Matching simulations with measured acoustic data from Roman Theatres using the ODEON programme

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In the context of the ERATO research project ("identification, Evaluation and Revival of the Acoustical heritage of ancient Theatres and Odea") funded by the European Union, acoustic measurements as well as computer simulations have been carried out in the Aspendos Theatre, Turkey and in the south theatre in Jerash, Jordan.

The simulations are made with the ODEON software, for which a new frequency-dependent diffraction method is currently being developed for implementation in future versions of the programme.

In order to make the virtual restorations of these ancient Roman theatres as correct as possible, it is important to attempt calibration of the models with respect to as many of the relevant acoustic parameters as possible. Thus, besides the overall value of reverberation time, we also try to match the variation with position of other important acoustic parameters, such as Strength and Clarity described in ISO 3382. With the new diffraction and scattering calculation method we hope to improve this match, because these phenomena are regarded very important for the acoustics in these open air theatres, in which the sound field is far from being a "normal" three-dimensional diffuse field.

The paper describes this exercise, the calculation parameters in ODEON that were adjusted in the process, and the extent to which it was successful.

1 Introduction

The following does not attempt to be a scientific description of the importance of implementing correct representation of scattering and diffraction in computer models for room acoustic purposes. Rather it is just a report on an experience in testing two different scatter/diffraction models implemented in the Odeon software version 7.1 through simulation of the acoustics of an open air Roman Theatre, from which extensive acoustic measurement data were available. The motivation for carrying out this exercise is to test both the accuracy of the latest version of the Odeon programme and the accuracy and fidelity of the simulations of this specific theatre, which is part of our contribution to the ERATO project. An open Roman theatre is not the type of "room" for which computer modelling is most often applied; but with most of the reverberant sound "evaporating" through the absent ceiling and most of the reflecting surfaces in these theatres being small and irregular, it is believed that this kind of "room" would constitute a relevant test object for the treatment of scattering and diffraction by the Odeon computer model.

2 The scatter/diffraction models in Odeon version 7.1

The new version 7.1 of the Odeon programme can treat scattered sound in two ways, either as in previous versions 1) by a frequency independent scatter coefficient which the user should choose as a combination of diffraction from the surface edges and scatter due to surface roughness, or 2) by a new method in which frequency dependant diffraction due to surface size and source/receiver distances and angle of incidence is taken care of by the program and only the scatter caused by surface details (roughness) not included in the modelled geometry need to be chosen by the user. With a tendency towards more detailed geometric modelling (using the much improved modelling tools in Odeon or imported from architects' CAD models), the new scattering method leaves less of the scatter properties to be based on guesses by the operator – or values representing the surface roughness scatter can be taken directly from measurements according to ISO 17497-1 However, still only one value representing the entire frequency range can be entered). The scatter calculation methods are described in depth in another paper at this conference [1]. Here it should just be mentioned that the scatter treatment is only applied to sound treated by ray tracing, which take over for sound reflected beyond the so called transition order, up to which the image source model (plus some early scatter treatment) is applied.

3 Modelling the Jerash Theatre

The south Theatre in Jerash, Jordan is a well preserved open Roman Theatre from early 2nd century a.d. Of the Skenae building only one storey is preserved; but almost the entire cavea area is intact. The Odeon model was based on available drawings, observations and photos taken on the site and on an advanced laser registration carried out by our ERATO partners from the Hashemite University in Jordan. The model contains 5092 surfaces including a hill in the landscape behind the skenae and a surrounding, totally absorbing box killing all rays escaping through the absent ceiling. Earlier studies [2] had shown, that this kind of detailing is necessary. The degree of detail represented in the model is illustrated in Figures 1 and 2.

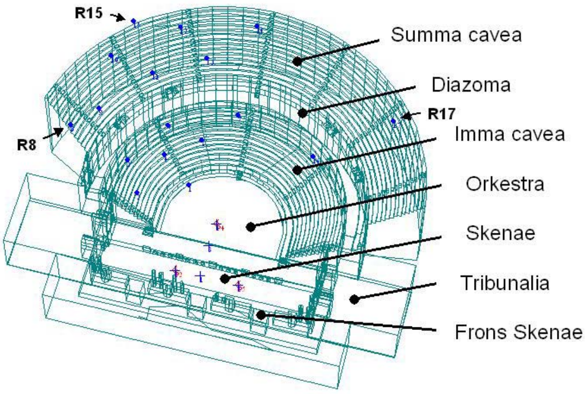

Figure 1: Wire view of the Odeon model of the South Theatre in Jerash, Jordan with the Latin names of the various elements indicated. Source positions are marked by red crosses and microphone positions shown by blue dots.

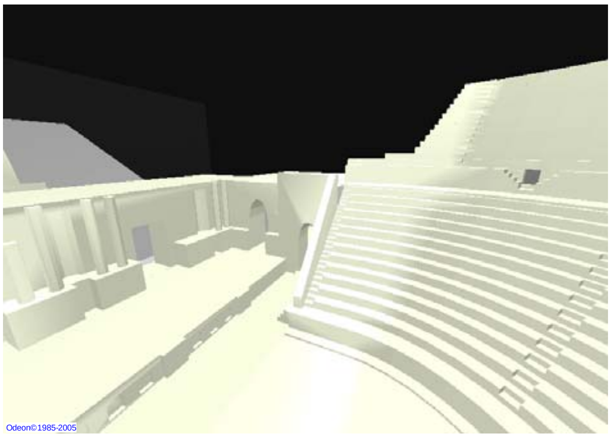

Figure 2: Surface view of the Odeon model of the South Theatre in Jerash, Jordan.

The choices of absorption and scatter values used in the model are described in Section 5.

4 Acoustic measurement data

The data used as reference for our simulations were provided by our Italian ERATO partners from the University of Ferrara [3]. For our purpose, we chose data from each of three source positions to each of 17 microphone positions, i.e. 51 position combinations in total.

Before submerging into the results of the present study - dealing with deviations between measurements and simulations only - it should be mentioned, that the acoustics of this theatre are characterized by a non vanishing reverberation time of 1.2 Sec., a rather low sound level which decreases by about 6 dB per distance doubling (unlike closed rooms, in which the level attenuation is more modest beyond the reverberation distance), i.e. the decrease with distance is as steep as in free field (without any reflections) - but with the general level being 6 – 8 dB higher. The low level of late reflected sound in particular implies that Clarity and - if the ambient noise level is sufficiently low - the intelligibility are higher than what would be expected from the measured reverberation time alone and from our experiences in closed rooms [4]. Thus, the position averaged value of C80 at 1000 Hz equals 6.2 dB, and D50 = 0,7. Another acoustic peculiarity of the space is the fact that the receiver averaged EDT value is considerably higher when the source is placed in the orkestra than when it is placed on the skenae, the vales being 1.5 Sec. and 0,9 Sec. respectively. Also the SPL is about 1dB louder when placed in the orkestra (likely due to shorter distance to the receivers in the cavea).

5 Tuning the model

As the new scattering calculation method has been developed in parallel with the ERATO project, the choices of absorption and scatter values have been made according to the old as well as to the new scattering model. In other words, also the absorption turned out to need adjustment for best fit to the measured reverberation time when the scattering method changed.

To the left in Table 1, the chosen values for low/mid-frequency absorption and scattering used at the different stages of tuning from the old to the new scattering model are shown together with the number of rays and the transition order.

For calculations with the old model (indicated in the table by Diffrac. Surf.: “-“), the scatter coefficient was set to 0,7 for the most of the surfaces (except for larger relatively smooth surfaces: frons skenas, diazoma and tribunalia given a scattering value of 0,2 and the essentially flat skenae floor and orkestra given the value 0,1). With these scattering values, the absorption that provided the best fit to the measured reverberation time was a quite sensible values for the rough stone surfaces of 0,06. However, this value was allowed to increase slightly in the 2 kHz (0,8) and 4 kHz (0,15) octaves to consider surface porosity. The 0,7 and 0,06 values for scattering and absorption respectively are listed in the first row of the table.

For the four parameters considered in this study the corresponding differences between measured and simulated values at 1000 Hz and averaged over the 51 source/receiver combinations are shown to the right in Table 1.

ODEON MODEL SETUP (Oblique Lambert + despike rays on)					DIFFERENCES (pos. averaged) measured – simulated			
α	Scatt. koef	# of rays	TO	Diffrac surf	ΔT AVR	ΔEDT AVR	ΔSPL AVR	ΔC80 AVR
0,06	0,7	0,5 mio	2	-	-0,01	0,24	1,00	-0,22
0,06	0,5	0,5 mio	2	-	-0,12	0,20	1,06	-0,16
0,06	0,7	0,5 mio	2	+	0,15	0,30		
0,06	0,1	0,5 mio	2	+	0,09	0,24	1,19	
0,04	0,1	0,5 mio	2	+	0,02	0,20	1,02	0,21
0,04	0,1	2,5 mio	2	+	0,03	0,21	1,01	0,21
0,04	0,1	0,5 mio	0	+	0,08	0,32	1,29	-0,63

Table 1: Odeon calculation parameter settings used in the Jerash model tuning process and corresponding position averaged deviations from measured data in the 1kHz octave band.

It is seen that the fine match of the T value is not mirrored in small deviations by the other parameters. Besides, the old model is very sensitive to the guessed scatter coefficient: changing this from 0,7 to 0,5 causes T to increase by 0,1 Sec. (as seen in the 2nd row) – probably because with less scattering, fewer rays are directed towards the open when reflected from the many vertical surfaces.

When activating the new scatter method (indicated in the table by Diffrac. Surf.: "+") – and keeping a high scatter coefficient (row three) - T drops by 0,15 Sec; but the difference reduces to 0,09 Sec. when the scatter coefficient is reduced as it should be to 0,1 (row 4), which was believed a reasonable value considering the general roughness of the stone surfaces in the theatre.

Still, the absorption needed re-adjusting from the previous value of 0,06 to 0,04, which is still a realistic guess. Attempts to improve fit by using five times as many rays (realizing that many are needed with this totally absorbing "ceiling") is seen to have no effect (row 6). Setting the new scatter method in operation from the very first reflection by setting TO=0 (last row), resulted in no improvement either - rather the opposite.

The two scenarios printed in red in the table, i.e. the best configuration of calculation parameters for the old and the new scatter models respectively, are compared in more detail in the following section.

6 Detailed comparison of old and new scattering model

In this section, we will extend the discussion of the position averaged deviations to other frequency bands and also look at the (population) standard deviations, STD's, found for the differences in the individual 3x17 positions. In each of the STD plots, a green shaded area indicates (mid/high frequency) measurement accuracy according to [5]. However, this reference is likely to be optimistic regarding the measurement accuracy, since according to [6] equally large or even large STD's can be caused by just small changes (30 cm) in microphone position – and to this should be added variance due to different procedures and equipment. Besides, it should be remembered that the observed differences per position are the result of both measurement and simulation errors. In other words, if the accuracy in simulations is equal to that of measurements according to [5], the combined error may already be √2 higher than indicated by the green shaded areas.

6.1 Reverberation time

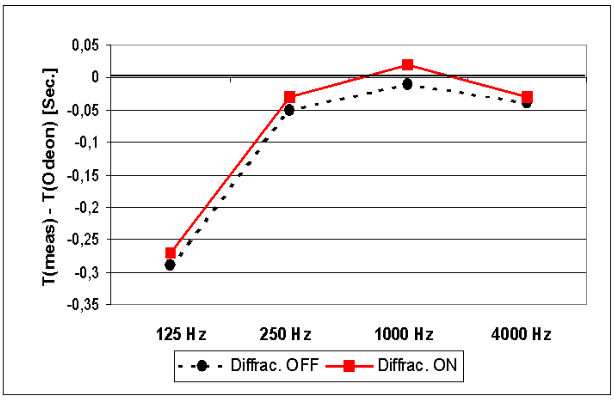

Figure 3: Position averaged differences between measured and simulated Reverberation Time from the Jerash Theatre using old (Diffrac. OFF) and new (Diffrac. ON) scattering models in the Odeon program.

In Figure 3 it is seen that the tuned match of T at 1 kHz is also valid at 250 Hz and 4 kHz but does not extend to the low frequencies where both models produce almost equal and definitely too high values. Thus, the new diffraction model is not (yet) capable of providing the expected effect of the extended diffraction at low frequency in this open theatre geometry. Although measurement errors are also larger at low frequencies, it is not likely that the 0,3 Sec. difference observed is due to the measurements only. Too high low frequency values of T were also experienced in simulations of the Aspendos theatre [2] (and are often experienced in large closed rooms too).

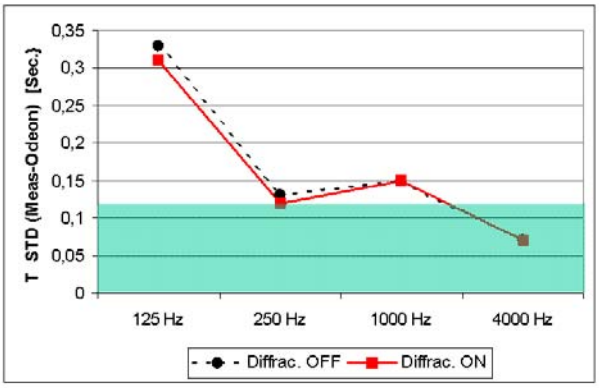

Figure 4: Standard deviations versus frequency of individual position differences between measured and simulated T values from the Jerash Theatre. Dotted and full lines refer to using old (Diffrac. OFF) and new (Diffrac. ON) scattering models in the Odeon simulation respectively.

Figure 4 shows the STD's relating to differences in individual positions. Of course we once more observe the large deviation at 125 Hz; but at higher frequencies the deviations are not serious. To some extent, this may just reflect the fact that the variance of T with position is normally quite low – both in measurements and simulations.

6.2 Early Decay Time

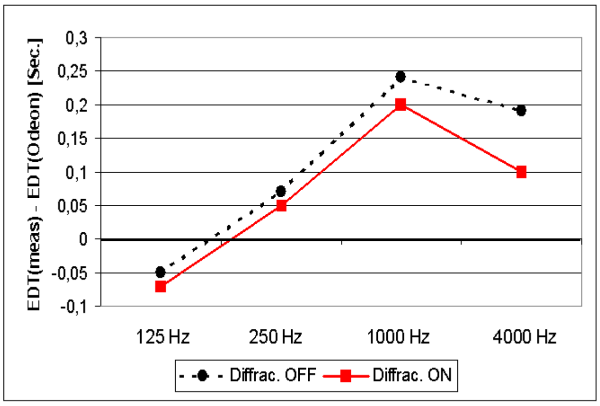

Figure 5: Position averaged differences between measured and simulated Early Decay Time from the Jerash Theatre. The different scattering models are indicated as in Figure 3.

Figure 5 shows that the about 0,2 Sec. difference at 1kHz found with both models (and already illustrated in Table 1) is the highest within the frequency bands investigated. Besides, it seems that in general the deviation is slightly less with the new diffraction model which is encouraging.

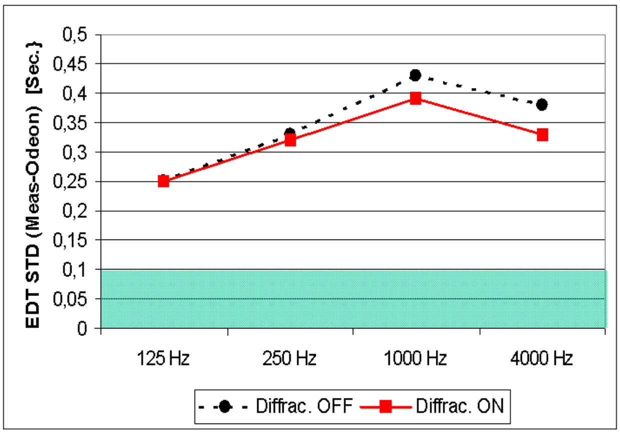

Figure 6: *Standard deviations of individual position differences between measured and simulated EDT values. The different diffraction models are indicated as in Figure 4.*

On the other hand, the EDT differences observed in Figure 6 within each position are far above what can be explained by measurement accuracy alone. However, again the new scattering model seems to be slightly more accurate than the old one.

6.3 Strength (SPL)

For SPL, the position averaged deviations and the STD's of the individual position differences are shown in Figures 7 and 8 respectively.

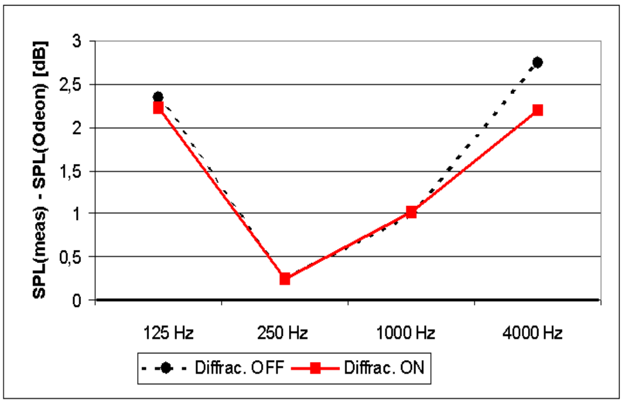

Figure 7: Position averaged differences between measured and simulated Strength (SPL) from the Jerash Theatre using two different scattering models.

The position averaged SPL deviates a modest 1dB at 1kHz but more at very low and very high frequencies. Again, the two scattering methods perform almost equally but with the new one being slightly better at high frequencies.

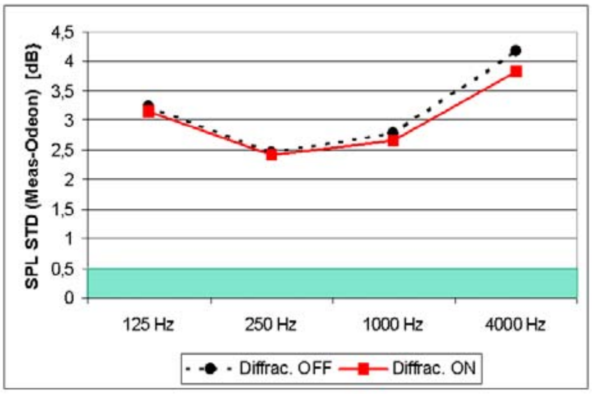

Figure 8: Standard deviations of individual position differences between measured and simulated SPL values using two different scattering models.

Per position, the STD of the differences are substantial: more than 5 times the reported measurement error. This was not like our experience with the Aspendos Theatre [2], which showed a close match between (our own) measurements and simulations in individual positions.

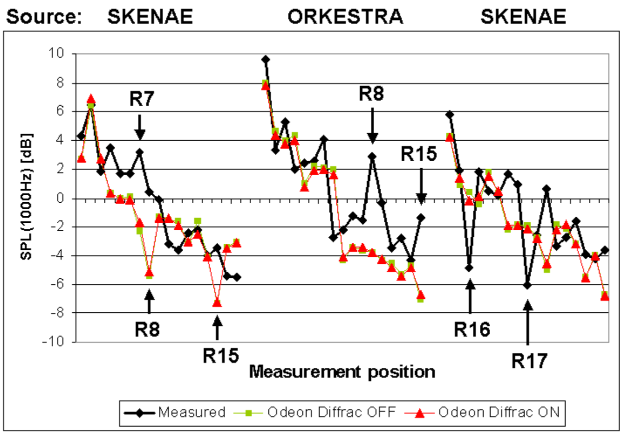

Figure 9: Measured and simulated SPL values a 1 kHz in the Jerash Theatre. Receiver positions deviating much from monotonic attenuation with distance are indicated.

In search for possible reasons in the modelled geometry, the actual measured and simulated 1kHz values for each position are shown in Figure 9. Here, the measurement receiver points are ordered according to distance for each of the three source positions. The general attenuation at larger distances (towards the right) is clearly seen. The two scattering models are very similar and both are obviously different from the measured values in certain positions. All three sets of values, however, show some surprising deviations from the expected monotonic attenuation with distance. Without being a complete explanation, it is worth noticing that the typical outlier points R 8, R15 and R17 were all placed near the outer edge of the cavea (see Fig. 2), where quite strong wind may have influenced the measurements and few reflected reflections hit the receivers in the simulations. The other outlier points R7 and R16 both happened to be placed just below the diazoma.

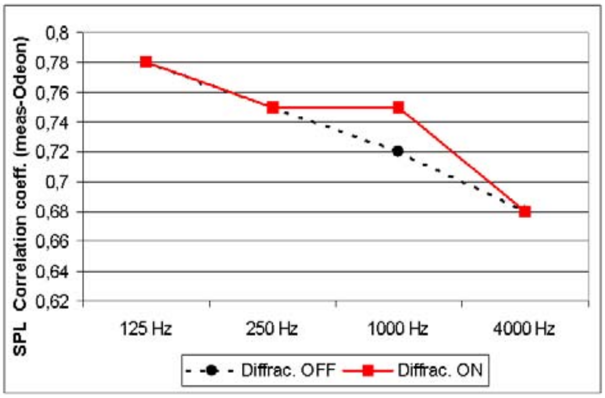

Figure 10: Correlation between measured and simulated SPL values from the Jerash Theatre obtained with two different scattering models in Odeon.

With the large position variance of the SPL parameter, it is also relevant to evaluate the performance of the scattering methods by comparing the correlation coefficients between the measured and simulated values in the two cases. As seen in Figure 10, the new model is slightly better - at least at 1kHz.

6.4 Clarity (C80)

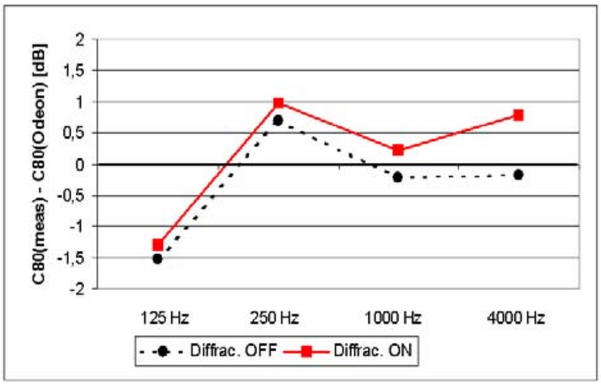

Figure 11: Deviations from measurements of position averaged, simulated C values

The deviations from the measurements of the position averaged and position individual simulated C values are shown in Figures 11and 12 respectively.

Whereas the position averaged differences are quite moderate – even at 125 Hz considering the large measurement errors at low frequencies – the differences in individual positions are again much larger than explainable by measurements errors alone; but slightly less when using the new diffraction method. Also this result is different from the Aspendos experience, where simulations and measurements matched well in most positions.

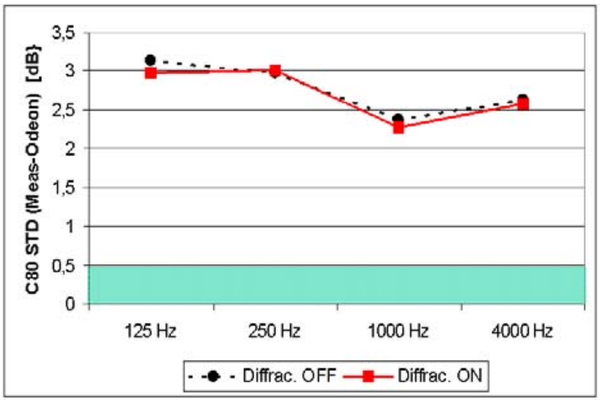

Figure 12: Standard deviations of individual position differences between measured and simulated SPL values using two different scattering models.

6.5 Definition (D50)

In order to end with a positive story, the position averaged differences in Definition, D50, are illustrated in Figure 13 showing very small errors except at 125 Hz where measurements are anyway unreliable.

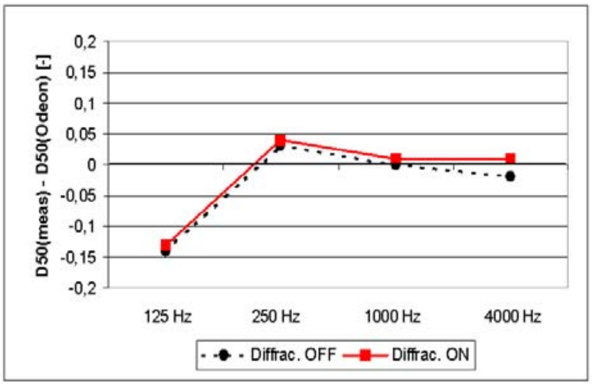

Figure 13: Deviations from measurements of position averaged, simulated C values

7 Discussion and conclusions

After the experiences presented above, it is tempting to look more deeply into the individual position data from measurements as well as from the simulations, and it may even be relevant to eliminate certain outliers in the data in order to obtain more general conclusions. Also we need to look at the Aspendos model again using the new scattering method in order to investigate the differences between the behaviour of the two theatres.

Still, it can be concluded that although it is a tough demand to expect exact values in each position, we have seen a slight tendency towards the new diffraction model being a slight improvement. However, it is clear that we are not yet able to model detailed position variations in the acoustic parameters.

Acknowledgements

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