Acoustically conserving the worship heritage of nossa senhora de penha de França church, goa

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ABSTRACT

This study presents a method of acoustically capturing the worship heritage of *Nossa Senhora de Penha de França church*, using objective acoustical parameters and derived acoustical parameters called 'acoustical worship impressions' of Sacred Factor (*SaF*), Intelligibility Factor (*InF*) and Silence Factor (*SiF*). The Subjective Perceptions were recorded in the church at a *Concert of Ketevan World Sacred Music Festival* with Viola da Gamba, Irish Harp and Flute. Multi-regressions of acoustical worship impressions on perception of Reverberance, Intimacy, Envelopment, Loudness, Clarity, Directionality, Balance, Noise and Echo (for each musical instrument) generated some significant results. Music rendered by Viola da Gamba was found favouring *SaF* (R^2 = 0.88, p value < 0.0001). Music rendered by Harp also favoured *SaF* (R^2 = 0.81, p value = 0.02). Music rendered by an ensemble of Viola da Gamba, Harp and Flute favoured *InF* (R^2 = 0.74, p value = 0.01). A significant relationship between Acoustical Worship Impressions and Objective Acoustical parameters is the negative correlation between *SaF* and *EDT* for ensemble (R = -0.82, p value = 0.05). The acoustically characterized worship experience thus works as a reference tool for future conservative interventions.

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1 INTRODUCTION

Each church, accommodating the conflicting conditions for sacred speech, sacred music, singing and silence in the sound decay[1,2] is meant to have a signature acoustical ambience which optimizes the sacred liturgy in a worship space to become a genuine celebration of ‘comfort’, 'awe', 'meaning' and ‘solace’[3-8]. This is the acoustical worship heritage of a church.

Nossa Senhora de Penha de França church is a seventeenth century church built in mannerist neo-roman style resting on the banks of River Mandovi in Panjim, Goa.

Fig.1 – Photograph of Nossa Senhora de Penha de França church pre and post-restoration.

2 ACOUSTICAL CHARACTERIZATION OF WORSHIP AMBIENCE: METHODOLOGY

This method of acoustically chararacterizing the worship ambience of a worship space is part of an ever-evolving research program that explores the aesthetics of worship through acoustically constituted categories[5-9]. The method presented here is an improvement over the earlier studies.

2.1 Impulse Response Tests

Impulse Response tests were conducted in compliance with the ISO-3382 standard[10] and objective acoustical parameters such as Noise Ambience (L_{Aeq}), Reverberation Time (RT), Rapid Speech Transmission Index (RASTI), Definition for Speech (D_{50}), Clarity for Music (C_{80}) and Centre time (TS) were measured using the laptop based ARTA software. The source was placed in the sanctuary and recordings were done in seven zones of the church.

2.2 Subjective Acoustical Tests

One of the concerts of Ketevan World Sacred Music Festival was organized at Penha de França Church on February 16, 2017. The musicians performed from the sanctuary floor beneath the sanctuary arch. This is marked as the Music source for the subjective acoustical tests that were incorporated into the concert. The musical instruments chosen were Viola da Gamba (V) (one of the most popular instrument for sacred music in Europe during the Renaissance and Baroque periods), Irish Harp (H) (being the only music played during the crusades) and Flute (F) (used in the time of King David and in the medieval era in Europe).

Twenty three listeners from amongst those attending the concert were chosen and seated at different locations in the church. Listeners (1 - 18) occupied seats in the nave of the church. Listener 19 was seated in the narthex of the church while listeners (20 - 23) were seated in the choir loft. The listeners were instructed to evaluate the subjective acoustical impressions for each genre of music performed for the concert using the evaluation sheets given to them.

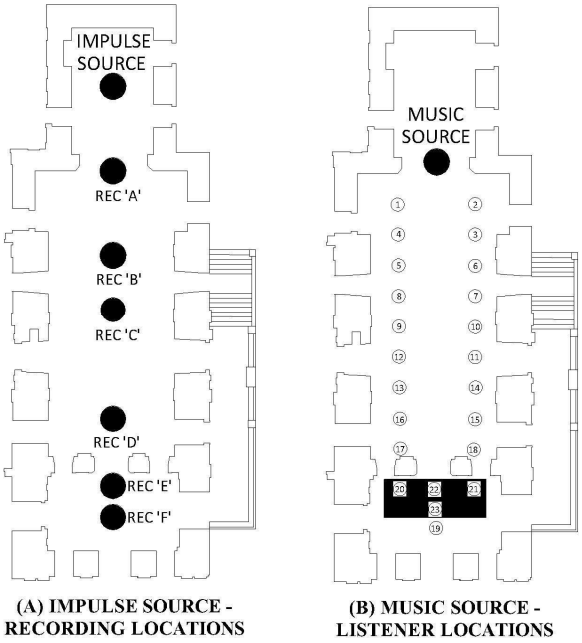

Fig.2 – Photograph showing the locations of Sources, Recorders and Listeners for the acoustical tests in Nossa Senhora de Penha de França church.

2.3 Subjective acoustical evaluation method

The subjective acoustic evaluation method employed in this study is derived from the earlier studies done by Beranek in concert halls[11] and by Carvalho to assess the subjective acoustical preferences in Portuguese churches[12]. The listeners scored on the acoustical qualities of the church using a given subjective acoustic evaluation sheet. Each of these qualities provided a seven point (-3 to +3) differential bipolar scale on the evaluation sheet (where a score=0 implied the listener was 'not sure')

This acoustic evaluation sheet spelled out:

1. Loudness (The overall loudness or strength of the sound) scaled from -3 (not audible) to +3 (optimally loud);
- Clarity (The degree to which the musical notes are distinctly separated in time and clearly heard) scaled from -3 (totally blurred) to +3 (totally clear);
- Reverberance (the persistence of sound) scaled from -3 (totally dry) to +3 (optimally live);
- Directionality (the auditory impression that the sound comes from the axis of the sound source due to the arrival of substantial amount of direct sound) scaled from -3 (very bad) to +3 (very good);
- Intimacy (the auditory impression of the apparent closeness of the orchestra) scaled from -3 (absence of intimacy) to +3 (optimally intimate);
- Envelopment (the sense of being immersed in the sound or surrounded by it which happens when there is substantial amount of reverberant sound) scaled from -3 (not surrounding at all) to +3 (optimally surrounding);
- Balance (the relative levels of bass and treble) scaled from -3 (totally unbalanced) to +3 (optimally balanced).
- Silence from Background Noise (where Background Noise is the sound heard other than from the source in the performance area) scaled from -3 (Extremely strong Background Noise) to +3 (Extremely weak Background Noise);
- Silence from Echoes (where Echoes are long delayed reflections that are clearly audible) scaled from -3 (clear echoes) to +3 (no echoes).
- The Overall Acoustical Impression (the overall impression of the acoustical quality of the room) scaled from -3 (very bad) to +3 (very good).

The listener, as guided before every test, judged to what degree the music played in the church was loud, clear, reverberant, well-directed, intimate, enveloping, tonally balanced, acoustically impressive and affected by echoes and background noise. These acoustical qualities of the music played in the church determine the comfort level of a listener. The music played in the church was hypothesized as capable of impinging a unique acoustical impression on different listeners seated at different locations in the church. The normalized scores of the acoustical qualities for different music genres in different seating zones of the church could be considered as subjective impressions the sound registered on the listeners. Therefore, the normalized scores of the subjective acoustical qualities were called subjective acoustical impressions (SAI) and are listed as:

- Subjective acoustical impression of Loudness (SAI_{LOUD})
- Subjective acoustical impression of Clarity (SAI_{CLAR})

- Subjective acoustical impression of Directionality (SAI_{DIR})
- Subjective acoustical impression of Balance (SAI_{BAL})
- Subjective acoustical impression of Intimacy (SAI_{INT})
- Subjective acoustical impression of Envelopment (SAI_{ENV})
- Subjective acoustical impression of Reverberance (SAI_{REV})
- Subjective acoustical impression of Echoes (SAI_{ECHO})
- Subjective acoustical impression of Background Noise (SAI_{NOIS})
- Subjective overall acoustical impression (SAI_{OVER})

The scored acoustical qualities were normalized into subjective acoustical impressions using Eqn. 1,

$$nX_{SAI} = 1 \quad \forall\ X_{meas} = X_{ref} \qquad (1)$$

$$nX_{SAI} = 1 - \frac{\Delta X}{X_{ref}} \quad \forall\ X_{meas} < X_{ref}$$

where, nX_{SAI} is the normalized value of the perceived acoustical qualities ($-1 \leq X_{SAI} \leq +1$),
X_{meas} is the measured value of the subjective acoustical quality ($-3 \leq X_{meas} \leq +3$),
X_{ref} is the optimal reference limit value of the subjective acoustic impression ($X_{ref} = +3$),
$\Delta X = |X_{ref} - X_{meas}|$

The polarity of the subjective acoustical impression is significant as it indicates the positive or negative impression of the subjective acoustical qualities on the listener.

2.4 Musician's Criterion

The Musicians' criterion was assessed through an evaluation sheet filled through an interview of each performing musician. Each question on the evaluation sheet provided a five point (-2 to +2) differential bipolar scale (where a score=0 implied the listener was 'not sure'). The questions posed to the performing musicians were:

1. Could you hear each other's rendition clearly?
2. Could you hear your own rendition clearly?
3. Did you enjoy playing your instrument in this church?
4. Did you enjoy playing solo?
5. Did you enjoy playing duet?
6. Did you enjoy playing in the ensemble?
7. Did you feel content performing in this church?
8. How would you rate this church for performance?

2.5 Derivation of Acoustical Worship Impressions

The process of enquiry has generated three distinct, theologically sound acoustically constituted worship parameters termed as 'Acoustical Worship Impressions' (AWI). The three distinct AWI were named as: sacred factor (SaF); intelligibility factor (InF) and silence factor (SiF). This method of characterizing the ethos of worship through acoustically constituted worship categories is termed as “acoustical characterization of worship ambience”.

Sacred Factor (SaF) evaluates reverential awe in a worship space. *Intelligibility Factor* (InF) measures the quality of the communion between the ‘Word’ and the ‘Listener’ which enables an intelligible communication between the ‘human’ and the ‘divine’ in a worship space.

Silence Factor (SiF) covers the extensive journey from solitude to serenity to surrender initiated by the aura of a worship space.

The 'Acoustical Worship Impressions' (SaF, InF, SiF) are constituted accommodating the following factors:

1. The impact of each perceived subjective acoustical quality on the *listeners perception of the Divine* (nY_{SAI}) (as described by the *sacred factor* (SaF), *intelligibility factor* (InF) and the *silence factor* (SiF)) was evaluated using the given subjective acoustical evaluation sheet where the perceived impact of each SAI on SaF, InF and SiF was noted on a three point (-1 to +1) differential bipolar scale as either 'impacting' (+1) or 'not impacting' (-1) (whereas a score=0 implied the listener was 'not sure').
2. The perception of a listener (as to how the subjective acoustical perceptions are related to the sacred factor, intelligibility factor and the silence factor in the church) is cumulative of all musical experiences (and not specific to any one musical genre). The perception is of the church and not of any specific musical instrument or rendition.
3. However, this general perception (of the connection between the three aspects of the Divine as described by the SaF, InF and SiF) is applied to normalize the different subjective acoustical impressions for each AWI of each musical genre.
4. These perceptions of each listener (nY_{SAI}) work as weights to normalize the cumulative impact of all the subjective acoustical impressions of each listener to constitute credible normalized acoustical worship impressions of sacred factor (SaF),intelligibility factor (InF) and silence factor (SiF) for each musical genre.
5. Thus, Normalized Acoustical Worship Impressions are constituted using Eqn. 2,

$$nAWI = 1 \qquad \forall \sum (Y_{SAI} X_{SAI})_{MEAS} = \sum (Y_{SAI} X_{SAI})_{REF}$$

$$nAWI = 1 - \frac{\Delta \sum Y_{SAI} X_{SAI}}{\sum (Y_{SAI} X_{SAI})_{REF}} \qquad \forall \sum (Y_{SAI} X_{SAI})_{MEAS} < \sum (Y_{SAI} X_{SAI})_{REF} \qquad (2)$$

where,

nAWI (as SaF, InF, SiF) is a normalized value of the perceived impact of acoustical qualities on the listeners perception of the Divine ($-1 \leq nAWI \leq +1$);

$\Delta \sum Y_{SAI} X_{SAI} = \sum (Y_{SAI} X_{SAI})_{REF} - \sum (Y_{SAI} X_{SAI})_{MEAS}$

X_{SAI} is the normalized value of the percieved acoustical qualities ($-1 \leq X_{SAI} \leq +1$),

Y_{SAI} measures perceived impact of acoustical qualities on the Acoustical Worship Impressions of Reverential Awe, Sacred Intelligibility and Sacred Silence ($-1 \leq X_{SAI} \leq +1$),

$\sum (Y_{SAI} X_{SAI})_{MEAS}$ is a calculated value from X_{SAI} and Y_{SAI}

$\sum (Y_{SAI} X_{SAI})_{REF}$ is the optimal reference limit ... $\sum (Y_{SAI} X_{SAI})_{REF} = 30$

6. The polarity of the normalized acoustical impression is significant as it indicates the absence or the presence of the sacred factor, intelligibility factor and the silence factor as perceived by the listeners and as constituted of the different subjective acoustical impressions for different genres of music. This revised calculation also permits the listeners to opine being not sure of the expected sacred experience in a worship space.

The subjective data was analyzed using *Excel* and *Origin 6.1 and Origin 8.0.*

This detailed process of acoustical characterization of worship ambience unearths the aesthetics of worship heritage of a given church and enables a hands-on programme of acoustical interventions to acoustically conserve the worship heritage.

3 RESULTS & DISCUSSION

3.1 Variance of Objective Acoustical Measures

A spectral analysis of the objective acoustical measures of mid-sanctuary recordings revealed the following trends:

- Low frequency reverberation has decreased post restoration.
- C80 values at 125 Hz and at 500 Hz have enhanced post restoration.
- D50 value at 500 Hz shows great improvement post restoration.

A spectral analysis of the objective acoustical measures of mid-nave recordings revealed the following trends:

- Slightly higher reverberation is observed at and above 500 Hz post restoration.
- Except at 1 KHz, C80 values are better post restoration.
- Except at 125 Hz, D50 values are better post restoration.

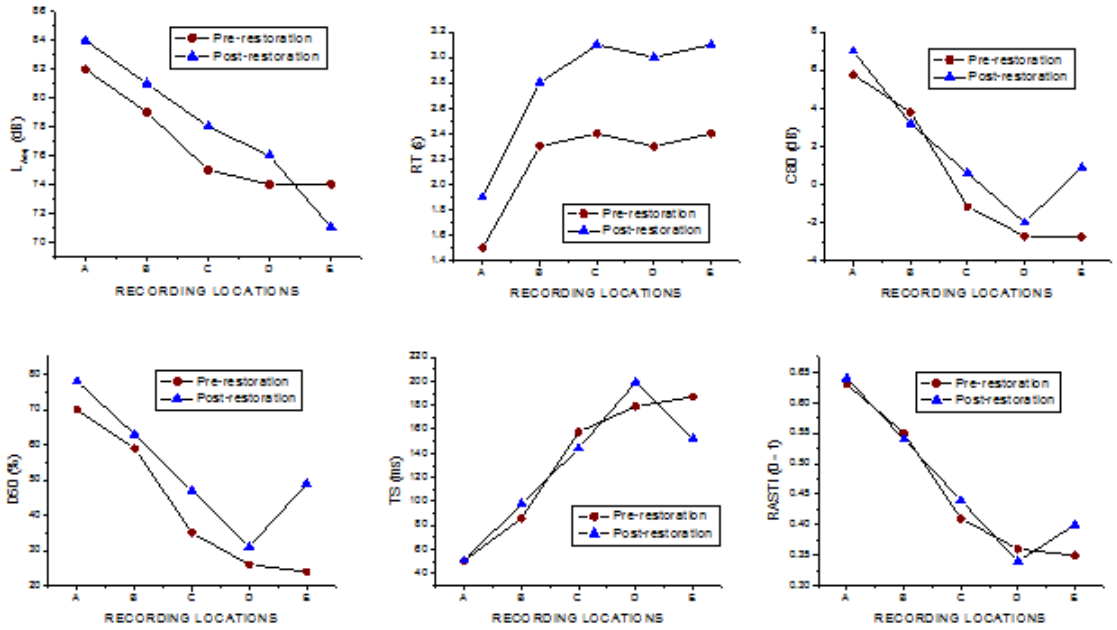

Fig.3 – Photograph showing the Pre-restoration and Post-restoration comparison of objective acoustical measures in Nossa Senhora de Penha de França church.

None of the objective acoustical parameters showed significant differences between the pre-restoration and post-restoration measured values at the benchmark significance level of $p < 0.05$.

3.2 Subjective Acoustical Impressions and Musician's Criterion

None of the subjective acoustical impressions (SAI) showed significant differences between the different music genres at the significance level of $p < 0.05$.
The perceived loudness of the instruments remarkably increased in the choir loft (by 7 dB) as compared to that perceived in the nave of the church.

Sophia Diniz playing Viola da Gamba, Joana Amorin and Rebecca Amorin playing the Flute and Harp respectively, expressed that all the musician's criteria were perfectly obliged in this performing space (of the church): They could hear other's and their own rendition optimally and clearly. They could play with ease. They enjoyed playing solo, duet and as an ensemble. They all expressed that they experienced optimal contentment while performing in this church. They rated this space a perfect 'five' for being an ideal space of performance on a scale of -2 to +2.

3.3 Multiregressions of Acoustical Worship Impressions

Multi-regressions of acoustical worship impressions on the subjective acoustical impressions of Reverberance, Intimacy, Envelopment, Loudness, Clarity, Directionality, Balance, Noise and Echo (for each musical instrument) generated some significant results.

The music rendered on the Viola induced a significant Sacred Factor ($R^2 = 0.88$, p-value <0.0001) as shown below:

$$SaF_{VIOLA} = 0.02 + 0.02\ SAI_{REV} + 0.02\ SAI_{INT} + 0.12\ SAI_{ENV} + 0.07\ SAI_{LOUD} + 0.03\ SAI_{CLAR} - 0.03\ SAI_{DIR} + 0.02\ SAI_{BAL} + 0.0004\ SAI_{SNOIS} - 0.03\ SAI_{SECHO}$$

The Sacred Factor for the Viola is seen positively correlating with the subjective acoustical impressions of Reverberance, Intimacy, Envelopment, Loudness, Clarity, Balance and Silence from Noise and is seen negatively correlating with the subjective acoustical impressions of Directionality and Silence from Echo.

The music rendered on the Harp induced a significant Sacred Factor ($R^2 = 0.81$, p-value $=0.002$) as shown below:

$$SaF_{HARP} = - 0.06 + 0.005\ SAI_{REV} + 0.15\ SAI_{INT} + 0.04\ SAI_{ENV} + 0.06\ SAI_{LOUD} - 0.01\ SAI_{CLAR} + 0.08\ SAI_{DIR} - 0.05\ SAI_{BAL} - 0.04\ SAI_{SNOIS} - 0.03\ SAI_{SECHO}$$

The Sacred Factor for the Harp is seen positively correlating with the subjective acoustical impressions of Reverberance, Intimacy, Envelopment, Loudness and Directionality and is seen negatively correlating with the subjective acoustical impressions of Clarity, Balance, Silence from Noise and Silence from Echo.

The music rendered by an ensemble of Viola da Gamba, Harp and Flute induced a significant Intelligibility Factor ($R^2 = 0.74$, p-value = 0.01) as shown below:

$$InF_{ENSEMBLE\ (V,H,F)} = 0.03 - 0.08\ SAI_{REV} + 0.1\ SAI_{INT} - 0.0008\ SAI_{ENV} - 0.01 SAI_{LOUD} + 0.02\ SAI_{CLAR} + 0.03\ SAI_{DIR} + 0.05\ SAI_{BAL} + 0.04\ SAI_{SNOIS} + 0.02\ SAI_{SECHO}$$

The Intelligibility Factor for the ensemble of Viola da Gamba, Harp and Flute is seen positively correlating with the subjective acoustical impressions of Intimacy, Clarity, Directionality Balance, Silence from Noise and Silence from Echo and is seen negatively correlating with the subjective acoustical impressions of Reverberance, Envelopment and Loudness.

Multi-regressions of acoustical worship impressions (for each musical instrument) on the objective acoustical measures generated a couple of significant results.

The Intelligibility Factor for the renditions of the Harp showed a significant positive linear correlation with Loudness (L_{Aeq}) (R = 0.81, p-value = 0.05) as shown below:

$$InF_{HARP} = -3.4 + 0.05\ L_{Aeq}$$

The renditions by the ensemble of Viola da Gamba, Harp and Flute impinged a Sacred Factor of significant negative linear correlation with Early Decay Time (EDT) (R = - 0.82, p-value = 0.05) as shown below:

$$SaF_{ENSEMBLE\ (V,H,F)} = 3.3 - 1.15\ EDT$$

4 CONCLUSIONS

The subjective and objective acoustical tests in the church verified the credibility of the restorative exercise undertaken in the church. Although not 95% significantly better, the considerable improvement in Definition for Speech(D_{50}), Clarity for Music(C_{80}) and L_{Aeq} post restoration makes the increase in Reverberation Time (RT) (from 2.2 s to 2.8 s) more effective thus creating an optimal "loud and intelligible liveness" in the church. Although statistically insignificant, the mean values of the subjective acoustical impressions indicate an overall perception of good subjective acoustics in the church.

This joyful subjective perception of the worship space confirms the fact that this restored "intelligibly loud and live and yet silent" worship space now elicits a heightened experience of the Divine as expressed by the clergy, the choir and the congregation that gathers for worship in the restored church.

The observed significant correlations and the accompanying prediction equations between some acoustical worship impressions of Sacred factor Factor (*SaF*), Intelligibility Factor (*InF*) and Silence Factor (*SiF*) and the objective acoustical measures and the subjective acoustical impressions of Reverberance, Intimacy, Envelopment, Loudness, Clarity, Directionality, Balance, Noise and Echo (for each musical instrument) divulges the *'acoustically characterized signature worship ambience*' of the tested worship space.

The acoustically characterized worship experience thus works as a reference tool for future conservative interventions.

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6 REFERENCES

1. V. O. Knudsen and C. Harris, *Acoustical designing in architecture*, John Wiley & Sons, New York, (1988).
2. C. Ettore and F. Martellotta, *Worship, Acoustics and Architecture*, Multi-Science, U.K, (2006).
3. R. K. Seasoltz, *The House of God: sacred art and church architecture*, Herder and Herder, New York, (1963).
4. A. Botton, *The Architecture of Happiness*, Hamish Hamilton, London, (2006).
5. Menino A. P. S. Tavares, S. Rajagopalan and S. Sharma, "Comparative Acoustical Studies of Two Goan Churches", *J. Revista de Acústica* 38, 3, (2007).
6. Menino A. P. S. Tavares, S. Rajagopalan, S. Sharma and Antonio P. O. Carvalho, "Acoustic Characterization of worship ambience – Old Goa's Capela do Monte, a comprehensive example." *Proc. 37th Inter-Noise 2008, **in08_0526**, Shanghai (China),* (2008).
7. Menino A. P. S. Tavares, S. Rajagopalan, S. Sharma and Antonio P. O. Carvalho, "Acoustic Characterization of Sacred Music rendered by a human whistle at the Divine Providence Church in Goa, India." *Proc. 20th ICA, Sydney (Australia),* (2010).
8. Menino A. P. S. Tavares, Antonio P. O. Carvalho, S. Rajagopalan and S. J. Sharma, "Evaluation of Acoustic Silence, Acoustic Intelligibility and Acoustic Sacred Factor in Goan Catholic churches." *Proc. 40th Inter-Noise 2011, Osaka (Japan),* (2011).
9. B. Shukla, and Menino A. P. S. Tavares, "Acoustical Analysis of a Buddhist Hall at Bomdila Monastery, India." *Proc. ICSV 2013, Bangkok (Thailand,* (2013).
10. ISO-3382, Acoustics - Measurement of the reverberation time of rooms with reference to other acoustical parameters, International Standard Organisation, Geneva, (1997).
11. Leo L. Beranek, *Music, Acoustics and Architecture.* John Wiley & Sons, New York, (1962).
12. Antonio P. O. Carvalho, "Analysis of Subjective acoustic measures and speech intelligibility in Portuguese churches." *Proc. 131st Acoustical Society of America Meeting, Indianapolis (USA)* (1996).