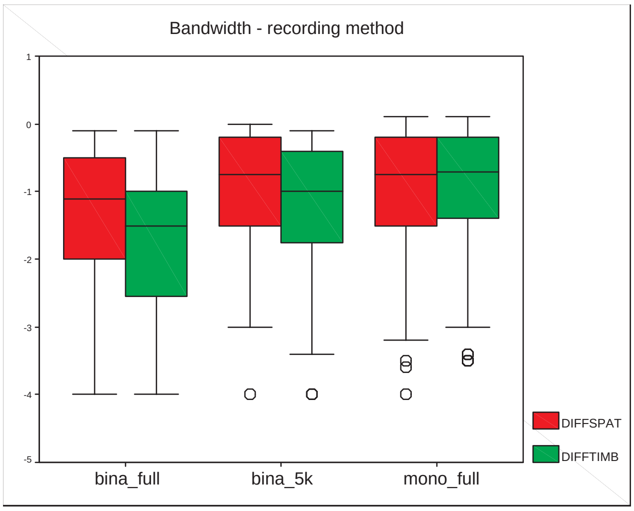

Figure 5: Results of the listening tests as a function of bandwidth/recording method.

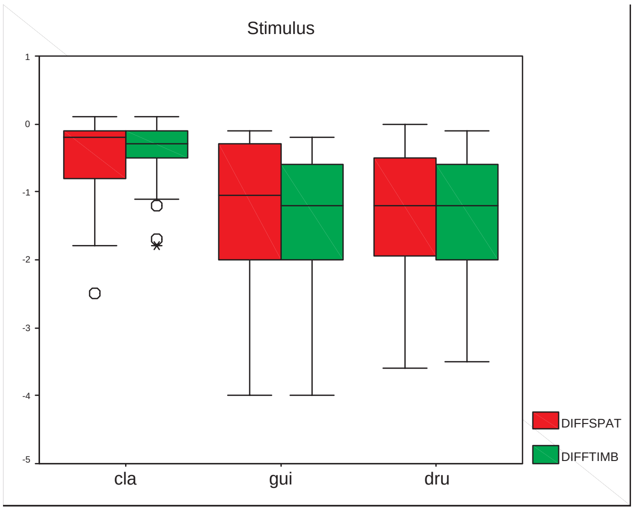

Figure 6: Results of the listening tests as a function of stimulus. The full bandwidth binaural tasks were excluded from this analysis.

one-sided t-test as recommended in the BS.1116. These t-tests were computed and no unreliable subjects were detected. The recommendation BS.1116 suggests as well that the statistical analysis of the data should be done with the analysis of variance (ANOVA). However, the data of our test did not fulfill the ANOVA assumptions, e.g., normal distribution. This might be due to several facts, but at least one explanation is that subjects used the answering scale differently. Some of them used the whole scale from 1.0 to 5.0 while someone else did not give any grades below 2.0 because they claim that none of the differences were "very annoying". Anyhow, the ANOVA cannot be applied to present data and instead the non-parametric Kruskal-Wallis test has been applied in the following analysis.

The first hypothesis was that the full bandwidth binaural recordings have defects at frequencies above 5 kHz. This has been suspected because they sounded unnatural bright and the utilized microphones and the pre-amplifier have been found unreliable in other recording sessions. In addition, the applied HRTFs have been measured earlier with different equipment than the real-head recordings. That possible has caused measurement inaccuracy at high frequencies [17].

Figure 5 shows the results as a function of bandwidth. It is clearly seen that binaural full bandwidth cases have gained lower grades than lowpass filtered binaural and full bandwidth monophonic cases. The differences are also statistically significant (Kruskal-Wallis test gives for DIFFSPAT $\chi^2 = 14.591, p = 0.001$ and for DIFFTIMB $\chi^2 = 56.164, p = 0.000$). This proves the hypothesis that binaural recordings have some recording artifacts over 5 kHz and these defects prevent the subjects to quantify the auralization quality properly. Thus, all binaural full bandwidth results were excluded for the rest of the analysis and lowpass filtered binaural and wideband monophonic results were combined together.

The second hypothesis was that auralized soundtracks were so good that they could not be distinguished from the recorded ones. This issue was studied as a function of stimulus and the results are depicted in Fig. 6. It can been seen that while the median is quite high (-1 corresponds to "perceptible but not annoying") the variance of the responses is large. However, auralizations with the clarinet stimulus have been graded so well that the differences were almost imperceptible. Also the results for more critical stimuli (guitar and snare drum) can be considered to be very good, because in the applied double-blind triple-stimulus hidden-reference test all possible small differences should be easily perceived.

The last interesting question was whether the diffraction modeling was needed in this case as there were no occluders between sound source and listening positions. The impulse responses in Fig. 3 suggest that diffraction modeling is important as it increases the reflection density and by this way complements the image source modeling method [26, 27]. However, the results in Fig. 7 suggest that diffraction modeling degraded the auralization quality in listening position r1 but enhanced the quality in position r2. Unfortunately, with non-parametric Kruskal-Wallis test this interaction could not be studied, but the timbral differences were significant both for listening position ($\chi^2 = 4.597, p = 0.032$) and for diffraction modeling ($\chi^2 = 7.990, p = 0.005$).

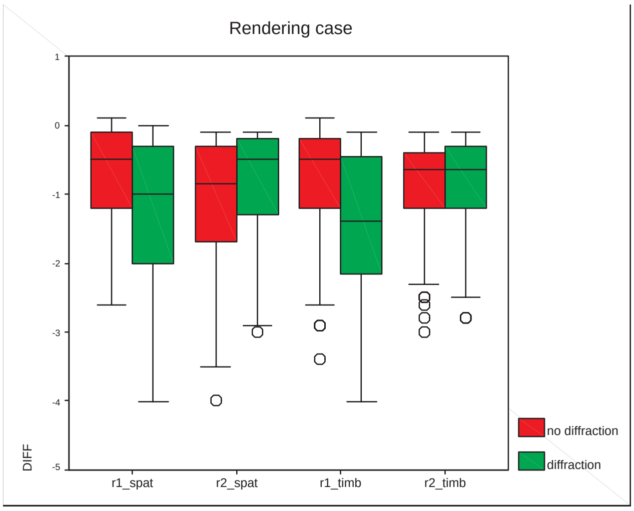

Figure 7: Results of the listening tests as a function of listening position and diffraction modeling. The full bandwidth binaural tasks were excluded from this analysis.

2.2. Objective evaluation

It would be interesting to know if the listening test results can be explained by analyzing signals objectively. Additionally, to still improve the auralizations it is necessary to know at which frequencies the perceived differences were.

The best possible way to evaluate objectively audible differences between recorded and auralized soundtracks would be a complete binaural auditory model. Unfortunately, such a model, which models both the spatial and timbral properties of human hearing, does not exist. However, monophonic timbral quality can be evaluated objectively with monaural auditory models.

The applied analysis method is a simplified auditory model, which models roughly the human cochlea. The model includes the sensitivity level as a function of frequency and it mimics the time and frequency resolution of human hearing. In other words, the analysis enables visualization of sound signals with the time and frequency resolution of human hearing. The detailed description of the model is presented in the other article [11].

The analysis is performed to two sets of monophonic drum signals (depicted in Fig. 8). These signals were chosen because the auralization with diffraction at the listening position r2 was graded best among drum signals in the listening test while the auralization with diffraction at the listening position r1 got the lowest grades.

The analysis motivated by auditory perception, for the signals in the left column of Fig. 8, are depicted in Fig. 9. The left column plots show nicely the sharp onset of the drum hits as well as the decaying sound field after each hit. Visual comparison of the recorded and the two auralized signals is quite difficult as they look pretty similar. However, visualized data matrices can be subtracted from each other and by this way three illustrations in the right column are calculated. It is interesting to see that the auralization without diffraction contained more energy than the auralization with diffraction. However, the lowest right column plot suggests that in the onsets of drum hits the auralization with diffraction had higher sound pressure levels than the auralization without diffraction at low frequencies below 500 Hz.

Another visualizations, for the right column signals of Fig. 8, are depicted in Fig. 10. At least three interesting things can be seen in these plots. First, surprisingly the recorded and the auralized with diffraction were almost identical signals above 6 kHz. Second, the subtraction between the recorded and the auralized with diffraction shows that these signals were very close to each other above 1 kHz. This confirms the listening test results since the auralization with diffraction at the position r2 scored the smallest perceived timbral differences. Finally, it can be noted that at the listening position r2 the auralization with diffraction contained more energy a little bit after the onsets of the drum hits, contrary to findings at the listening position r1 (see the lowest plots in the right column of Figs. 9 and 10 for comparison).

The other subtraction figures show that the audible differences found in listening tests were mostly below 600 Hz. This is not very surprising as the image-source method performs best at high frequencies where the dimension of the surfaces are greater than the wavelength of the sound.

2.3. Discussion about evaluation

Subjects claimed that the auralizations were close to recordings. Especially, monophonic and lowpass filtered binaural soundtracks were reported to sound very similar. Small differences were perceived both in the spatial properties and in the timbral quality, especially with transient-like signals. However, all binaural auralizations were reported to be very natural sounding and subjects told that they really sounded inartificials.

It seems that the perceived inaccurateness of auralization is mostly below 600 Hz. This is not very surprising as the image-source method performs best at high frequencies where the dimension of the surfaces are greater than the wavelength of the sound. Another modeling defects might be in material absorption treatment because material absorption coefficients are difficult to define correctly for all surfaces.

The objective analysis showed that while the diffraction modeling increased the reflection density, actually most of these diffracted components were in opposite phase and thus canceled partly the contribution of specular reflections. Torres et al. [13] explained that phenomenon and, indeed, when the sound source is visible to the lis-

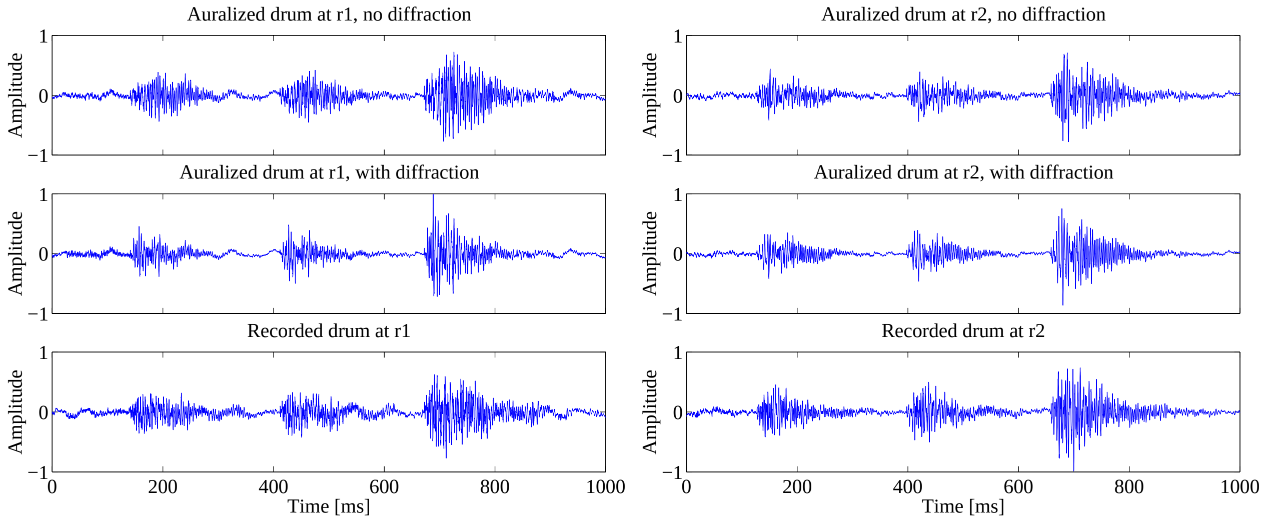

Figure 8: Excerpts of modeled and measured monophonic soundtracks at the listening positions r1 and r2.

tening position, diffracted components are mostly in opposite phase. Another question is if the diffraction modeling needs to be included in such a geometry. In the presented results it did not enhance the quality of auralizations significantly although it is clearly audible. Naturally, in some other geometry where the sound source is occluded the diffraction modeling certainly is very important and have to considered in auralization.

Finally, the objective evaluation with the proposed analysis method confirmed the listening test results. The auralization with diffraction at the position r1 was judged to contain the biggest timbral differences while auralization with diffraction at the position r2 obtained the smallest differences. These results can be seen in the middle right column plots in Figs. 9 and 10 since at least above 1 kHz the color of the plot in Fig. 10 is much closer to gray than in Fig. 9.

3. CONCLUSIONS

This paper has described the evaluation process of both monophonic and binaural auralizations. The evaluation is based on subjective and objective comparison of recorded and auralized sound signals. The results indicate that with clarinet sound the designed auralization system performed so well that auralized signals were hardly distinguished from the recorded ones. Even with a transient-like wideband signals the auralizations were judged to be very close to recordings. It can be concluded that the presented evaluation results ensure that plausible and natural sounding auralization can be realized with the image-source method and statistical late reverberation.

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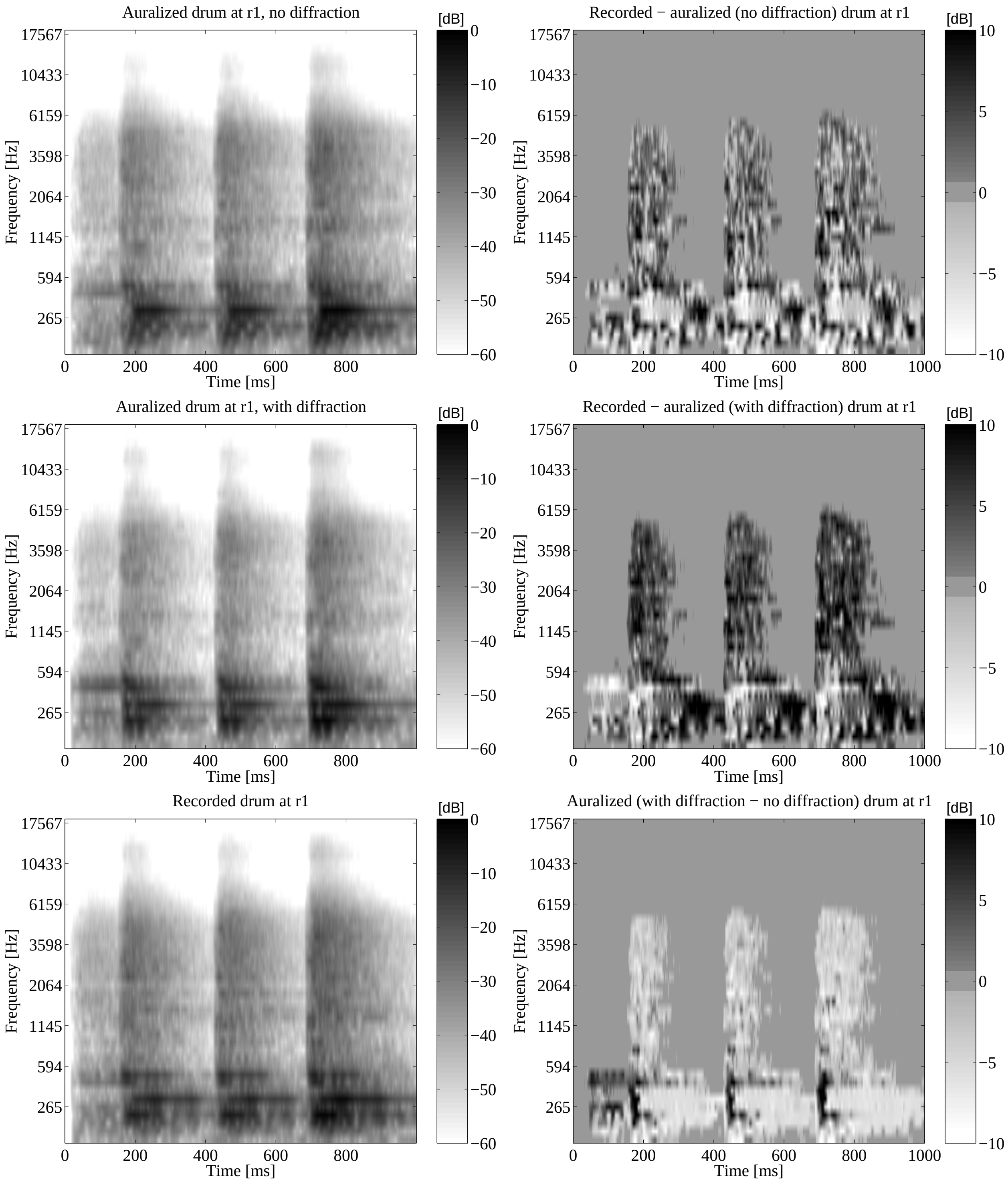

Figure 9: Visualizations, motivated by auditory perception, of the soundtrack excerpts depicted in the left column of Fig. 8. Before calculating the subtraction plots everything below -35 dB level was cut to highlight the most audible differences.

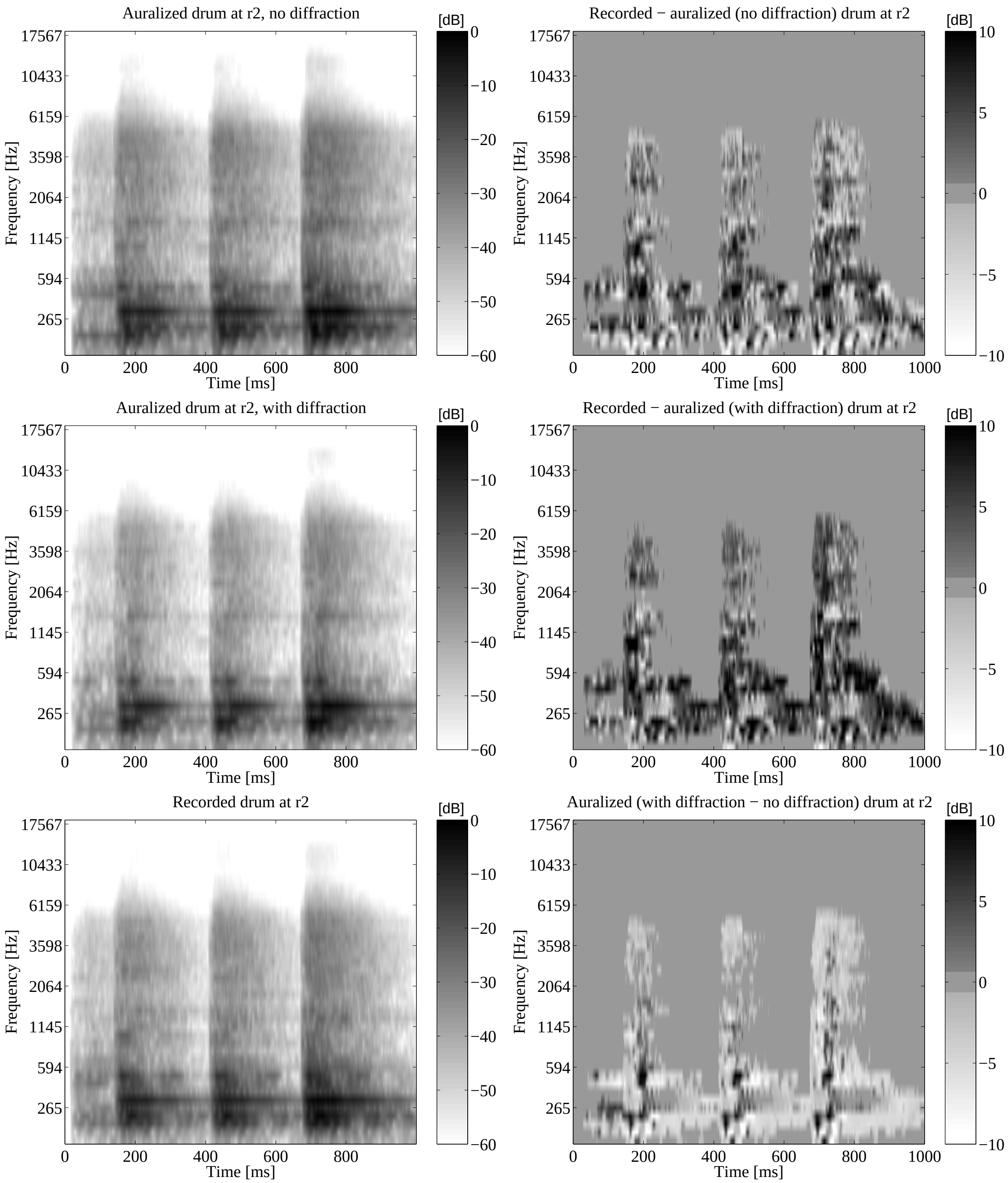

Figure 10: Visualizations, motivated by auditory perception, of the soundtrack excerpts depicted in the right column of Fig. 8. Before calculating the subtraction plots everything below -35 dB level was cut to highlight the most audible differences.