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Prediction of acoustic comfort and acoustic silence in Goan Catholic churches

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ABSTRACT

Acoustic Comfort and Acoustic Silence are determinants of tranquility in a worship space. The results presented here are part of a study that investigates the behaviour of acoustically constituted worship parameters in six Catholic churches (Goa, India). Acoustic comfort is quantified through an *Acoustic Comfort Impression Index* which measures the net comfort induced through the optimization of the desired subjective acoustic impressions for different types of music and different music sources. *Silence Factor* is constituted through the normalization of equivalent noise level (L_{Aeq}) and the subjective acoustic impressions of background noise and echoes. Regression analyses of the derived acoustic parameters generate significant results. Acoustically, the *Silence Factor* quadratically decays with L_{Aeq} and the *Acoustic Comfort Impression Index* is predicted as a multiregression on the subjective acoustic impressions of balance and clarity. Architecturally, the *Silence Factor* linearly grows with the width of the nave (of the church) whereas, the *Acoustic Comfort Impression Index* does not significantly relate with any of the tested architectural parameters. *Silence Factor* was found to linearly grow with *Acoustic Comfort Impression Index* in a church. The predictability of *acoustic comfort* and *acoustic silence* from acoustic and architectural measures can be developed into a design tool for the prediction of a *tranquility factor* in worship spaces.

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1. INTRODUCTION

A Worship Space needs the several factors of acoustics (speech, music, singing and silence) to be well blended[1,2] and purposefully used for an optimized experience of the Divine[3,4]. In a church, *Faith becoming music is part of the process of the Word becoming flesh*[5,6]. Moments of deep silence along with recitation of *Canticles*, singing of *Psalms* and making music through lyre and harp enables Christians in a church to prepare for the celebration of the sacraments and optimally experience being the mystical Body of Christ during community worship[7].

The results presented here are part of a research program that explores the aesthetics of worship through acoustically constituted categories[8,9]. *Acoustic Comfort Impression Index* (ACII) acoustically characterizes the fundamental subjective disposition of comfort that a worship space induces in a worshipper through singing and music. *Silence Factor* (SiF) is a derived acoustic parameter that characterizes the worship aesthetic of silence. The variance of ACII and SiF, as reported here, is based on field measurements done in the following six Catholic churches of Goa, India: Capela do Monte church (CH1), Bom Jesus Basilica (CH2), our Lady of Pilar church (CH3), our Lady of Divine Providence church (CH4), Holy Spirit church (CH5) and Holy Trinity church (CH6). The first five churches (CH1 – CH5) built during the Portuguese era in Goa are European derivatives subtly influenced by the Indian worship aesthetics. The sixth church (CH6) is a contemporary style church. Thus, these tested churches can be considered as very good representative global models of church architecture, therefore the results presented here could be applied to other churches. The observed relationship between SiF and the acoustic comfort impressions of different types of music and of music rendered from different music sources indicates the music source and the type of music that can optimize the ambience of silence in a church.

The purpose of this work is to show that the *Silence Factor* (SiF) can be significantly quantified through evaluation of acoustic comfort impressions and also to show that the *Acoustic Comfort Impression Index* (ACII) and the *Silence Factor* (SiF) can be significantly predicted through evaluation of acoustic parameters and architectural measures.

2. EXPERIMENTAL DETAILS

A. Architectural measures

The simple statistics of the architectural details of the sample churches are shown in Table 1.

The tabulated architectural parameters measured or evaluated in the sample churches are: Total sound absorption (ABS_{TOT}); Average coefficient of absorption (C_{ABS}); Total surface area of church (A_{TOT}); Total surface area of church nave (A_{NV}); Maximum height of the church (H_{MAX}); Maximum height of church nave (H_{NV}); Maximum length of the church (L_{MAX}); Maximum length of church nave (L_{NV}); Volume of church (V_{TOT}); Volume of nave (V_{NV}); Average height (H_{AVG}); Maximum nave width (W_{NV}); Average width (W_{AVG}); Minimum nave width (W_{MIN_NV}); Average nave width (W_{AVG_NV}); Minimum nave height (H_{MIN_NV}); Average nave height (H_{AVG_NV}); Nave proportions (L_{NV} / H_{NV}) and (W_{NV} / H_{NV}).

Table 1: Simple statistics of the architectural details of the six churches surveyed

	Minimum	Mean	Maximum	Median	Standard Deviation	Skewness	Kurtosis	Confidence
ABS_{TOT} (m^2)	47.3	199	387	163	143	0.49	-1.93	114.64
C_{ABS}	0.03	0.048	0.07	0.04	0.02	0.73	-1.73	0.01
A_{TOT} (m^2)	250	755	1168	805	369	-0.36	-1.56	295
A_{NV} (m)	81	328.5	630	296	238	0.20	-2.60	191
H_{MAX} (m)	15	21.17	30	21.5	5.71	0.39	-0.28	4.57

H_{NV} (m)	9	18.67	30	18	7.28	0.39	0.15	5.83
L_{MAX} (m)	30	41.83	61	34.5	15.01	0.88	-1.89	12.01
L_{NV} (m)	14	22.17	36	18	9.77	0.86	-1.64	7.81
V_{TOT} (m^3)	2974	9382	18858	6726	7052	0.75	-1.83	5642
V_{NV} (m^3)	837	5657	13613	3556	5244	0.88	-1.17	4196
H_{AVG} (m)	8	11.67	16	10.5	3.61	0.48	-2.20	2.89
W_{NV} (m)	9	13.67	23	11.5	5.85	0.88	-0.67	4.68
W_{AVG} (m)	7	13	17	15	4.38	-0.79	-1.81	3.51
W_{MIN_NAVE} (m)	9.2	11.77	18	10.1	3.58	1.32	0.82	2.87
W_{AVG_NAVE} (m)	8.85	12.71	18	11.6	4.19	0.35	-2.48	3.35
H_{MIN_NAVE}(m)	9	13.1	16.5	14.05	2.97	-0.56	-1.49	2.37
H_{AVG_NAVE} (m)	12.3	16.94	21.75	17.125	3.32	0.04	-0.23	2.65
L_{NV}/H_{NV}	0.81	1.28	1.92	1.11	0.47	0.73	-1.71	0.38
W_{NV}/H_{NV}	0.39	0.82	1.42	0.75	0.35	0.99	1.62	0.28

The large values of the standard deviation (SD) of the Volume of the churches (V_{TOT}) and the naves of the churches (V_{NV}) indicate the large variance in the volume of the churches chosen which justifies them as sufficiently representative of different architectural genres of churches available.

B. Experimental setup for subjective acoustic measurements

Two locations in each church were chosen as music sound sources. '*Music Source A*' (MA) was the floor of the North East/West nave – sanctuary corner of the church and '*Music Source B*' (MB) was the floor of the Choir Loft of the church. The entire church floor was conceptually divided into four zones: Listener zone 'A' (The Sanctuary or The Main Apse); Listener zone 'B' (The Northern Floor of the Nave); Listener zone 'C' (The Middle Floor of the Nave); Listener zone 'D' (The Southern Floor of the Nave). Altogether nineteen normal listeners (age: 24 to 57) with an above average aptitude for music and acquainted with the liturgy in a worship space, were chosen and trained for the subjective acoustic tests. Some of the listeners had to be audiometrically tested (250 Hz – 8 kHz) to ascertain their normal hearing conditions. For instance, the locations of the tested music sources (MA and MB) and listeners seating for the subjective acoustic tests in the *Holy Spirit church* are shown in Figure 1.

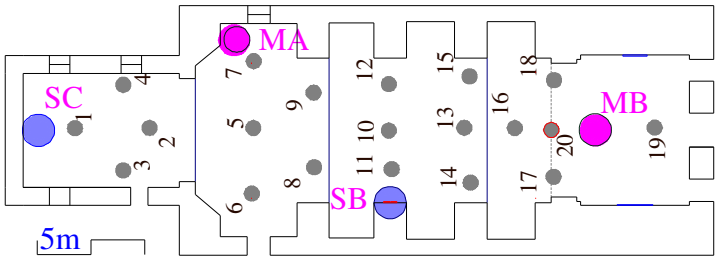

Figure 1: The locations of Listeners and music sources in *Holy Spirit church.*

The musical instruments that were tested in the churches are: Cello (designated as Music Type 'P'); Clarinet (designated as Music Type 'Q'); Ensemble of Cello, Clarinet, Violins and Guitar (designated as Music Type 'R'); Violins in Duet (designated as Music Type 'S') and The Human Whistle (designated as Music Type 'T'). The musical instruments used in the subjective acoustic tests were chosen because of their popularity at different liturgical functions in Goa from where the churches in the final sample were selected. The Human

whistle being a very proximate simulation of the Human voice (in singing) was also added to the list so that an option for instrumental music and also the rendition of the human voice was inherently present in the subjective preference. The cellist played "Bach's Suite No. 2". The clarinet player played "Motet: Fera Pessima" a traditional Christian Lenten hymn. The Human Whistle rendition was also the tune of "Motet: Fera Pessima". The ensemble and the violinists played "Piedade Saibinni in minor and major" a Goan devotional classic.

C. Subjective acoustic evaluation of music

The Subjective Acoustic Evaluation method[10] employed in this study is based on the method used to assess the subjective acoustic preferences in Portuguese churches[11,12]. The listeners scored on the acoustic qualities of the church using a seven point differential scale on the evaluation sheet. This acoustic evaluation sheet spelled out: *seven desirable acoustic qualities* (Loudness, Clarity, Reverberance, Directionality, Intimacy, Envelopment, and Balance); *two undesirable acoustic qualities* (Background Noise, Echoes) and *the overall acoustic impression*. These acoustic qualities of the music played in the church determined the comfort level of a listener. The averaged scores of the acoustic qualities for different music sources and types in different seating zones of the church could be considered as subjective impressions that the sound registered on the listeners[13]. Therefore, the averaged scores of the subjective acoustic qualities were called Subjective Acoustic Impressions (SAI) and are listed as:

- Subjective Acoustic Impression of Loudness (SAI_{LOUD});
- Subjective Acoustic Impression of Clarity (SAI_{CLAR});
- Subjective Acoustic Impression of Directionality (SAI_{DIR});
- Subjective Acoustic Impression of Balance (SAI_{BAL});
- Subjective Acoustic Impression of Intimacy (SAI_{INT});
- Subjective Acoustic Impression of Envelopment (SAI_{ENV});
- Subjective Acoustic Impression of Reverberance (SAI_{REV});
- Subjective Acoustic Impression of Echoes (SAI_{ECHO});
- Subjective Acoustic Impression of Background Noise (SAI_{NOIS});
- Subjective Overall Acoustic Impression (SAI_{OVER}).

D. Evaluation of equivalent noise level

The sound pressure level of the interior noise as heard at the centre of the unoccupied nave of the church was recorded for 149 equal intervals of 5 s using the integrated sound level meter (SLM) function of an Audio Tool Box 2.0 (ATB) and the equivalent sound level (L_{Aeq}) calculated.

E. Derivation and evaluation of Acoustic Comfort Impression Index (ACII)

Reverential Awe, Intelligibility and Silence as constituted of subjective acoustic impressions were hypothesized as determinants of 'comfort' in a worship space[14]. The net desired effect was named as *Acoustic Comfort Impression* (ACI) and indexed as *Acoustic Comfort Impression Index* (ACII). A difference was drawn between the *desired Subjective Acoustic Impressions* (dSAI) in worship space and the *undesired Subjective Acoustic Impressions* (uSAI) in a worship space in order to acoustically comprehend and optimize this 'Religious Feeling of Comfort and Solace'. The experience of reverential awe was expressed as an average of the following desired Subjective Acoustic Impressions (dSAI): SAI_{INT}, SAI_{ENV}, SAI_{REV} and SAI_{OVER}. The quality of intelligibility of speech, singing and music was judged as an average of the following desired Subjective Acoustic Impressions (dSAI): SAI_{LOUD}, SAI_{CLAR}, SAI_{DIR} and SAI_{BAL}. The quality of silence was judged from the following

undesirable Subjective Acoustic Impressions (uSAI): SAI_{ECHO} and SAI_{NOIS}.
The *desired* and *undesired* Subjective Acoustic Impressions (dSAI and uSAI) were evaluated as averages of the eight desired $dSAI_i$ and the two undesired $uSAI_j$ respectively. The net difference score between the desired and the undesired was averaged and coded as the *Acoustic Comfort Impression* (ACI) of the worship space.
Finally The Acoustic Comfort Impression Index (ACII) at each zone of the worship space was evaluated using Equation 1.

$$ACII = 1 - \left| \frac{ACI_x}{ACI_{ref}} \right| \qquad (1)$$

where, ACI_{ref} is the reference value of ACI in the given worship space $ACI_{ref} = 6$; ACI_x is the difference between ACI_{ref} and the averaged value of ACI in the zone x (0 - 6).

F. Derivation and evaluation of Silence Factor (SiF)

The church should provide a refuge where one is not disturbed by the noise and turmoil of the outside world. It was hypothesized that in order to optimize the effect of speech and music in the sacred liturgy an ambience of Silence was necessary therefore subjective impressions of echoes (SAI_{ECHO}) and background noise (SAI_{NOIS}) were undesirable. The equivalent ambient noise level (L_{Aeq}) was hypothesized as the objective counterpart for the characterization of 'Silence'. These subjective and objective parameters when normalized were converted and construed as positive determinants of the 'silence ambience' and as such constituted the religious experience denoted by the *Silence Factor* (SiF). The normalized value of equivalent ambient noise level (L_{Aeq}) was hypothesized to be the Objective Silence Factor (oSiF) and the arithmetic mean of the normalized values of Subjective Silence from echoes (sS_{ECHO}) and Subjective Silence from noise (SS_{NOIS}) was hypothesized to be the Subjective Silence Factor (sSiF). The SiF was hypothesized to be the arithmetic mean of the Objective Silence Factor (oSiF) and the Subjective Silence Factor (s SiF).
The *Undesired Subjective Acoustic Impressions* were given an optimal reference value equal to 7 considering the latter to be the maximum value that can be scored on the semantic scale used for the evaluation of the subjective acoustic parameters. However, these undesirable subjective impressions of echoes and noise were expressed as their respective equivalents in terms of Subjective Silence from echoes (sS_{ECHO}) and Subjective Silence from noise (sS_{NOIS}). Consequently, the normalized values of sS_{ECHO} and sS_{NOIS} were calculated using Equation 2,

$$nSS = \frac{\left| X_{meas} - X_{ref} \right|}{X_{ref}} \qquad \forall\, X_{meas} \qquad (2)$$

where,
X_{meas} is the measured value of the subjective acoustic impressions.
nSS is the normalized value of the Subjective Silence impressions (sS_{ECHO} and sS_{NOIS});
$X_{ref} = 7$ is the optimal reference value of the subjective acoustic measures (SAI_{ECHO} and SAI_{NOIS}).

The optimal reference value for equivalent ambient noise level (L_{Aeq}) was fixed as 35 dB based on existential conditions. The value of 35 dB(A) reflected one of the lowest available noise ambience level in churches of Goa as found in the *Capela do Monte* (CH1).

Consequently, the measured value of L_{Aeq} was normalized (nL_{Aeq}) as follows:

$$nL_{Aeq} = 1, \qquad \forall\, L_{Aeq\ meas} \le L_{Aeq\ ref}$$

$$nL_{Aeq} = 1 - \frac{\left| L_{Aeq_{meas}} - L_{Aeq_{ref}} \right|}{L_{Aeq_{ref}}}, \quad \forall\, L_{Aeq\ meas} > L_{Aeq\ ref} \qquad (3)$$

where,
$L_{Aeq\ meas}$ is the measured value of L_{Aeq}; nL_{Aeq} is the normalized value of L_{Aeq},

$L_{Aeq\ ref}$ = 35 dB is the optimal reference value of L_{Aeq}.

3. RESULTS

A. Inter-church variance of ACII and SiF

Simple statistics of the averaged ACI for different sources (MA and MB) and ACI for different music types (P, Q, R, S, and T) in the sample churches are presented in Table 2.

The comparison of the churches for the averaged values of ACI for different music sources and types is shown in Figure 2.

Table 2: Simple statistics of the averaged Acoustic Comfort Impressions (ACI) in the six churches surveyed

Statistics	ACOUSTIC COMFORT IMPRESSION (ACI)						
	MA	MB	P	Q	R	S	T
Minimum	1.72	1.37	2.03	0.96	2.16	0.94	2.71
Mean	3.43	2.80	3.49	2.89	3.86	3.47	3.47
Maximum	4.71	3.66	4.76	3.97	5.04	4.66	4.06
Median	3.63	2.94	3.61	3.08	4.07	3.80	3.48
Standard deviation	0.85	0.65	0.88	0.84	0.75	0.92	0.44
Skewness	-0.52	-0.68	-0.36	-0.80	-0.72	-1.30	-0.41
Kurtosis	-0.81	-0.51	-1.03	0.37	-0.35	1.78	-0.11
Confidence	0.34	0.26	0.35	0.34	0.30	0.37	0.17

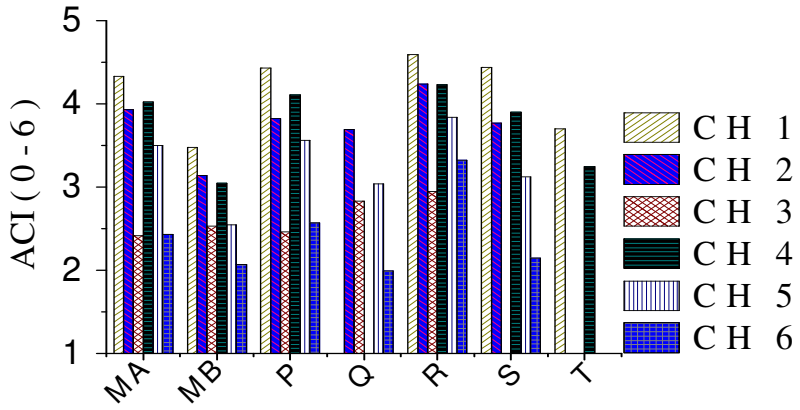

Figure 2: Inter-church comparison of mean ACI values for different music types (P, Q, R, S, and T) and music sources (MA and MB).

The music rendered from the nave floor (MA) and the music from the ensemble (R) showed better averages of ACI. The *Bom Jesus Basilica* (CH2) was found with better ACI scores for the clarinet (Q) while *Capela do Monte* (CH1) was better for the cello (P), ensemble (R), violins (S) and the human whistle (T). Both the music sources of *Capela do Monte* were found better than the music sources of other churches. Overall, *Capela do Monte* registered the best acoustic comfort impression for music.

The simple statistics of ACII and SiF in the sample churches are shown in Table 3. The inter-church variance of the SiF and ACII is shown in Figure 3.

SiF was prominent in *Capela do Monte* (CH1) and *our Lady of Divine Providence church* (CH4). The best scores of ACII were seen in *Capela do Monte* (CH1).

Table 3: Simple Statistics of ACII and SiF in the six churches surveyed

Statistics	SiF	ACII
Minimum	0.54	0.32
Mean	0.75	0.44
Maximum	0.87	0.56
Median	0.77	0.47
Standard deviation	0.12	0.09
Skewness	-1.15	-0.27
Kurtosis	1.38	-1.64
Confidence	0.10	0.08

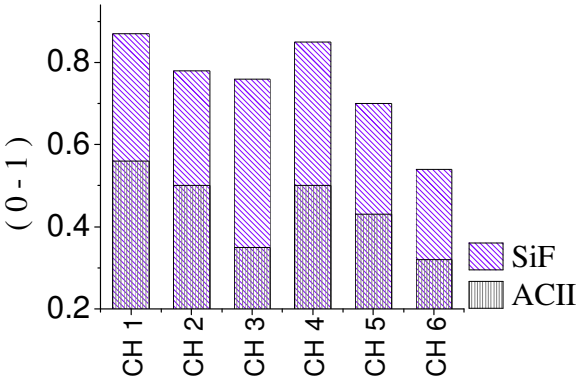

Figure 3: The inter-church variance of SiF and ACII.

B. Significant relationships of ACII and SiF and constituent parameters

The best prediction equations for SiF, ACII and the constituent acoustic measures along with their respective coefficients of determination (R^2), values of standard deviation (SD) and the probability (p) values (for either 'F Statistic tests' or 'Chi-Square tests') (depending on the type of the fit) in the church are shown in Table 4. A confidence greater than 99% (p = 0.01) was generalized and denoted as 'p < 0.01'. The corresponding best fits are elucidated in Figure 4.

Table 4: Best prediction equations (for averaged four points/church data points in six churches = 24 points)

EQUATION	R^2	SD	p - value
$SiF = 0.92 + 0.010\ L_{Aeq} - 0.0003\ L_{Aeq}^2$	0.95	0.03	<0.01
$SiF = 0.37 + 0.85$ ACII	0.59	0.074	<0.01
$SiF = 0.22 + 0.21\ e^{ACI[S]/3.81}$	0.81	0.0033	<0.01
$SAI_{NOIS} = 4.79 - 0.20\ L_{Aeq} + 0.0032\ L_{Aeq}^2$	0.72	0.30	<0.01
$ACII = 41.12 + 1.45\ SAI_{BAL} - 6.054\ SAI_{CLAR}$	0.69	2.6	0.17
$SiF = 0.98 - 0.02\ W_{NV}$	0.69	0.07	0.04
$L_{Aeq} = 28.68 + 0.99\ W_{NV}$	0.77	3.52	0.02

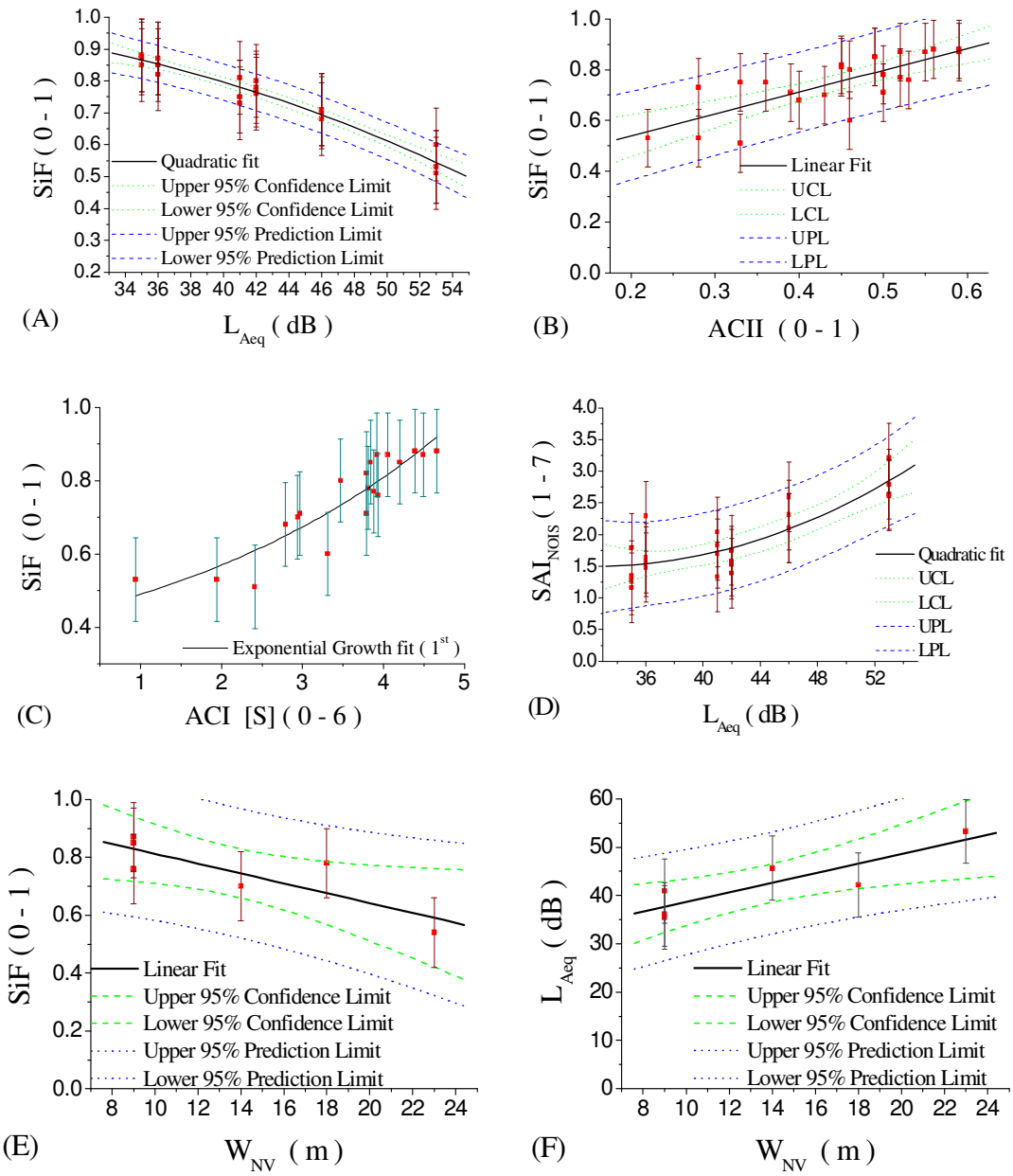

Figure 4: Best fits: (A) Quadratic fit of SiF on L_{Aeq} (B) Linear fit of SiF on ACII (C) Exponential growth fit of SiF on ACI [S] (D) Quadratic fit of SAI_{NOIS} on L_{Aeq} (E) Linear decay of SiF on W_{NV} (F) Linear growth of L_{Aeq} on W_{NV}.

4. CONCLUSIONS

The results showed that 'Acoustic Silence' and 'Acoustic Comfort', as expressed by the Silence Factor (SiF) and the Acoustic Comfort Impression Index (ACII) respectively, can be characterized and significantly predicted by specific acoustic parameters and architectural measures.

The following conclusions can be made with significant confidence:

- Silence Factor (SiF) in churches quadratically decays with equivalent noise level (L_{Aeq}).
- The subjective acoustic impression of background noise (SAI_{NOIS}) quadratically grows with L_{Aeq};
- SiF linearly grows with the Acoustic Comfort Impression Index (ACII);
- Amongst the music types the acoustic comfort impression of the music rendered by the violins causes the Silence Factor to exponentially grow in a church;
- ACII is best predicted as a multiregression on the subjective acoustic impressions of Balance (SAI_{BAL}) and Clarity (SAI_{CLAR});
- Both Silence Factor (SiF) and its constituent acoustic parameter, equivalent noise level (L_{Aeq}), are significantly predictable as a linear regression on the maximum width of the church nave (W_{NV}).
- While SiF linearly decays with W_{NV}, L_{Aeq} linearly grows with W_{NV};

A significant predictability of SiF and ACII and their constituent acoustic parameters opens up the possibility of designing acoustic comfort and acoustic silence to optimize the worship ambience of a church for a tranquil experience of the Divine. The globally representative nature of the tested churches makes it possible to apply these results to other Catholic churches of the world and also to other Christian denominations' churches.

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