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Acoustic Characterization of the Rupestrian Pilgrimage Church of St. Michael's in Gravina in Puglia

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ABSTRACT
Rupestrian churches are very special semi-open acoustic spaces. Their acoustic features are strongly characterized by stone materials that (in the present stage) define their boundaries, and by more or less large openings. Consequently, strong frequency dependent effects are observed. The pilgrimage rupestrian church of St. Michael's in Gravina is one of the largest in Apulia and characterized by large flat surfaces. Acoustic measurements were carried out with a portable equipment. Results are discussed in the paper, pointing out that the combination of geometry and surface finishing determined a reverberant but yet clear acoustics, with a significant frequency imbalance which emphasizes bass sound (where modal behaviour also appears), and finally an impressive spacious and enveloping sound.
Keywords: rupestrian churches, acoustical measurements, 3D acoustic mapping

1. INTRODUCTION
Rupestrian churches and, more generally, rupestrian settlements represent an invaluable cultural heritage which is typical of Southern Italy and, in particular, of Apulia, representing an almost unique feature among Western European countries. Such settlements were built using natural caverns, generally due to karstic activity, or deliberately excavated in stone. They resulted, in most cases, from the spreading of Greek monks following the iconoclastic prosecution in the Eastern regions.

However, in many cases rupestrian settlements were established after assaults to cities that induced the population to find a refuge in caverns, forests, and along the slopes of hills where they built their houses and their worship places. The main difference compared to other examples of caverns [1-3] is that where natural caverns did not fit their needs, they created new ones (as it generally happened for churches) by excavating the stone and trying to imitate the shape and the architectural characteristics of "normal" churches.

The case of the Church of St. Michael's (Figure 1) exemplifies this approach to excavating spaces that resembled ordinary worship buildings. Its origin could date back to the destruction of the ancient city in 456 AD. However, since many of the places dedicated to St. Michael the Archangel were originally dedicated to pagan divinities, it cannot be excluded that the site has origins much further back in time.

When the natural cave welcomed the Michaelic cult it was modeled to become a real temple, probably in an era between the 8th and 10th centuries. Today the cave-church has five intercommunicating naves perpendicularly, marked by 14 quadrangular pillars. Round arches branch off from these and divide the interior space into naves and bays. The five naves end in apses with three altars in a central position; they are separated from the bema by a step on which once rested balustrades with barriers or wooden elements of the iconostasis.

The first nave, entering on the left, has remained similar to its original state: in the apse it preserves a triptych of frescoes with Christ Pantocrator in the center, St. Paul on the right, St. Michael on the left, datable to the 12th-13th century. Although the current liturgical layout of the presbytery denotes the use of the church according to the Western rite, as well as the absence of decorative or architectural elements that suggest the use of Eastern worship practices, it is not possible to exclude that, at least at its origins, the church was used for the Byzantine rite.

An acoustic analysis of the space was carried out in order to better understand how the peculiar geometry

Figure 1 – Panoramic image of the interior of the church

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and the surface finishing (in its current and in its original state) influenced the awe-inspiring nature of this place, and its attitude to host worship rituals.

2. MATERIALS AND METHODS

2.1 Main characteristics of the room

Among the Apulian rupestrian churches, St. Michael's is one of the largest (Table 1), with a volume of 640 m^3, a floor surface of about 200 m^2 and about 12 m^2 openings. On the material level, the church has few frescoed surfaces but most of the flat stone surfaces show a layer of whitewash in a fairly good state of conservation. No furniture was in the church during the measurements which were carried out under unoccupied conditions.

Table 1 – Summary of main geometric features

Property	
Floor surface	190 m^2
Overall surface	730 m^2
Volume	640 m^3
Average height	3.5 m

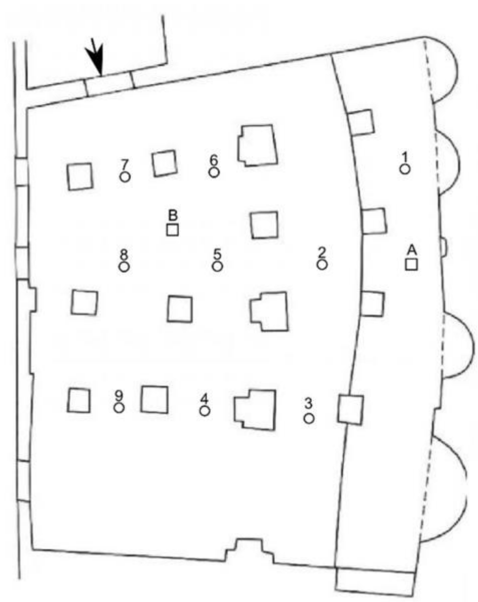

Figure 2 – Plan of the church with location of source (A,B) and receiver (1-9) positions

2.2 Measurement techniques

All the measurements were carried out with portable instruments. An omni-directional sound source (Look-line D301) located in front of the altar (Position A) and in the congregation area (Position B) was used to simulate sound emission from the priest and from the congregation (Figure 2). The source was fed by an equalized sine sweep played back by a smartphone and generated using MATLAB according to Müller and Massarani[4] so that the spectrum of the radiated sound was substantially flat from 50 Hz to 16 kHz. The duration of the sweep was kept short (about 8 s) in order to prevent negative effects due to lack of doors, determining significant air circulation which may compromise the time-invariant hypothesis, preserving at the same time frescoes and soft stone from any mechanical stress due to long lasting loud sounds. Impulse responses were collected using a portable B-format microphone (Soundfield ST-350) connected to a multi-channel recorder (Tascam DR-680) and a pair of binaural microphones (Soundman OKM II) worn by one of the authors and connected to a second recorder (Tascam DR-07). The measurement chain was previously tested in the lab to ensure that the "open loop" settings did not create any sync problem.

All the measurements were carried out complying with ISO 3382[5] standard, and, despite the small dimensions of the churches, at least two sound source position and an average of 9 receivers were used. Microphones were placed at a height of 1.7 m from the floor to take into account that the congregation was standing during the celebration. Given the small dimension of the churches only one person stayed in the room during the measurements. Impulse responses (IR) were calculated by deconvolving the signal used to fed the sound source and, despite a significant background noise due to birds and other natural sounds, provided an average S/N ratio of about 55 dB. The measured IRs were then processed in order to calculate the most important acoustic parameters and to investigate room resonances

3. RESULTS

3.1 Reverberation parameters

The observed reverberation time (Fig. 3) is very similar to those observed in smaller rupestrian churches, with a strong emphasis on low frequencies, while medium and high frequencies are influenced by the porous nature of the stone. From this point of view it should be noted that in rock churches, the need to have numerous vertical support elements determines an increase in the exposed surface as the volume increases, therefore this leads to a corresponding increase in the obtainable acoustic absorption.

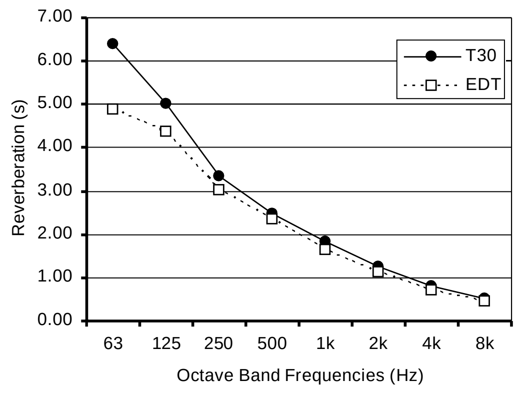

Figure 3 – Reverberation time (T30) and early decay time (EDT) as a function of frequency

A significant difference appears between EDT and T30 at low frequencies, potentially attributable to the presence of resonances (Figure 4) in the vertical direction (where the height is on average between 3 and 3.5 m, with consequent fundamentals between 50 and 60 Hz). To support the interpretation of the long low frequency T30, it is interesting to observe the spectrum of one of the measured IRs, showing clear modal behavior with four peaks located respectively at 59 Hz, 65 Hz, 72 Hz and 89 Hz, the first one being in agreement with the first vertical mode for a space with a height of 2.8 m.

Point-by-point variations can be observed but being visible at all frequencies they are therefore attributable only to the different relationship between source and receivers, mostly as a consequence of the masking effect produced by the many pillars.

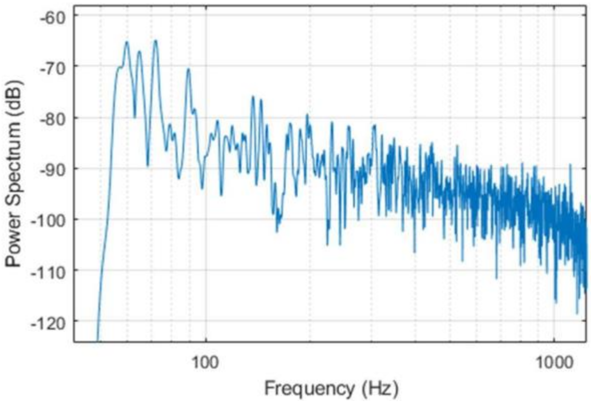

Figure 4 – Spectrum measured for combination A_01

3.2 Clarity and speech intelligbility

The relatively low medium and high frequency reverberation time determines an average value of STI equal to 0.57, with a maximum of 0.63 at receivers close to the source, and minimum values never lower than 0.5, therefore corresponding to a sufficient intelligibility which, however, could considerably increase considering the capacity of the church. and the consequent possible reduction of the reverberation time in the presence of a full occupation.

Given the larger dimensions of this church, it is also interesting to observe the trend of the parameters of clarity as a function of distance (Fig. 5). To provide a comparison with values expected for a space with comparable volume and T30, values derived from Barron theory [6] and from the revised version using increased control of early reflections [7,8] are shown. In the second case, the additional parameters were chosen assuming a source located close to hard reflecting surfaces (corresponding to a scattering coefficient s = 0.2), and a space with large reflecting surfaces (corresponding to parameter k = 0.7).

A decrease in measured values can be observed as a function of distance with a slope that is steeper than the expected one (whatever the model used to calculate). This results from measured values that are 4-5 dB higher than prediction at receivers within 8 m from the source. The explanation for this behavior is that strong early reflections (comparable with direct sound) come from the hard and reflective surfaces that surround both source and receivers.

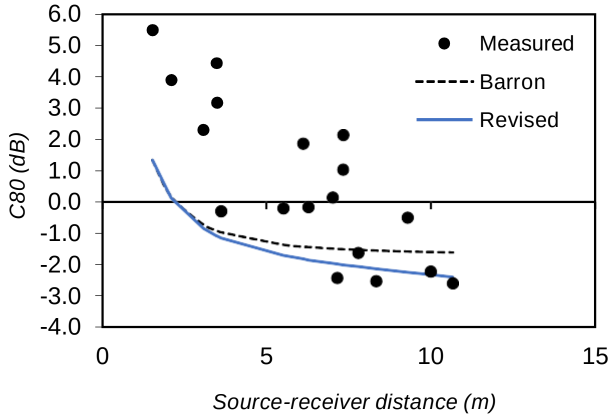

Figure 5 – Plot of C80 (averaged among 500-2000 Hz octave bands) as a function of source receiver distance

3.3 Spaciousness

As for the spatial parameters, the extension of the church, especially in width, combined with the many obstacles, induces lateral energy fraction values that are, on average, equal to 0.28 when the source is in A (Fig. 6). For the same reason, 1-IACC should also be affected. However, the presence of a "forest of pillars" [9] determines a partial compensation of this effect. In fact, when the source is in A, the average of 1 – IACC is 0.74 (quite close to values observed in other smaller rupestrian churches [10]), while when the source is in B the average value stands at 0.68 largely due to the lower measured values at points 5, 6 and 7 which are very close to the source.

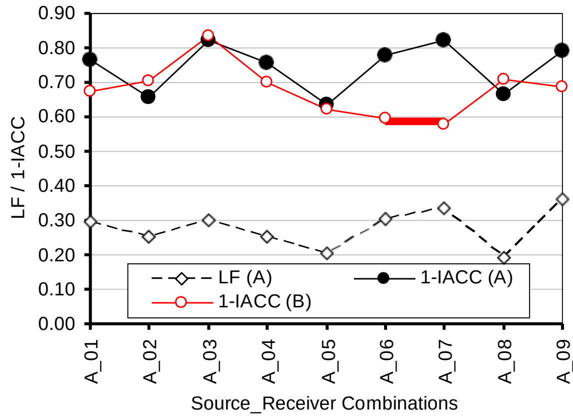

Figure 6 – Plot of Lateral Fraction (LF) and 1-IACC as a function of source and receiver combinations

3.4 Spatial distribution of early reflections

In order to finally explain some of the observed results, with particular reference to high clarity, STI, and strong lateral reflections, a directional map of the early reflections was obtained from the B-format recordings, taking advantage of the procedure discussed in Ref. 11.

As shown in Figure 7, the early part of the IR is characterized by strong reflections coming from the horizontal surfaces as well as from the side walls (particularly from the left side) where sound is reflected despite the presence of the large pillars.

Similar results were found at different source-receiver combinations, emphasizing the role of strong reflections bouncing between the floor and the ceiling and contributing to keep high clarity.

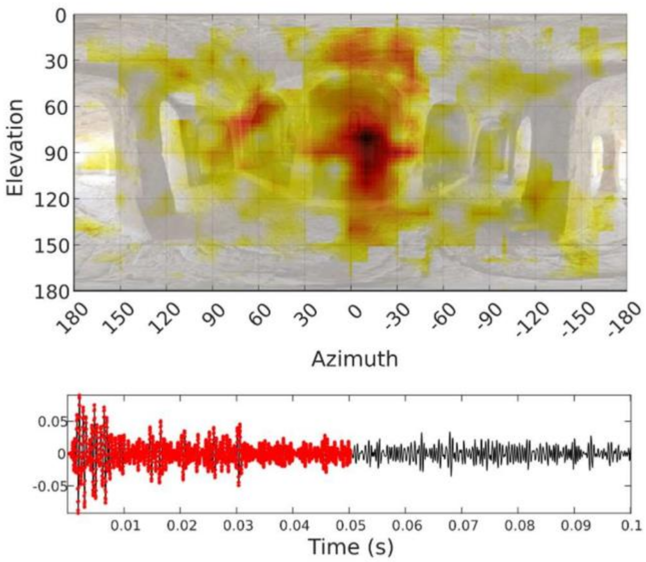

Figure 7 – Directional map at receiver 02 when source was in position A, time interval from 0 to 50 ms, at 2 kHz octave band frequency

4. DISCUSSION AND CONCLUSIONS

The paper investigated one of the largest rupestrian churches found in Apulia and dedicated to Michaelic cult. This ritual space, characterized by large flat horizontal surfaces made of stone, is characterized by a strongly unbalanced acoustic where low frequencies are resonant and reverberant, while medium and high frequencies are characterized by much lower reverberation times and high clarity, suitable for speech even under unoccupied conditions. Analysis of spatial distribution of reflections confirmed the role of flat horizontal surfaces in combination with some strong lateral reflections that also contributed to keep lateral fraction and inter-aural cross correlation coefficients at reasonable levels suggesting a fully enveloping sound.

Such results suggest that under fully occupied conditions acoustics might become even clearer and appropriate for preaching and ritual ceremonies, while keeping a very long low frequency reverberation that emphasized ritual singing. In fact, analyses of typical Byzantine chants have demonstrated the role of low frequencies that are used to produce almost continuous notes that interact very well with the resonant qualities of the investigated spaces.

In addition, the current state of the surface finishes (i.e. flat stone surfaces with thin layer of whitewash that is crumbling in large areas), is likely to return an absorption coefficient of about 0.05 at mid frequencies. As found in other rupestrian churches, plaster (with frescoes) was likely to cover the surfaces in the origin, thus realistically reducing absorption coefficients. Thus, it is reasonable to assume that a more reverberant acoustics, although equally characterized by much slower low frequency decay, would have characterized the space in its origin. However, the occupants are also likely to dramatically change acoustic conditions, making it even more unbalanced.

Further investigations are under way to properly analyse this condition by means of simulation tools.

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