Churches as auditoria: analysis of acoustical parameters for a better understanding of sound quality

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The research

The acoustic characterisation of buildings for music performances:

Worship buildings can be used as auditoriums?

Theoretical models and software

Experimental measurements
The aim and the results

A contribution to the data collection on the acoustic performance of the Churches aimed to their use as auditorium.

Deeper knowledge on the influence of the internal geometric complexities on the acoustic field, such as:
- lateral chapels,
- coupled rooms,
- diffusive elements or obstacles to the sound propagation,
- orientation of surfaces,
- convex surfaces than can create sound concentration.
The Churches

10 Churches - rectangular plan (nave – 2 aisles)
with/without lateral chapels and/or cupolas,
volume = 2183 - 43540 m³
The Churches

14 Churches: central plan with/without dome/cupolas
volume = 1409 - 43756 m³
The Churches

6 Medieval Cistercian Abbeys
volume = 3390 - 14970 m³

Northern Italy

Southern France
The 3 Provençal Sisters

WORSHIP SOUND PLACES- MUSÉE DU QUAI BRANLY, NOVEMBER 3-4, 2015 (PARIS)
MEASUREMENTS – longitudinal plan

Measured data in 10 Italian churches (XI-XVI sec., V=2200÷43,000 m³)

<table>
<thead>
<tr>
<th>Church</th>
<th>Points</th>
<th>V [m³]</th>
<th>S [m²]</th>
<th>C50 [dB]</th>
<th>C80 [dB]</th>
<th>D50 [%]</th>
<th>EDT [s]</th>
<th>RT20 [s]</th>
<th>RT30 [s]</th>
<th>TS [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.Lorenzo</td>
<td>17</td>
<td>43540</td>
<td>2040</td>
<td>-9.2</td>
<td>-6.7</td>
<td>16.3</td>
<td>5.1</td>
<td>5.1</td>
<td>--</td>
<td>387.1</td>
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<tr>
<td>SS.Annunziata</td>
<td>27</td>
<td>26603</td>
<td>1815</td>
<td>-8.8</td>
<td>-6.5</td>
<td>17.6</td>
<td>4.7</td>
<td>4.2</td>
<td>--</td>
<td>362.8</td>
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<tr>
<td>S.M.Castello</td>
<td>26</td>
<td>21100</td>
<td>1755</td>
<td>-9.8</td>
<td>-6.5</td>
<td>12.9</td>
<td>3.8</td>
<td>3.6</td>
<td>3.6</td>
<td>308.2</td>
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<tr>
<td>N.S.Consolazione</td>
<td>15</td>
<td>18842</td>
<td>1065</td>
<td>-10.2</td>
<td>-7.7</td>
<td>14.7</td>
<td>4.5</td>
<td>5.2</td>
<td>4.6</td>
<td>368.9</td>
</tr>
<tr>
<td>S.Agostino</td>
<td>24</td>
<td>14500</td>
<td>1223</td>
<td>-8.9</td>
<td>-5.2</td>
<td>15.5</td>
<td>2.7</td>
<td>2.5</td>
<td>2.3</td>
<td>227.8</td>
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<tr>
<td>S.M.Vigne</td>
<td>18</td>
<td>14000</td>
<td>1308</td>
<td>-8.5</td>
<td>-5.8</td>
<td>17.5</td>
<td>3.6</td>
<td>4.1</td>
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<td>296.2</td>
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<tr>
<td>S.Donato</td>
<td>21</td>
<td>4650</td>
<td>340</td>
<td>-7.6</td>
<td>-4.1</td>
<td>18.4</td>
<td>2.3</td>
<td>2.3</td>
<td>2.4</td>
<td>193.2</td>
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<tr>
<td>S.Matteo</td>
<td>12</td>
<td>3211</td>
<td>338</td>
<td>-6.5</td>
<td>-3.3</td>
<td>20.7</td>
<td>2.3</td>
<td>2.4</td>
<td>2.5</td>
<td>185.1</td>
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<tr>
<td>S.Siro di Struppa</td>
<td>11</td>
<td>3827</td>
<td>383</td>
<td>-7.4</td>
<td>-3.5</td>
<td>18.5</td>
<td>2.6</td>
<td>2.8</td>
<td>2.8</td>
<td>202.0</td>
</tr>
<tr>
<td>SS.Cosma e Damiano</td>
<td>12</td>
<td>2183</td>
<td>241</td>
<td>-6.3</td>
<td>-2.8</td>
<td>22.3</td>
<td>2.0</td>
<td>2.0</td>
<td>2.2</td>
<td>164.9</td>
</tr>
</tbody>
</table>
### Measured data in 10 Italian churches (XI-XVI sec., $V=2500\div49,000\ m^3$)

<table>
<thead>
<tr>
<th>Church</th>
<th>Measur. points</th>
<th>$V\ [m^3]$</th>
<th>$S_{\text{tot}}\ [m^2]$</th>
<th>$C50\ [\text{dB}]$</th>
<th>$C80\ [\text{dB}]$</th>
<th>$D50\ [%]$</th>
<th>EDT\ [s]</th>
<th>RT20\ [s]</th>
<th>RT30\ [s]</th>
<th>TS\ [ms]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.Maria Assunta</td>
<td>28</td>
<td>49471</td>
<td>1837</td>
<td>-10.53</td>
<td>-8.29</td>
<td>11.58</td>
<td>6.12</td>
<td>6.16</td>
<td>5.61</td>
<td>467</td>
</tr>
<tr>
<td>S.Zita</td>
<td>12</td>
<td>29220</td>
<td>1107</td>
<td>-11.67</td>
<td>-9.54</td>
<td>8.75</td>
<td>8.79</td>
<td>8.77</td>
<td>8.90</td>
<td>666</td>
</tr>
<tr>
<td>Chiesa del Gesù</td>
<td>16</td>
<td>25595</td>
<td>1580</td>
<td>-9.22</td>
<td>-6.74</td>
<td>14.38</td>
<td>3.97</td>
<td>3.86</td>
<td>3.05</td>
<td>314</td>
</tr>
<tr>
<td>N.S.del Rimedio</td>
<td>12</td>
<td>18040</td>
<td>731</td>
<td>-9.19</td>
<td>-7.21</td>
<td>12.17</td>
<td>5.60</td>
<td>6.19</td>
<td>6.20</td>
<td>411</td>
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<tr>
<td>S.Maria Immacolata</td>
<td>18</td>
<td>16262</td>
<td>860</td>
<td>-8.82</td>
<td>-6.79</td>
<td>15.24</td>
<td>4.89</td>
<td>4.95</td>
<td>4.46</td>
<td>365</td>
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<tr>
<td>S.Caterina</td>
<td>17</td>
<td>11650</td>
<td>905</td>
<td>-10.15</td>
<td>-6.81</td>
<td>10.75</td>
<td>3.73</td>
<td>3.69</td>
<td>3.69</td>
<td>297</td>
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<tr>
<td>S.Croce S.Camillo</td>
<td>10</td>
<td>3955</td>
<td>269</td>
<td>-8.11</td>
<td>-5.59</td>
<td>15.84</td>
<td>3.21</td>
<td>3.21</td>
<td>3.22</td>
<td>252</td>
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<tr>
<td>S.Pietro in Banchi</td>
<td>13</td>
<td>2584</td>
<td>189</td>
<td>-7.79</td>
<td>-4.69</td>
<td>15.16</td>
<td>2.80</td>
<td>2.83</td>
<td>2.87</td>
<td>224</td>
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<tr>
<td>S.Luca</td>
<td>6</td>
<td>2494</td>
<td>140</td>
<td>-8.44</td>
<td>-6.24</td>
<td>14.05</td>
<td>3.77</td>
<td>4.00</td>
<td>4.07</td>
<td>290</td>
</tr>
</tbody>
</table>
Reverberation Time at 500 Hz – Optimal values

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Reverberation Time

\[ y = 0.19 \times + 1.36 \]

\[ R^2 = 0.50 \]

Theatres

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Clarity Index C80

\[ y = -0.21x - 2.77 \]
\[ R^2 = 0.40 \]

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Mean RT as function of SR distance
C80 as a function of SR distance.

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D50 as function of SR distance

Source - Receiver Distance [m]

D50 [%]

0 10 20 30 40 50 60 70

0 10 20 30 40 50 60

Longitudinal Plan [1,2]
Central Plan [4]
Cistercian Abbeys [3]
CONSIDERATIONS

Worship buildings with more articulated volumes (Gesù Church, with 7 cupolas) are more adequate for music performances. For this aim, almost all the central plan Churches are not appropriate, unless some acoustic corrections are realised. The RT distribution for Churches with rectangular plan and two aisles without cupolas was significantly different from the ones with central plans. Among these last ones, bigger volume Churches presented more scattered RT values.

And other considerations....
CONSIDERATION ON THE HISTORICAL PERIOD

In the French Cistercian Abbeys some acoustic features may have been intentionally prosecuted by the Ancient Architects.

Average values of RT in the range 500-1000 Hz

The values are higher than in other churches with almost the same volume.

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CONSIDERATION ON THE EFFECT OF THE GEOMETRY ON RT

The RT under the dome is lower in larger volume churches, but higher in smaller ones.
CHARACTERISTICS OF THE CHURCH OF S. ZITA

- Construction of 1874
- Both domes are in reinforced concrete
- Pavement in marble,
- Interior simply painted
- On the pavement
  - Wooden desk

<table>
<thead>
<tr>
<th></th>
<th>VOLUME (m³)</th>
<th>SUPERFICIE (m²)</th>
<th>ALTEZZA (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cupola grande</td>
<td>3619</td>
<td>904</td>
<td>12.3</td>
</tr>
<tr>
<td>Tamburo cupola</td>
<td>3850</td>
<td>620</td>
<td>7.7</td>
</tr>
<tr>
<td>Tot. Cupola grande</td>
<td>7588</td>
<td>1649</td>
<td>20</td>
</tr>
<tr>
<td>Lucernario</td>
<td>119</td>
<td>125</td>
<td>10</td>
</tr>
<tr>
<td>Cupola minore</td>
<td>710</td>
<td>320</td>
<td>9.5</td>
</tr>
<tr>
<td>Totale cupole</td>
<td>8298</td>
<td>1969</td>
<td>30</td>
</tr>
<tr>
<td>pavimento</td>
<td>1180</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Camera principale</td>
<td>21600</td>
<td>(laterale) 2650</td>
<td>18.3</td>
</tr>
<tr>
<td>Sup. connessione grande</td>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sup. connessione piccol</td>
<td>92</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sup. connessione totale</td>
<td>592</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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CHARACTERISTICS OF THE CHURCH OF S. GIORGIO

- The period of construction is around 1695
- Pavement in marble,
- Interior highly decorated

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**Sul pavimento panche di legno**

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<table>
<thead>
<tr>
<th></th>
<th>VOLUME (m³)</th>
<th>SUPERFICIE (m²)</th>
<th>ALTEZZA (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cupola</td>
<td>540</td>
<td>280</td>
<td>5.8</td>
</tr>
<tr>
<td>Tamburo cupola</td>
<td>1833</td>
<td>560</td>
<td>13</td>
</tr>
<tr>
<td>Tot. Cupola pavimento</td>
<td>2373</td>
<td>840</td>
<td>18.8</td>
</tr>
<tr>
<td>Camera principale</td>
<td>3510</td>
<td>1200</td>
<td>11.7</td>
</tr>
<tr>
<td><strong>TOTALE</strong></td>
<td><strong>5885</strong></td>
<td><strong>2500</strong></td>
<td><strong>30.5</strong></td>
</tr>
<tr>
<td>Sup. connessione</td>
<td></td>
<td>141</td>
<td></td>
</tr>
</tbody>
</table>
TRIDIMENSIONAL MODELS FOR THE SIMULATION

S. Zita

S. Giorgio

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SIMULATIONS RESULTS

SPATIAL DISTRIBUTION OF TR$_{20}$ IN THE FREQUENCY RANGE 125 Hz – 4 kHz FOR

S. Zita

SPATIAL DISTRIBUTION OF TR$_{20}$ IN THE FREQUENCY RANGE 125 Hz – 4 kHz FOR

S. Giorgio
For both churches with domes having $\alpha > 0.3$ the minimum of RT disappear with $\alpha > 0.7$ the minimum is reached in the positions near the dome,
CONSIDERATION ON THE MEASUREMENT CAMPAIGN


- Churches are listening spaces that differ from concert halls and theatres
- Differences are due to the coexistence of speech and music being radiated from several positions that varied with the evolving liturgy
- In addition the room complexity may induce different research teams to place sources and receivers in a different way reducing measurement comparability
Aims of the proposal

- Define a group of standardised source positions
- Define a minimum number and a rule to place receivers
- Define the equipment characteristics as a function of the measurement purpose
Source placement
Source placement
Source placement

- A) Altar (reference) position
  - At 2 m distance
  - On the symmetry axis (provided that no focusing effects may be detected)
  - At 1.5 m from the floor
B) High Altar position
- At 1 m distance from the vertical surface
- On the symmetry axis (provided that no focussing effects may be detected)
- At 1.5 m from the basement of the altar
• C) Ambos position
  • Located at the symmetrical position opposite the actual ambos (to prevent interference)
  • or at 2 m from the edge of the chancel
  • At 1.5 m from the floor
Source placement

- **D) Choir position**
  - Located at the centre of the area occupied by the singers
  - or at the centre of the wooden stalls
  - in any case the source must be at least 1 m far from walls
  - the height must be 1.5 m from the floor
**Source placement**

- **E) Organ position**
  - Located close to the centre of the organ pipes, at a distance of 1 m
  - If the span of the pipes is larger than 6 m 2 positions (E1 and E2) should be used
  - If the centre of the pipes cannot be reached the source height must be 2 m from the floor
Source placement

- F) Pulpit position
  - Located on the pulpit, provided that it is easily accessible
  - The source height should be at least 1.7 m and, in any case overcame the balustrade by at least 0.5 m
  - The source directivity should be close to human voice
Source placement

- G) Dome position
  - Located 1 m off the axis of the church
  - 2 m from the centre of the dome
  - 2 m within the projection of the dome
  - 1.5 m from the floor
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** Receivers placement **

Minimum 9 receivers
Receivers placement

L/6
Receivers placement
Receivers placement

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Source and receiver combinations

<table>
<thead>
<tr>
<th>Source</th>
<th>Receivers in the main volume</th>
<th>Receivers in secondary volumes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A, altar</td>
<td>All + 3 control rec.</td>
<td>All</td>
</tr>
<tr>
<td>B, high altar</td>
<td>50% + 2 control rec.</td>
<td>At least one in the same “volume” where the source is located</td>
</tr>
<tr>
<td>C, ambos</td>
<td>50% + 2 control rec.</td>
<td></td>
</tr>
<tr>
<td>D, choir</td>
<td>50% + 3 control rec.</td>
<td>None</td>
</tr>
<tr>
<td>E, organ</td>
<td>50%</td>
<td>At least 5 receivers under the dome</td>
</tr>
<tr>
<td>F, pulpit</td>
<td>50%</td>
<td>At least one in the same volume where the source is located</td>
</tr>
<tr>
<td>G, dome</td>
<td>50%</td>
<td></td>
</tr>
<tr>
<td>H…Z, extra</td>
<td>50%</td>
<td></td>
</tr>
</tbody>
</table>
# Measurement equipment

<table>
<thead>
<tr>
<th></th>
<th>Basic</th>
<th>Intermediate</th>
<th>Advanced</th>
<th>Rendering</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sound source</strong></td>
<td>Every source complying with ISO 3382</td>
<td>Electro-acoustic omni-directional</td>
<td>Electro acoustic, omni-directional + sub-woofer</td>
<td>Same as Advanced, Lw&gt;100 dB if V&gt; 50000 m³</td>
</tr>
<tr>
<td><strong>Signal</strong></td>
<td>Noise, impulse, deterministic</td>
<td>Deterministic (MLS, sweep)</td>
<td>Deterministic (MLS, sweep) preferably equalized</td>
<td>Same as Advanced, but constant amplitude equalized sweep is preferred</td>
</tr>
<tr>
<td><strong>Microphones</strong></td>
<td>Omni-directional</td>
<td>Omni + figure8</td>
<td>Omni+figure8 (or B-format) + dummy head</td>
<td>B-format + dummy head</td>
</tr>
<tr>
<td><strong>Freq. Range (Hz)</strong></td>
<td>125-4000</td>
<td>125-4000</td>
<td>63-8000</td>
<td>63-16000</td>
</tr>
<tr>
<td><strong>Sampling</strong></td>
<td>44.1 kHz, 16 bit</td>
<td>44.1 kHz, 16 bit</td>
<td>44.1 kHz, 16 bit</td>
<td>48 kHz, 24 bit</td>
</tr>
<tr>
<td><strong>Measurable parameters</strong></td>
<td>T30, EDT and, with restrictions on the source, C, D, Ts, G</td>
<td>T30, EDT, C, D, Ts, G, LF, LG</td>
<td>T30, EDT, C, D, Ts, G, LF, LG, IACC</td>
<td>All</td>
</tr>
</tbody>
</table>

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