CROWD NOISE MEASUREMENTS AND SIMULATION IN LARGE STADIUM USING BEAMFORMING

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ABSTRACT

The noise generated by the crowds and organized fans during sporting events has created a challenge for sport facility management. The new demand for full compliance to National Football League rules on crowd noise, and cities' regulations on noise ordinance require new methods or approaches in measuring such environmental conditions. Given their dynamic range and possible classification, noise levels generated by large crowds have influenced the outcome of games, and recent analysis of the available data shows an increase in noise related penalties. This situation has provided more excitement for the spectators and greater participation in the events, however sound intensity of 95 to 110dBA is now the typically reported range of recorded noise levels within various sport arenas.

This paper describes a new approach in measuring crowd noise, and estimating the contribution of various frequency ranges for evaluation of the existing, and in this case, the proposed University of Michigan (UM) newly designed addition of skyboxes to the football stadium. Data were measured using Acoustic Camera spherical array, 120 channel data recorders, and utilizing various acoustic software for data reduction, computer modelling, simulation and analysis. The measured and simulated results based on these parametric studies are compared against selected well-known stadiums for their crowd noise conditions. The frequency domain and spectral analysis are used as input to the computer modelling, simulation and analysis of the space. Using newly developed room acoustic indicators provide a new approach in estimating the impact of the reflected sound contribution to the crowd noise; given the skyboxes as part of the new addition with their unique facade and window geometry.

INTRODUCTION

Architecturally speaking, not all stadiums are designed equally since the space geometry for each sport varies given the required acoustic performance. The desired crowd noise is not loud enough because the vocal cords are not strong enough, and or the fans are not large in number, or they do not react in harmony. The National Football League in USA has had an uncomfortable position with the crowd noise issue, and may soon rely on a wireless communication system designed within the players helmet to over come this noise issue **[1-2].** Noise is defined as unwanted sound, however in sport entertainment, this definition does not hold to be true by the fans. The ear can just distinguish a difference of loudness between two noise sources when the there is a 3dBA difference between them, and when the two sound sources of the same pressure level and frequency are combined. The resultant level is considered twice as loud when the two sounds differ by 10 dBA. The discipline of architectural acoustic requires designers to estimate the reverberation time as one of the indexes for room acoustic studies. Acoustic performance evaluation of various stadiums shows that the reverberation time varies for low, mid and high frequencies. Reverberation time is define as the time in seconds that it takes for the sound to drop off to a point 60dBA below the starting sound, and it is shown as RT60 or T60. Most reported RT is for 500Hz or the average of 500 HZ and I000 HZ. Measured data for 250 Hz and lower are not reliable, and calculated results at early stage of the design are good enough to 125 Hz only, given the feedback from acoustic society members and published data **[3-5].**

METHODOLOGY

Current architectural practice for stadium design has to rely on diffused sound filed conditions. Applying statistical methods where the absorption coefficient is weighted by the surface area and the number of sound rays hitting each surface is used to estimate the contribution of each surface absorption at each frequency range. The average absorption is then used along with effective Volume (V) calculated from mean free sound path length and surface area using the statistical RT equations shown below.

Once the Average Absorption Coefficient ($\overline{\alpha}$) is calculated for each frequency band (i), this can be multiplied by the total exposed surface Area (S) for each method. The Sabine's function also takes in to account the attenuation constant (m) of air such that:

RT60 Sabine 's Equation. (1)

$$L_{60} = \frac{0.16V}{S.\bar{\alpha}} \qquad L_{60} = \frac{0.16V}{S.\bar{\alpha} + 4mV}$$

RT60 Eyring - Norris's Equation (2)

$$L_{60} = \frac{0.16V}{-S.\ln(1-\bar{\alpha})}$$

RT60 Millington and Sette 's Equation (3)

$$L_{60} = \frac{0.16V}{-\sum_i S_i.\ln(1-\alpha_i)}$$

Sabine' s equation is consider to be for a "LIVE" room according to Eyring [8] and his formula includes the mean free path in an enclosure to characterize by a diffuse sound filed is shown in Equation 2 assuming the successive reflections by the boundaries having an average absorption coefficient ($\bar{\alpha}$). Each time a wave hits the surface boundaries a fraction of the ($\bar{\alpha}$) is absorbed and (1-$\bar{\alpha}$) is the reflected part. The Millington and Sette equation 3 was created to limit the (α) to be less than 1. The uses of these calculations indicates the waves or ray hit ratio for each individual surface, where for each surface

$$\bar{\alpha} = \sum_i S_i.\ln(1-\alpha_i)$$

Statistical methods do not show individual contributions due to physical geometry, however the estimations of the count numbers of hits on each surface give the absorption coefficients for each frequency range, and provide a better overall sound experience in the space. These procedures are used to estimate the RT and sound decays for the UM stadium, and the results are compared against measured data with similar large-scale sport arenas within USA **[4, 6-9].** See **Table 1.**

Table 1

Selected sport arenas within USA.

#	USA Selected Stadium
1	Astrodome Huston TX (1988)
2	Bankone ball park Phoenix AZ-closed
3	Bankone ball park Phoenix AZ -open
4	Kingdome seattle WA 1994
5	Miller park Milwakii W (roof Closed)
6	Safeco Park Field seattle WA (roof closed)
7	Baleco Park Field seattle WA (roof open)
8	Silverdome Pontiac MI
9	Superdome New Orleans LA
10	Texas stadium Dallas TX
11	AVERGAE Measured USA selected Stadiums

Table 2

Reported data of RT 60 by [3] using TEF system for selected sport arenas within USA

#	63Hz	125Hz	250Hz	500Hz	1kHz	2kHz	4kHz
1	17.65	11.4	6.47	5.38	4.72	4	2.85
2		8.56	7.6	6.03	5.47	4.59	2.29
3		5.73	5.54	4.93	4.65	3.96	2.29
4	22.5	18.8	11.3	6.03	5.2	4.3	3.1
5		15.25	12.33	9.15	7.05	4.45	3.36
6		19.21	12.5	8.09	5.05	6.5	4.49
7		5.13	3.3	4.09	4.73	4.16	3
8		5.4	6.3	9.7	9.3	8.3	3.5
9	7.4	7.2	6	6	5.95	5	4.6
10	12.5	12	11.5	7.5	6.5	5.5	4.25
11	15.01	10.87	8.28	6.69	5.86	5.08	3.37

Table 3

Calculated bass and extended bass ratios for selected sport arenas within USA

#	Ex Low Freq.Avg	Low Freq.Avg	Mid Freq.Avg	Bass Ratio	Ex Bass
1	11.84	8.94	5.05	1.77	2.34
2		8.08	5.75	1.41	
3		5.64	4.79	1.18	
4	17.53	15.05	5.62	2.68	3.12
5		13.79	8.10	1.70	
6		15.86	6.57	2.41	
7		4.22	4.41	0.96	
8		5.85	9.50	0.62	
9	6.87	6.60	5.98	1.10	0.72
#	12.00	11.75	7.00	1.68	2.01
#	12.06	9.58	6.28	1.53	1.92

Application of EDT, RT and BR

The Bass Ratio (BR) is defined as the averaged Early Decay Tim (EDT) of 125 HZ and 250 HZ divided by the averaged EDT of 500 HZ and 1000 HZ, however the EDT is for 10dBA of sound energy decay, and since it does not include the reflection it will not be as useful for the large arenas. A bass ratio using RT60 is also used to show the performance of the large scale music halls. Typically, the BR for small halls reaches 1 or unity, and the BR for large size concert halls is between 1.1 and 1.2. Given the demand for evaluation of the crowd noise for various venues in stadiums, there is a need for accurate low and mid frequency measurements.

Using the reported data on various well known stadiums, the BR were calculated using RT60 data, and the results show that using the "Low" and "Extended Low" frequency in BR calculation do represent the contribution from the reflected components from the surrounding surfaces within the stadiums. The calculated and measured RT using the Time, Energy Frequency (TEF) system analyzer for selected stadiums for six different octave center frequencies of 125, 250, 500, 1K, 2K and 4K frequency range from bass to treble tones are shown in **Table 2.** The RT in large stadiums varies from 5 to 7 for mid frequency, 7 to10 for low and 15 to 20 for extended low frequency by including 63 Hz. The differences in low and mid frequencies shown in **Table 3** (shaded cell)are more obvious for stadiums with data on open and closed roof settings, also the correlation between the BR and the extended BR for similar bands of frequencies.

Application of the Acoustic Camera

The Acoustic Camera was used to measure from both center and side filed positions within the UM stadium. The system produces images of sound sources or "localizes" sound sources using the Beam forming technique. Delay-and-sum Beam forming, is one of the oldest and simplest array signal processing algorithms…"as far back as 1880. The acoustic images consist of color contours indicating where the most significant noise sources are located. Detailed review of this technique are described in References [10,11]. The system consists of a microphone array with camera, data recorder, and Noise Image software running on a laptop PC. Fig. 1 shows the typical system components used by the Acoustics Camera and the actual setting for crowd noise measurements within the UM stadium during the game in shown in Fig. 2.

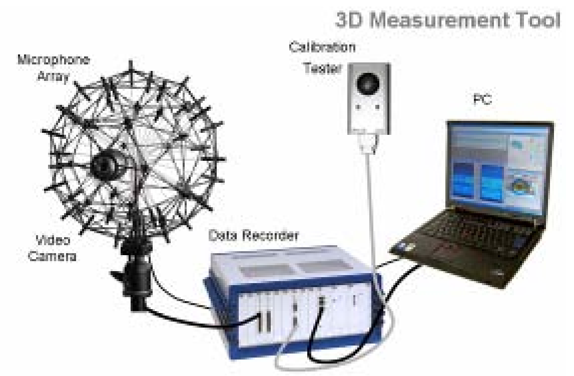

Figure 1. *Acoustic Camera recording system*

Figure 2 . *Acoustic Camera actual experimental set up for measurements within the UM stadium*

RESULTS

The net result from the system is a sound image superimposed onto a 3-D CAD model for specific application. Data can be analyzed for specific time periods and frequency ranges allowing results to be correlated with standard architectural acoustic measures. The measured results were used to simulate the sound source in two diffrent computer programs. one an acoustic program called Acoustic 3D and the acoustic part of the ECOTECT software[9]. It is possible to simulate the building geometry and its surface characteristics. (e.g. material and or surface properties). The objective of this study is not only to visualize the noise performance of the space for validation and or correlations of computer simulation results, but also to produce a protocol for future on site data collection given the dynamic frequency of the crowd noise.

The 120 small microphones record the crowd noise within playing field. The software allows the user to pinpoint exactly how much sound individual people and musical instruments make in a crowd of a hundred thousand. Other factors such as the duration of the yells from the crowd, and the length of time it takes the crowd to reach "full loudness", the point at which the noise intensity level remains steady had to be evaluated for peak measurements, and their spectral characteristics.

Crowd participation was almost entirely controlled by the student section and their effort. If all 109,840 individuals had yelled at the same intensity, the measurement would have increased to 102 or 103 dBA, Leq.(10) within the centre of the open top field, which is a significant sound increase. Digital recording of the data measured within the UM football centre are shown in **Figs. 3 and 4**. In addition, the spectators' peak noise as time series data measured over the length of a game at various sound level thresholds of 80 dBA, 90 dBA, and 100 dBA and up is shown in **Fig. 5** as RGB colours respectively.

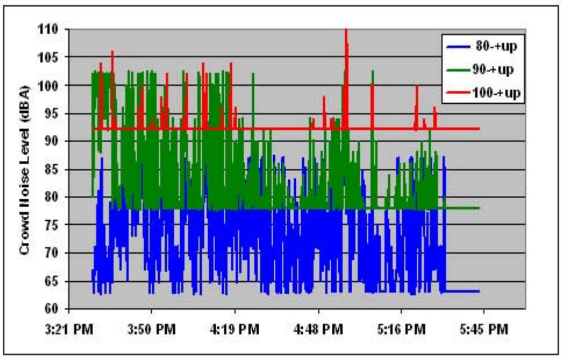

Figure 5 *A time series measured data in the stadium for crowd noise at 80 dBA, 90 dBA, and 100 dBA and up*

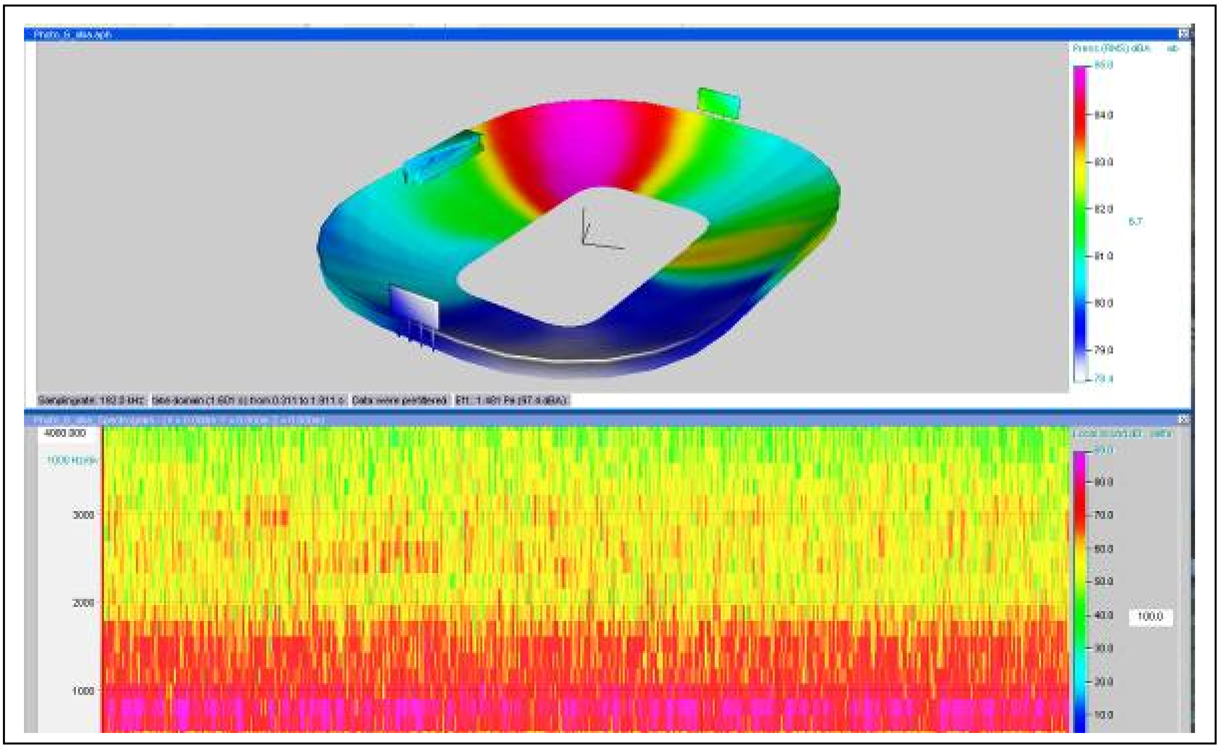

Figure 3 *Sound image of the crowd noise and its spectral characteristics*

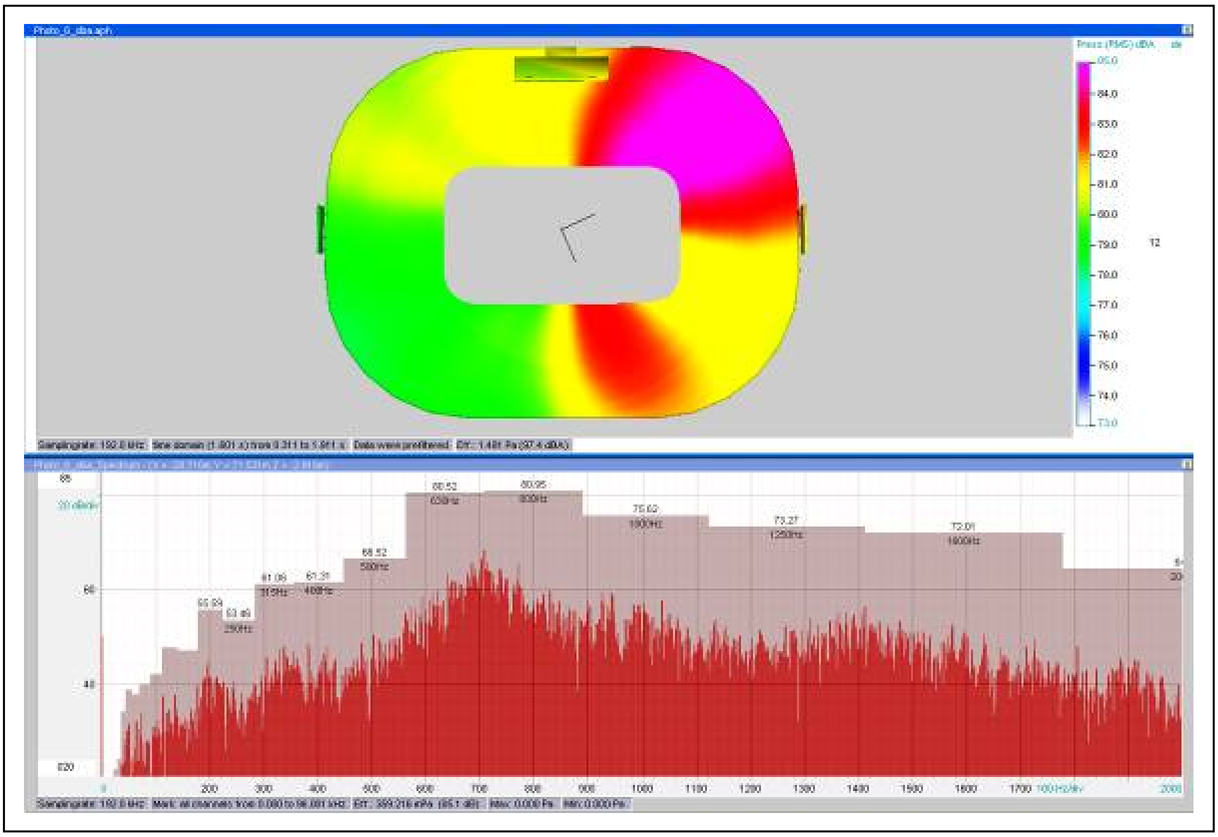

Figure 4 *Sound image of the students' section crowd noise and the peak frequency.*

ANALYSIS

The 400,000-square-foot addition includes two multi-story masonry structures on both the east and west sides of the stadium tilted downward to avoid high sun set ray reflections while redirecting the crowd noise reflection toward the playing filed; the end zones will remain open. The volume of the seating area in the stadium space is within the 250m (width) 200m (length) and 45 meters in height that will stand 3 meter higher than the current scoreboards at their highest point, include 83 suites and 3,000 club seats at a cost of $226 million. The addition of luxury boxes as shown in **Fig. 6** to Michigan Stadium and their unique design and building geometry will make a contribution to the so called desired crowd noise or louder "Big House" acoustic by the fans according to tests results and real time measured data during the game.

Figure 6 *Proposed sky boxes within the stadium*

During halftime at a Saturday football game against Minnesota, the sound in Michigan Stadium at the 50-yard line was measured to predict what impact the planned renovations would have in making the stadium louder. The measured results were used as an input in computer simulation modelling for various parametric studies.

Acoustic Camera data was post processed to produce Acoustic Photos files for each crowd noise condition and measurement position. The methodology and calculation procedures were applied for the UM stadium with and without the sky boxes. Each sound source and intensity was simulated using the Acoustic Camera data.

The sound recording was generated taking the crowd noise into account by using sound from prior to the start until after the sound reverberation had stopped. An Acoustic Photo file was generated for as many locations and time intervals required for these computer simulations. These simulations uses 3D acoustic views and the dynamics of the sound rays within the space during the steady state behavior, this visualization of the sound field as it interacts with the interior surfaces of the space allows the calculation of time histories for specific points of interest in the space. This data can then be used to correlate the UM model for acoustic metrics in a space based methodology. The 3D acoustic models including the spectral characteristic of the crowd noise are shown for selected zones in **Figs. 3 and 4.**

Sabine's equation (1) provides a good index for the sound behavior in a fairly reverberant space with a uniform distribution of absorptive material. This is due the Sabine's assumption that the sound decays continuously and smoothly, a scenario that requires a homogenous and diffuse sound field without major variation within the space surface properties. The calculated RTs in **Fig. 7** are based on measured data using Sabine's concept and show the impact of open and closed roof top for two major stadiums. The results show the open roof top has obviously lower RT at lower frequencies.

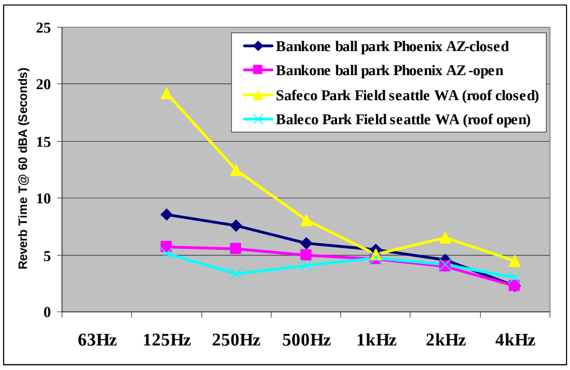

Figure 7 *RTs 60 dBA based on measured data for existing stadiums with their roof top open and closed.*

As the surface characteristics or the absorption in a space is increased, the calculated results obtained by equation (1) become less reliable. As an example if we compute the reverberation for a totally dead space such as an anechoic chamber with the absorption coefficients of it's boundaries to be set at 1.0, then the reverberation time would be 0.0; however Sabine's equation results in a finite RT. A different approach has been used for less reverberant spaces using equation (2) by the Norris-Eyring that assumes an intermittent decay with the arrival of fewer and fewer reflections. This equation provided a different set of results as shown in **Table 4** for both existing and proposed stadium design with the new sky boxes. This equation gives the correct value of 0.0 for a completely dead space but is more complex and only valid for spaces with the same value of absorption for all surfaces **[9].** Large sport facilities have a wide variety of absorption coefficients given their interior surface materials and in this case the Millington-Sette as shown in form of equation (3) produces the most closest estimations to real time measured data. The Millington-Sette equation was used to see the impact of the new sky boxes on the sound condition within the stadium. The results as shown in **Fig. 8** are based on calculated RT as a function of selected frequencies. The plotted results show that the existing stadium's RT is very close to the proposed design at low frequency. The variations of the surface absorption coefficients within the large amount of glazing surfaces used by the proposed sky boxes as shown in **Fig 6** has increased the RT at middle frequencies by a noticeable amount. This means that it will be much louder or noise created by the crowd will last longer in the new stadium as compared to the average measured RT for selected major stadiums. The volume of the space was assumed to be a closed space for the purpose of this comparison as part of these parametric studies.

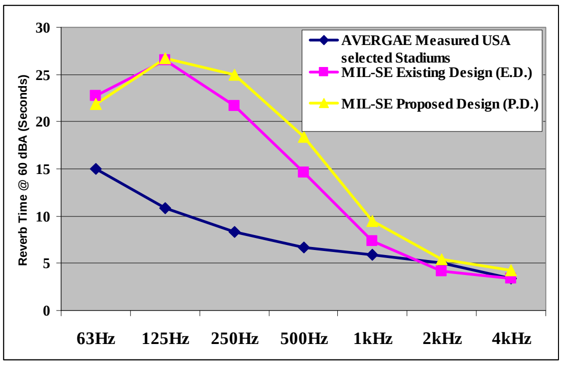

Figure 8 *RTs 60 dBA based simulation data for existing stadiums and the proposed new skyboxes*

The early decay and the RT60 were calculated using equations 1 through 3, using the Existing Design (E.D.) and the Proposed Design (P.D.) with the new sky boxes and the results of various Bass Ratios using low and extended low frequencies are shown in **Table 4.[9]**

Table 4

Calculated RTs 60 and the related low and extended bass ratios for existing and proposed design

#	UM- Stadium	63Hz:	125Hz:	250Hz:	500Hz:	1kHz:	2kHz:	4kHz:
1	SABINE E.D. (Eq.1)	3.33	3.4	3.45	3.54	3.46	3.38	3.33
2	NOR-ER E.D. (Eq.2)	2.24	2.31	2.36	2.46	2.38	2.3	2.24
3	MIL-SE E. D.(Eq.3.)	22.76	26.51	21.64	14.63	7.4	4.18	3.35
4	SABINE P.D.(Eq.1)	3.72	3.81	3.87	4	3.9	3.8	3.73
5	NOR-ER P. D.(Eq.2)	2.62	2.72	2.77	2.91	2.81	2.7	2.63
6	MIL-SE P D. (Eq.3)	21.83	26.69	24.92	18.39	9.46	5.38	4.3

#	Ex Low Freq.Avg	Low Freq.Avg	Mid Freq.Avg	Bass Ratio	Ex Bass
1	3.39	3.43	3.50	0.98	0.97
2	2.30	2.34	2.42	0.96	0.95
3	23.64	24.08	11.02	2.19	2.15
4	3.80	3.84	3.95	0.97	0.96
5	2.70	2.75	2.86	0.96	0.95
6	24.48	25.81	13.93	1.85	1.76

Comparisons with the average indexes of other well known stadiums are shown in **Table 4**. The larger extended BR (by almost by 1 second) calculated using RT60 Millington equation indicates reflected sound contributions from the new sky boxes' facade and or operable windows are much higher to the playing field [6-9]. This condition has created an opportunity to have the spectators participate in altering the RT or the decay time during the game by having the crowd noise to be created or generated at certain times for maximum impact on the space reflective components. There are major concert hall designs that allow for variable space volumes. The change in volume does impact the reverberation times. The simulation results show by opening the operable windows within sky boxes, it is possible to alter the contributions of reflected components within the same volume of space. The ray diagram in **Fig. 9** shows the reflected sound from the closed and open window into the field from the new sky boxes. The direct (**red**) and first reflected (**blue**) sound ray simulated for various crowd locations are shown in **Fig. 10.**

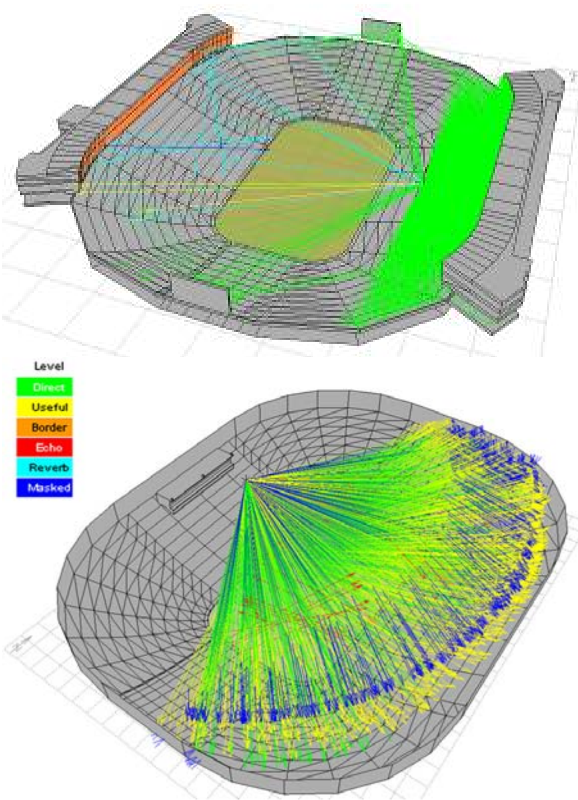

Figure 9 *Simulation of the open top stadium with and without the new sky boxes*

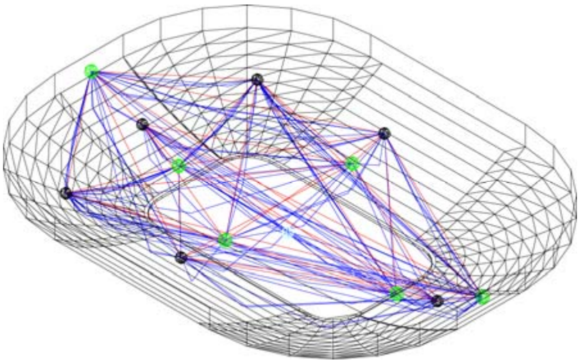

Figure 10 *Image of the direct (**Red**) and1st reflected (**Blue**) sound rays showing the simulated crowd noise for various locations.*

The sound pressure levels calculated from the simulated crowd noise source (**black**) at the receiver (**green**) data do correlate with the measure data at selected frequencies. Surface absorption was used to account for spectator's body absorptions. **Figs. 11** show the localized measuring of the crowd noise and the organized sequence of crowd cheering "Go Blue". Given the intensity and spectral characteristic of the large size spectators or crowd noise exceeding 100,000 people; it is conceivable to create adverse acoustic conditions for the opposing team on the filed. The calculated RT and the Bass ratios as shown in **Fig. 12** show the best estimates given the available simulation tools and input data.

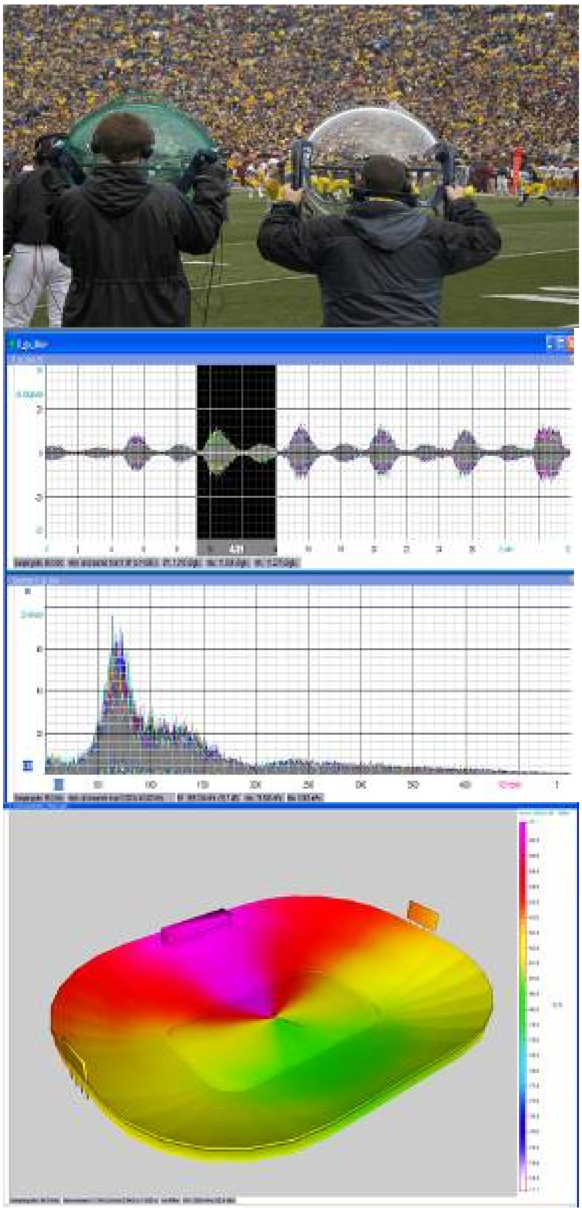

Figure 11 *the localized measuring of the crowd noise and the organized sequence of crowd cheering "Go Blue".*

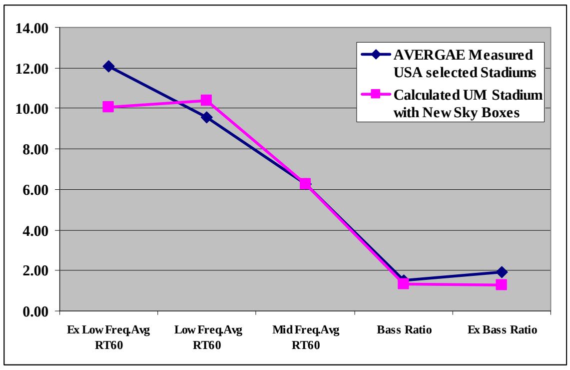

Figure 12 *Comparison of the UM stadium with the new sky boxes and average for selected stadium*

CONCLUSION

For the biggest football stadiums, the reverberation time is one means of determining acceptable acoustics. The UM open-air stadium is compared to enclosed stadiums which often have reverberation times exceeding 10 seconds and which makes speech difficult to understand. Reducing the unwanted sound, the echoes and reverberation requires designers to shape and or treat building surfaces. Hard, smooth objects reflect sound similar to light. Change of surface angles allows the sound to reflect in a desired direction.

The new design of the skyboxes allows the reflected sound to be aimed toward the playing field, and the glazed wall surface combined with organized crowd noise brings the advantage to the home team. Fibreglass and other porous materials that absorb sound are often used to reduce the sound level. However, the design of partially operable windows allows skybox users finer control over the available sound either reflected by the glass surfaces or absorbed at strategically selected times during the game. NFL football game crowd noise levels range between about 95 to 105dBA with occasional peaks approaching 110 dB. The sound system design must be at least 10 dB louder in order to be understood over that noise. This will be a problem when crowd noise reaches the 115-dBA level that can damage a fan's hearing if exposed for any length of time. Under these conditions, it is not permitted for a sound system to produce intelligible sound, and any attempt would put the public at risk.

Crowd noise will pose a significant challenge to sound systems. However, the final renovation planned for the UM stadium and its architectural acoustics along with the sound system are well designed, and most fans will be relatively unaware of either as they enjoy the game. Although a sport facility is not the same as a concert hall, the required architectural elements in size and geometry to solve the sound reflections in the low frequency range remain a major challenge in architectural acoustic design, and moreover present a unique demand in recording such effects or the total impact of low frequency sound energy.

ACKNOWLEDGEMENT

Special thanks to the University of Michigan's Athletic Department for access to the stadium during the game, and Dr. Ralf Schröder of Gfai Tech GmbH. for providing the acoustic camera recording system.

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