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# Relationship between acoustic worship ambience and speech intelligibility in Goa's Bom Jesus Basilica

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## ABSTRACT

The acoustic worship ambience in the church is defined through the derived Acoustic Worship Indices (AWI), namely Sacred Factor (SaF), Intelligibility Factor (InF) and Silence Factor (SiF). The Speech Intelligibility in the church was evaluated through RASTI tests for different sound source locations (altar [SA], pulpit [SB] and high altar [SC]) and for different postures (sitting [SIT] and standing [STAND]) and the Modified Rhyme Tests based Subjective Speech Intelligibility (SSI) scores for different source locations (SA, SB and SC) and for different languages (English [ENG] and Konkani [KONK]). SaF was found to regress significantly on SSI [SA] ($R^2$ = 0.88) and RASTI[SIT] ($R^2$ = 0.92); InF regressed the best on SSI[SC] ($R^2$ = 0.84) and SSI[ENG] ($R^2$ = 0.89) while SiF was best predicted through RASTI[STAND] ($R^2$ = 0.93) and SSI[ENG] ($R^2$ = 0.60). The possibility of a predictable connection between speech intelligibility and acoustic worship ambience can help enhance the liturgical functions in the church.

## 1. INTRODUCTION

The worship ambience proper to the Sacred Liturgy of a worship space depends on the balance between speech, music, singing and silence[1-4]. As speech constitutes a major portion of Christian Liturgy, good speech intelligibility would augur well for the liturgical celebration in a church. The relationship between Speech Intelligibility and other acoustic parameters in Catholic churches has been studied[5-6]. It would certainly benefit corporate worship if a functional relationship between Speech Intelligibility and the worship ambience is established. The worship ambience in a church is acoustically characterized using the Acoustic Worship Indices (AWI)[7]. This study presents some of the significant relationships between speech intelligibility and three distinct AWI: Sacred Factor (SaF); Intelligibility Factor (InF) and Silence Factor (SiF) in Old Goa's Bom Jesus Basilica (a significant Catholic church of Goa, a former Portuguese colony in India).

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## 2. BOM JESUS BASILICA: THE SAMPLE CHURCH

The Basilica of the Bom Jesus (shown in Figure 1) begun its construction in 1594 and was completed by 1605, and forms part of ancient 'Golden Goa'[8,9]. It is one of the best examples of baroque architecture in India. The architectural details of the Basilica are shown in Table 1. The ground floor plan of Bom Jesus Basilica is shown in Figure 2.

**Figure 1**: Photographs (exterior and interior) of Bom Jesus Basilica, Goa, India.

**Table 1**: *Architectural details.*

| ARCHITECTURAL MEASURES | DESCRIPTION | UNITS | VALUES |
|---|---|---|---|
| Total Absorption | $ABS_{TOT}$ | $m^2$ | 630 |
| Absorption Coefficient | $C_{ABS}$ | - | 0.12 |
| Total Floor Area | $A_{TOT}$ | $m^2$ | 1168 |
| Nave Floor Area | $A_{NV}$ | $m^2$ | 630 |
| Maximum Height | $H_{MAX}$ | m | 21 |
| Maximum Nave Height | $H_{NV}$ | m | 21 |
| Maximum Length | $L_{MAX}$ | m | 61 |
| Nave Length | $L_{NV}$ | m | 36 |
| Total Volume | $V_{TOT}$ | $m^3$ | 18858 |
| Nave Volume | $V_{NV}$ | $m^3$ | 13613 |
| Total Average Height | $H_{AVG}$ | m | 16 |
| Maximum Nave Width | $W_{NV}$ | m | 18 |
| Average Width | $W_{AVG}$ | m | 16 |
| Minimum Nave Width | $W_{MIN\ NV}$ | m | 18 |
| WIDTH Average NAVE | $W_{AVG\ NV}$ | m | 18 |
| Minimum Nave Height | $H_{MIN\ NV}$ | m | 16.5 |
| HEIGHT Average NAVE | $H_{AVG\ NV}$ | m | 18.8 |

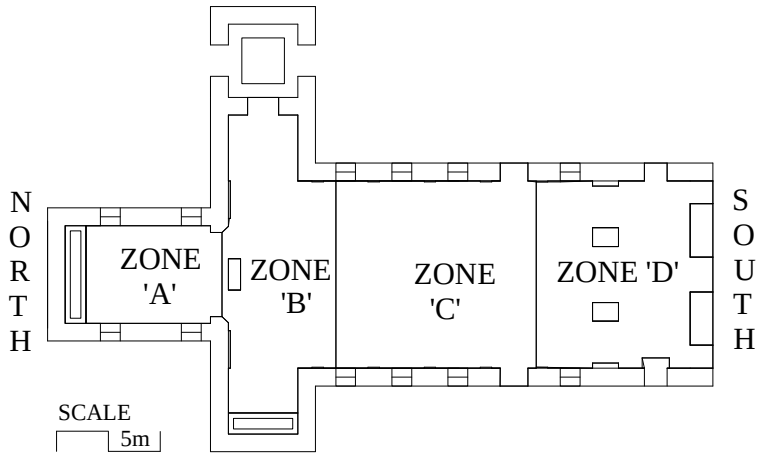


**Figure 2:** Basilica Ground Floor Plan with the zones demarcation (Floor plan courtesy: Engr.Thomas D'Costa).

## 3. METHODOLOGY AND TERMINOLOGY

### A. Subjective Speech Intelligibility (SSI) evaluations

Twenty trained normal listeners were spatially seated into four seating zones within the church. The altar, pulpit and High altar locations were chosen as Speech Source positions 'SA', 'SB' and 'SC' respectively. The Source and the Listener locations are shown in Figure 3.

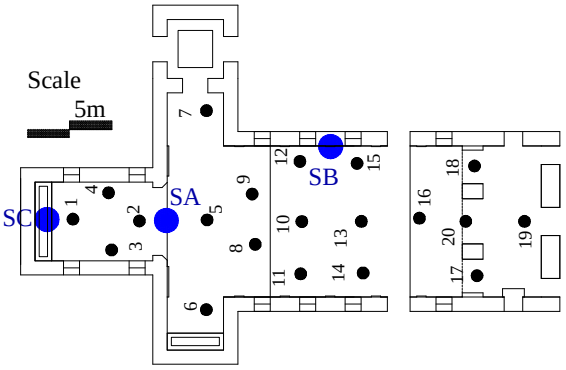


**Figure 3**: The locations of Listeners (1 to 20) and three Signal Sources (Speech).

The speakers (a Catholic Priest and a Lady Theatre Art Professional) alternately read out selected 50 words in Konkani and English languages from the prepared Modified Rhyme Test [MRT] word lists.

The Subjective Speech Intelligibility Index (SSII) was evaluated as the averaged and indexed value of the percentage of words understood by the listener. The subjective data was analyzed using *Excel* and *Origin 6.1*.

### B. Rapid Speech Transmission Index (RASTI) measurements

A standard RASTI test signal was uploaded on the PC and played through an amplified speaker setup at the 'SPEAKER' positions near 'SA', 'SB' and 'SC' around 1.6 m above the floor to represent a standardized speech situation during the service. The ATB microphone was setup at different 'LISTENER' locations in the church for the sitting mode and standing mode

respectively. The RASTI value at each listener location was averaged over a minimum of three measurements. The averaged value of RASTI for each listener zone (i.e. sanctuary, northern nave, middle nave and the southern nave) was also obtained.

### C. Evaluation of Acoustic Worship Indices: SaF, InF and SiF

Objective acoustic parameters [Noise Ambience Sound Level ($L_{Aeq}$), Reverberation Time (RT), Loudness (G), Rapid Speech Transmission Index (RASTI) and Energy Time Graph (ETG)] were directly measured in the unoccupied church using a '*Terrasonde Audio Tool Box 2.0*' [henceforth coded as 'ATB'] and '*Terralink*'. Other important objective monaural acoustic parameters: Definition [$D_{50}$], Clarity [$C_{80}$], Initial Time Delay Gap [ITDG], Center time [TS], and Early Decay time [EDT] were evaluated in compliance with the ISO-3382 standard[10]. Subjective acoustic impressions of loudness, reverberance, intimacy, envelopment, directionality, clarity, balance, echoes and background noise were evaluated. The subjective and objective acoustic measures were normalized such that the normalized parameters are equal weighted constituents of the hypothesized Acoustic Worship Indices (AWI).

Sacred Factor (SaF) as worship parameter is a description of the evolution from *Awe* to *Reverence* and *Metanoia* that one experiences in a worship space. InF measures the quality of the communion between the 'Word'[11-12] and the 'Listener'. It also measures the intelligibility of the communication between the 'human' and the 'divine'. The extensive journey from *solitude* to *serenity* to *surrender,* that ought to happen in a worship space, comprehensively constitutes the religious experience denoted by the *Silence Factor* (SiF).

## 4. RESULTS AND DISCUSSION

### A. Subjective Speech Intelligibility (SSI)

A detailed positional variance of mean SSI for the different sources (SA, SB and SC) and languages (KONK and ENG) and the church (CH) is shown in Figure 4. The simple statistics of the SSI data for the different variants is shown in Table 3.

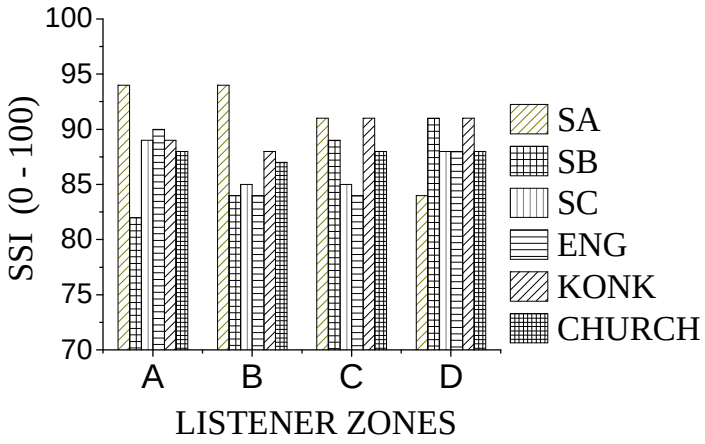


**Figure 4**: Positional (A, B, C and D) variability of SSI values within Bom Jesus Basilica controlling for Sound Source Position (SA, SB and SC) and Language (English and Konkani).

**Table 2**: *Simple statistics of Subjective Speech Intelligibility (SSI) and Subjective Speech Intelligibility Index (SSII) in Bom Jesus Basilica.*

| SIMPLE STATISTICS | SSI | | | | | | SSII |
|---|---|---|---|---|---|---|---|
| | 0 - 100 | | | | | | 0 - 1 |
| | SA | SB | SC | ENG | KONK | CH | CH |
| Minimum | 84 | 82 | 85 | 84 | 88 | 87 | 0.87 |
| Mean | 91 | 87 | 87 | 87 | 90 | 88 | 0.88 |
| Maximum | 94 | 91 | 89 | 90 | 91 | 88 | 0.88 |
| Median | 92 | 87 | 86 | 86 | 90 | 88 | 0.88 |
| Standard Deviation | 4.53 | 4.33 | 1.98 | 3.03 | 1.21 | 0.30 | 0.00 |
| Skewness | -1.72 | -0.03 | 0.21 | 0.35 | -0.27 | 1.64 | 1.64 |
| Kurtosis | 2.89 | -4.53 | -4.72 | -3.87 | -3.93 | 2.88 | 2.88 |
| Confidence | 4.44 | 4.24 | 1.94 | 2.97 | 1.19 | 0.30 | 0.00 |

From amongst the three speech sources in Bom Jesus Basilica, the source ‘SA’ registered a better score of the mean Subjective Speech intelligibility (SSI) and from amongst the languages ‘Konkani’ (KONK) showed better SSI than the ‘English’ as observed in Figure 4. In the listener seating zones, amongst the sources, SSI for ‘SA’ was better at zones ‘A’, ‘B’ and ‘C’ whereas SSI for ‘SB’ was better at zone ’D’. Interestingly, SSI for ‘SC’ was found better than SSI for ‘SA’ at zone ‘C’. In the listener seating zones, amongst the languages, SSI for ‘KONK’ was found to be better at all the zones in the nave of the church whereas SSI for ‘ENG’ was fractionally better in the sanctuary.

## B. Rapid Speech Transmission Index (RASTI)

The simple statistics of the values of RASTI in Bom Jesus Basilica are shown in Table 3.

**Table 3:** *Simple statistics of RASTI in Bom Jesus Basilica.*

| SIMPLE STATISTICS | RASTI | | | | | |
|---|---|---|---|---|---|---|
| | 0 - 1 | | | | | |
| | STAND | SIT | SA | SB | SC | CH |
| Minimum | 0.33 | 0.32 | 0.36 | 0.14 | 0.21 | 0.33 |
| Mean | 0.39 | 0.37 | 0.52 | 0.34 | 0.22 | 0.38 |
| Maximum | 0.47 | 0.42 | 0.71 | 0.62 | 0.26 | 0.42 |
| Median | 0.38 | 0.37 | 0.52 | 0.30 | 0.21 | 0.38 |
| Standard Deviation | 0.07 | 0.04 | 0.16 | 0.21 | 0.03 | 0.05 |
| Skewness | 0.45 | -0.06 | 0.20 | 0.87 | 1.73 | -0.10 |
| Kurtosis | -3.39 | 0.74 | -3.03 | 0.15 | | -5.33 |
| Confidence | 0.06 | 0.04 | 0.16 | 0.21 | 0.03 | 0.05 |

The variability of RASTI mean values for the different signal sources (SA, SB and SC) and recording modes (STAND and SIT) in the four (A, B, C and D) recording zones of the church is shown in Figure 5.

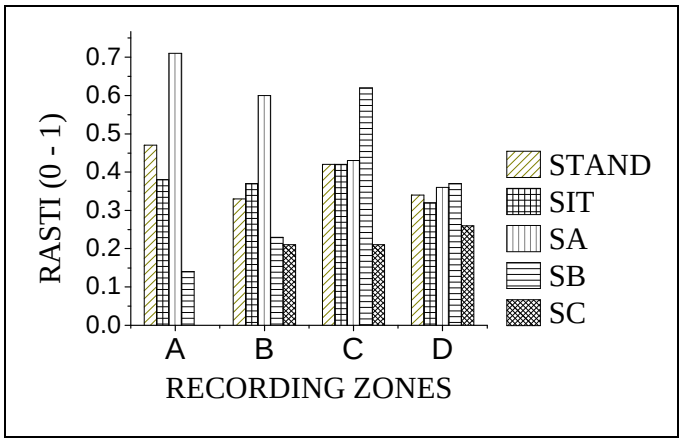


**Figure 5:** Zonal variability of RASTI mean values in Bom Jesus Basilica.

Better values of RASTI were recorded in the standing mode of the device in the sanctuary and the narthex than the scores tallied in the middle of the church. In zone 'A' the sitting mode registered better values of RASTI. The altar location (SA) favored RASTI in zones 'A' and 'B' whereas the zones 'C' and 'D' showed a higher value of RASTI in favor of the Pulpit location (SB).

## C. Significant differences among variants of SSI and RASTI

The significantly different populations of SSI and RASTI values in Bom Jesus Basilica based on paired t-test are shown in Table 4.

**Table 4**: *Significantly different variants of RASTI and SSI in Bom Jesus Basilica*.

| Set no | Data | Mean | Variance | N | t - test | |
|---|---|---|---|---|---|---|
| | | | | | t value | p value |
| 1 | RASTI [SA] | 0.46 | 0.015 | 3 | 2.81 | 0.11 |
| | RASTI [SC] | 0.23 | 8.33E-4 | 3 | | |
| 2 | SSI [ENG] | 86.5 | 9 | 4 | -1.97 | 0.14 |
| | SSI [KONK] | 89.75 | 2.25 | 4 | | |

Though the Subjective Speech Intelligibility averages are slightly in favor of the Altar Source Position (SA) (Table 2), the difference between the means is not statistically significant to make a subjective preference of the Altar as the better source location for subjective speech intelligibility (SSI) whereas the Konkani language (KONK) can be confidently (86%) preferred as the better language to deliver speech in Bom Jesus Basilica (Table 4). [This is significant because the listeners knew both the languages sufficiently well]

The RASTI values seemed directly proportional to the distance between the source and the recording position.

On an average, the standing (STAND) posture seems to be more favorable than the seating (SIT) posture (Table 3) but the difference between the means is not statistically significant to make a preference of standing as the better posture for objective speech intelligibility (RASTI). However, the Altar position (SA) is found to be a better source location than the High Altar (SC) for RASTI (Table 4) and consequently for an optimal effect of the spoken liturgy.

## D. Acoustic Worship Indices (AWI)

The simple statistics of the values of AWI (SaF, InF and SiF) in the church are shown in Table 5. The significantly different populations of AWI in Bom Jesus Basilica based on paired t-test are shown in Table 6.

**Table 5:** *Simple statistics of Acoustic Worship Indices - AWI.*

| STATISTICS | SaF | InF | SiF |
|---|---|---|---|
| Minimum | 0.74 | 0.88 | 0.76 |
| Mean | 0.83 | 0.90 | 0.78 |
| Maximum | 0.88 | 0.91 | 0.80 |
| Median | 0.85 | 0.90 | 0.77 |
| Standard Deviation | 0.06 | 0.01 | 0.02 |
| Skewness | -1.56 | -0.89 | 0.93 |
| Kurtosis | 2.82 | -0.50 | 0.90 |
| Confidence | 0.06 | 0.01 | 0.02 |

**Table 6:** *Significantly different variants of Acoustic Worship Indices - AWI in Bom Jesus Basilica.*

| Set no | Data | Mean | Variance | N* | t - test | |
|---|---|---|---|---|---|---|
| | | | | | t value | p value |
| 1 | SaF | 0.83 | 0.0037 | 4 | -2.43 | 0.093 |
| | InF | 0.90 | 1.97E-4 | 4 | | |
| 2 | SaF | 0.83 | 0.0037 | 4 | 1.59 | 0.209 |
| | SiF | 0.78 | 2.92E-4 | 4 | | |
| 3 | InF | 0.90 | 1.98E-4 | 4 | 8.20 | 0.004 |
| | SiF | 0.78 | 2.92E-4 | 4 | | |

*N is the number of samples.

Amongst the AWI (Table 6), the value of Intelligibility Factor (InF) is found to be significantly better than that of Silence Factor (SiF) (>99% confidence), the value of Sacred Factor (SaF) is found to be significantly better than that of Intelligibility Factor (InF) (91% confidence). The difference between the mean values of SaF and SiF is comparatively less significant (79% confidence). The Sacred Factor indicates the inherent capacity of a worship space for reverential awe while Intelligibility Factor and Silence Factor indicate the potential of a worship space for meaningful intelligibility and serene silence respectively.

## E. Relationship between Speech Intelligibility and Acoustic Worship Indices (AWI)

Different linear and non-linear regression models were explored and different significance tests done using *Origin 6.1* to ascertain the confidence in the predictability and measurability of the Acoustic Worship Indices (AWI): SaF, InF and SiF from SSI and RASTI values.

A confidence greater than 99% ($p = 0.01$) was generalized and denoted as '$p < 0.01$'.The Best Fits of the AWI on the acoustic measures along with the regression equation, Prediction and Confidence Limits and the Standard Error Bars are shown in Figure 6.

While graphically representing the fits, the standard error of estimates (computed by *Origin 6.1* as a square root of the mean of squared deviations) are also plotted as vertical bars showing the vertical distances of every data point from the line or curve of average relationship. The 95% Upper Prediction Limits (UPL) and Lower Prediction Limits (LPL) and the 95% Upper Confidence Limits (UCL) and Lower Confidence Limits (LCL) are also shown in the plots.

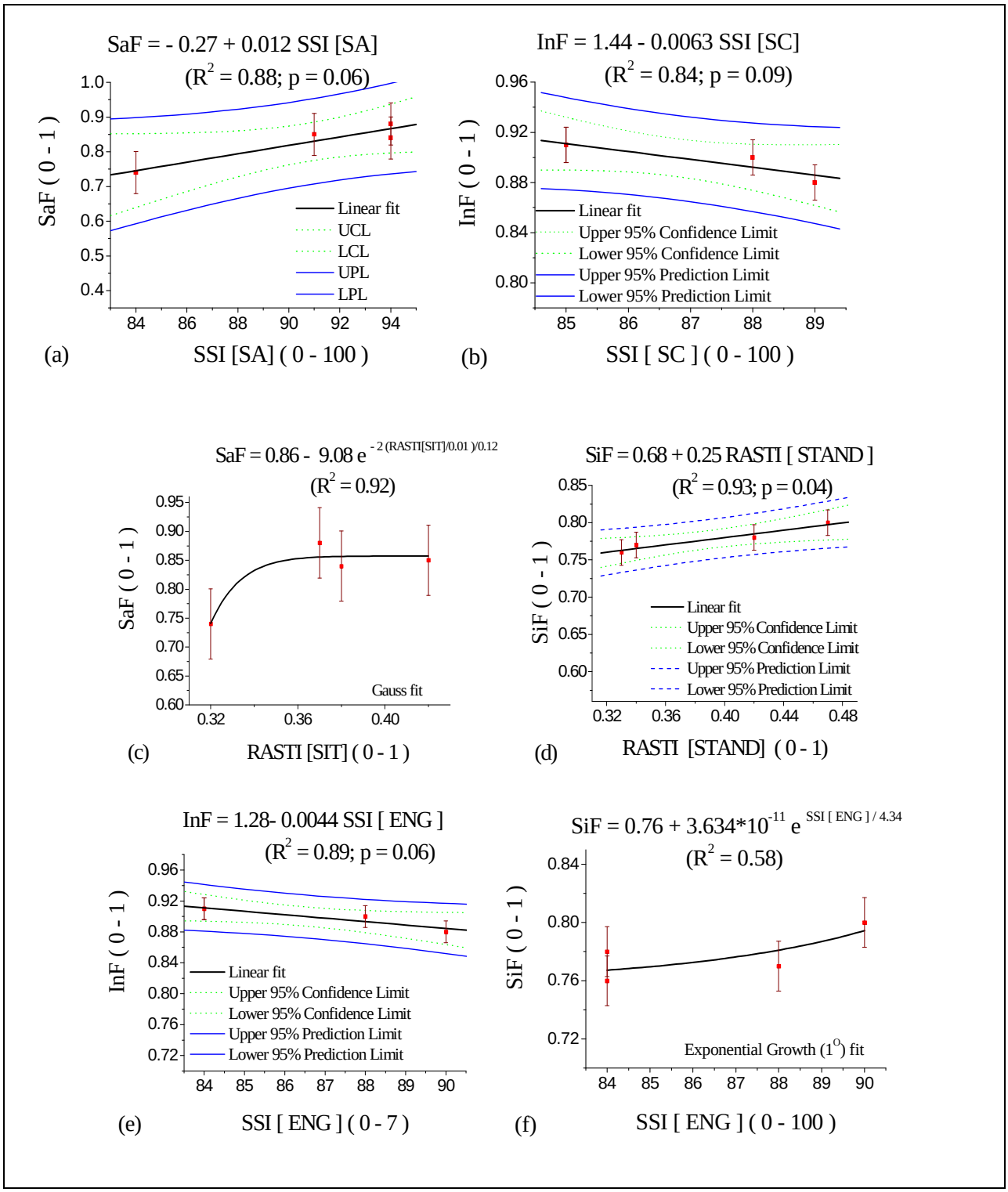


**Figure 6**: Best fits of AWI for the specific averages of RASTI and SSI in *Bom Jesus Basilica*: (a) Linear Fit of SaF on SSI (SA), (b) Linear Fit of InF on SSI (SC), (c) Gauss Fit of SaF on RASTI (SIT), (d) Linear Fit of SiF on RASTI (STAND), (e) Linear Fit of InF on SSI (ENG), (f) Exponential Growth Fit of SiF on SSI (ENG).

## 5. CONCLUSIONS

The following conclusions can be drawn about speech intelligibility and acoustic worship ambience from the results found in Bom Jesus Basilica.

a. Although the listeners understood both the languages very well and took part in the liturgical celebrations conducted in both the languages, the Konkani language is favored over English language for Subjective Speech Intelligibility (SSI).
b. Rapid Speech Transmission Index (RASTI) values are significantly better at the altar (SA) than at the High altar (SC).
c. None of the three sound source positions (SA, SB and SC) show any significant preference regarding SSI values and none of the postures (SIT and STAND) show any significant preference for RASTI values.
d. The significance differences between SaF, InF and SiF and a significantly better mean value of Intelligibility Factor (InF) in the church imply that the capacity for meaningful intelligibility has precedence over reverential awe and serene silence in Bom Jesus Basilica. This has to be weighed with the fact that the subjective as well as the objective acoustic tests were conducted in a closed door church during the evening beyond the visiting hours of tourists. The equivalent noise ambience inside the church during the measurements ($L_{Aeq}$) was around 42 dB, indicating sufficient “silence” in the church. This result therefore implies that the church is good for intelligibility.
e. Sacred Factor (SaF) in the church is evaluated as linear growth on subjective speech intelligibility (SSI) at the altar (SA) (Figure 6 a) and as a gaussian fit on RASTI for the sitting posture (SIT) (Figure 6 c). This implies that speech intelligibility from the altar location and for the sitting posture is suitable to not only predict but also enhance the Sacred Factor in the church.
f. Intelligibility Factor (InF) in the church is predicted as linear decay on subjective speech intelligibility (SSI) at the High altar (SC) (Figure 6 b) and as a linear decay on subjective speech intelligibility (SSI) for English language (ENG) (Figure 6 e). This implies that speech intelligibility from the high altar location and for English language is suitable to only predict but not enhance the Intelligibility Factor in the church.
g. Silence Factor (SiF) in the church is evaluated as linear growth on RASTI for the standing posture (STAND) (Figure 6 d) and as exponential growth on subjective speech intelligibility for English language (ENG) (Figure 6 f). This implies that speech intelligibility for the standing posture and for English language is suitable to predict and enhance the experience of serene silence in the church.

The best fits (Figure 6) show SaF, InF and SiF uniquely relating with SSI and RASTI thus confirming the profound capacity of the AWI to acoustically comprehend the worship ambience of a church. These significant relationships can therefore be useful in attaining the optimally desired worship ambience in Bom Jesus Basilica (and perhaps in other churches) by configuring the speech intelligibility parameters.

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