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The Acoustics of the Catacombs

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The catacombs are underground places. This paper reports the results of acoustic measurements carried out inside the catacombs of "San Gennaro" (Naples) and in those one of "San Callisto" (Rome). Originally the catacombs were also used to perform sacred functions, although we don't know the type of these functions i.e. if they were spoken, sung or performed as psalms. This paper presents acoustic measurements carried out in catacombs using the impulse response method, and by the analysis of the monaural acoustic parameters, (T_{30}, EDT, C_{80}, D_{50} and STI), the authors intend to understand the type of religious ceremony performed in the catacombs. If the catacombs had been reverberant places, they could not have been used for prayers because the echoes would have created difficulties in concentration and meditation for the devotees due to the poor speech comprehension.

Keywords: catacombs, acoustic measurements, reverberation time, impulse response.

1. Introduction

There are some studies in literature about the acoustics of the underground locations during the prehistoric period (Reznikoff, 2008). It was observed that in the areas of the caves with sound resonances some drawings of animals were painted; some studies focus on the acoustics of the caves (Iannace *et al.*, 2010; Ianniello, 2011), while others check how the acoustics could influence auditory experience. Also acoustic measurements inside underground locations in Peru were carried out (Abela *et al.*, 2008). Acoustic measurements carried out in prehistoric underground places are reported (Jahn *et al.*, 1996) and in which were observed resonances in the range of frequencies between 95 Hz and 120 Hz. This paper considers a possibility that these resonances favored the development of certain forms of singing and speech (Wallin, 2000). There are related acoustic measurements (Jimenéz González *et al.*, 2008) and numerical models (Picó *et al.*, 2006) of the Parpalló cave in Spain in order to investigate the existence of acoustic clues which could support the hypothesis that this place had been used during prehistory for social meetings and cult ceremonies. Furthermore some studies performed on the acoustic properties of prehistoric graves in Scotland (Watson *et al.*, 1999) have shown a link between the sound sensation, the vision and the spatial impression.

The catacombs are underground places that could be considered as the cradle of Christianity and the archive of the early Church and their sculptures and paintings demonstrate the uses, the customs and the traditions of the ancient Christians.

Not many things are known about the types of religious functions that took place in the catacombs during the period of the early Christians. It is known that the use of musical instruments was not allowed during religious functions (Garbini, 2012). In literature there are some studies exploring the acoustics of the early Christians churches (Suárez *et al.*, 2013), but there are not any studies about the acoustics of the catacombs, therefore the present work aims to investigate the acoustic measurements performed inside the catacombs of "San Gennaro" in Naples and in "San Callisto" in Rome, where religious rituals could have been celebrated. Particularly this paper investigates if the religious functions inside above mentioned places were spoken, sung or performed with psalms.

In fact, if the catacombs were reverberant places, they could not be used for prayers, meetings and religious functions because the echoes would have created difficulties in concentration and meditation for the devotees due to the poor speech comprehension.

2. The catacombs

The catacombs were excavated in tuff or other easily removable, but solid enough to create a negative architecture, ground. They were places used for reunions and visits to the graves of the martyrs (Stevenson, 1978), and they were diffused in different religions (the Phoenicians, the Greek and pre-Hellenic, the Etruscans and the Jews used to bury their deceased in underground rooms) and in the different areas of Europe and Mediterranean Asia, but for the Christians these cemeteries were places designed for waiting for the resurrection after death. In Italy the principal cities with the catacombs are Naples, Rome, Perugia, Syracuse. The catacombs were generally made up of long narrow tunnels and low ambulatory and were interconnected at various levels by staircases. The elevated costs of the ground surfaces for the construction of cemeteries had an influence on the development of the construction of underground locations (Deichmann, 1993). From 5th century A.C. after the transfer of the relics of the saints and the martyrs into the churches located inside the walls of the cities, the catacombs were abandoned as cemeteries and disappeared soon. No earlier than at the end of the Middle Ages these places were rediscovered and studied again. The catacombs often have been described as sad places of death or as places of the persecution and a shelter for persecuted Christians, but the studies and the researches have not confirmed these common beliefs. The purpose of this paper is the evaluation of the acoustic properties of the catacombs, in particular one place which is intended to be appraised through acoustic measurements Furthermore, this paper examines what kind of possible religious functions could have been celebrated in these places, as the catacombs were places of burial, reunions and cult of the Christian communities. If these places had been very reverberant, they could not have been used for prayers, meetings and religious functions because the echoes would have created difficulties in concentration, meditation and a poor speech comprehension.

Due to the impossibility to connect to the electricity grid, the use of the whole equipment was not possible. As recommended by ISO 3382 (ISO 3382, 2012), toy balloons, inflated with air were used as sound sources; in fact the balloon explosion produces an impulse that excites the sound field; furthermore, the background noise is very low because of the underground locations and the distance from anthropic noises; also at the frequency of 63 Hz the toy balloons' explosion gives a sufficient SNR ratio. The impulse response was measured by the microphone type GRAS 40 AR 1/2", connected to 01 dB Symphony system to a pc portable computer. The impulse response was elaborated with the software dBBATI and the monaural acoustic parameters T_{30}, EDT, C_{80}, D_{50} and STI were analyzed. The sound sources were positioned in different points of the catacombs – at the height of 1.6 m from the floor (the height of a potential orator), while microphone points were positioned at the height of 1.6 m from the floor in different positions of the walkable area to simulate the possible position of listeners; the acoustic measurements were carried out without the audience. This methodology has been already verified in other complex environments with good results (e.g., the caves (Iannace *et al.*, 2014) and the large theatre of Pompeii (Iannace *et al.*, 2013)).

Furthermore the spatial distribution of acoustic parameters C_{80} and D_{50} was measured to obtain a single number in the average values of 500 Hz, 1.0 kHz and 2.0 kHz (Barron, 1993), because this frequencies are important for the speech comprehension.

2.1. The catacombs of "San Gennaro" in Naples

On the hill of *Capodimonte*, there is a modern entry to the catacombs of "San Gennaro". It is a place without the labyrinths of the narrow ambulatories, but with spacious architecturally well-finished environments illuminated by ample skylights from wide openings on the side of the hill (de Jorio, 1839). The catacombs are composed of two levels partially overlapped. Figure 1 shows the map of the two levels of the catacombs (Fasola, 1977).

The inferior hallway (Fig. 2) is actually constituted by a long trapezoidal room 16 m long, around 6 m wide to the entry and 11 m to the fund, with a height of around 6 m, decorated with paintings. In the center of the environment there is the baptistery; three galleries radiate from the lower vestibule towards the east (the "region of the labyrinth" developing towards east for around 80 m).

The hypogeum of the second level draws its origin from what is called "hallway of the superior catacomb" or "*Basilica Adiecta*" (Fig. 3), it is found at a level of around 3 m higher than the inferior hallway. The triplex ample arcade, that actually divides two rooms, is a transformation realized when in the central part of the superior catacomb was created to honor of "San Gennaro". The vast underground basilica is around 70 m long, 10 m wide and up to 11 m high. The excavation and the realization of such hallway are dated at the end of the 5th century when the cult of the martyrs' graves was definitely affirmed and the presence of all the faithful believers required big spaces. The decadence of the catacombs of "San Gennaro" started during the 8th century when the bishops' remains were transferred into the urban basilica, and since the 8th to the 18th century the catacombs suffered from great negligence and indiscriminate devastations. In the 18th century the catacombs were rediscovered and the actual state of the catacombs has almost been unchanged in comparison to its configuration of the 8th century. Table 1 shows the average geometric dimensions of the two levels of the catacombs.

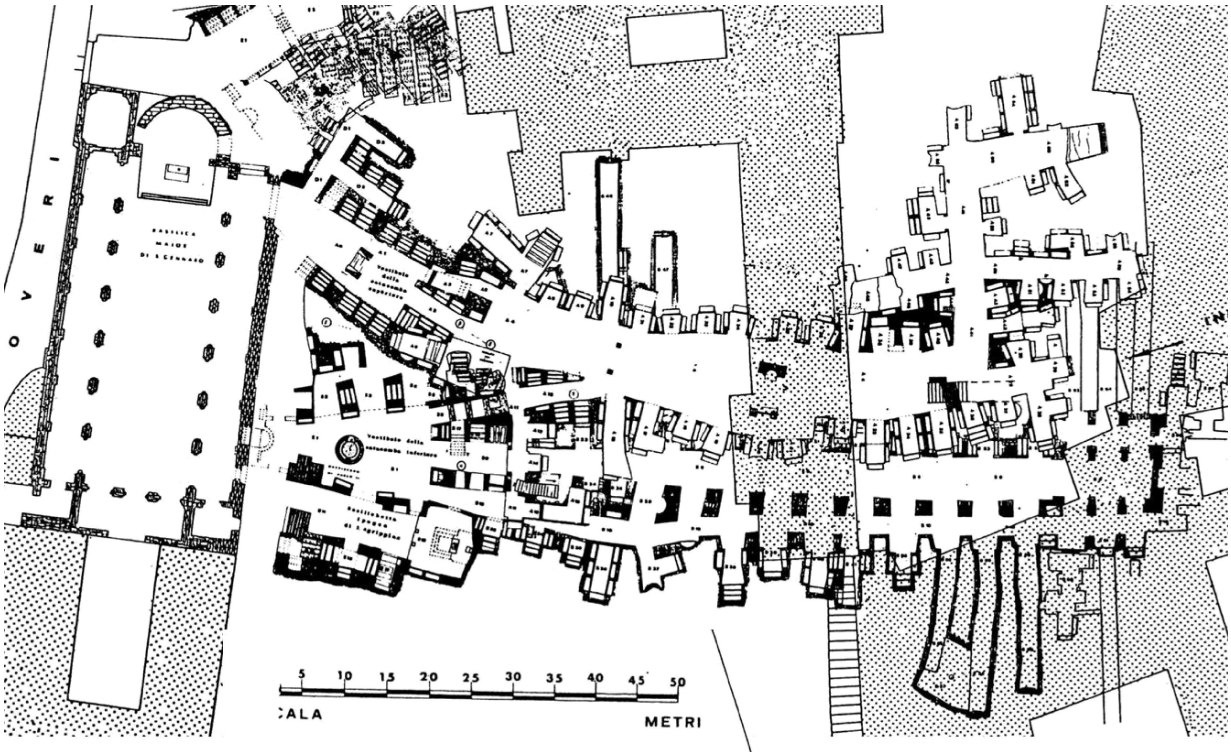

Fig. 1. Map of the two levels of the catacombs of "San Gennaro".

Fig. 2. First level of the catacombs of "San Gennaro", principal corridor.

Fig. 3. Second level of the catacombs of "San Gennaro", *Basilica Adiecta*.

Table 1. Average geometric dimensions of the catacombs.

Level	Length [m]	Width [m]	Height [m]
First	66.5	9.5	6.0
Second	56.0	9.5	6.0

Acoustic measurements in the catacombs of "San Gennaro"

The acoustic measurements were carried out on August 2012 (Trematerra *et al.*, 2013), the air temperature was 15–17°C, and the relative humidity was 70%. At the first level (Fig. 4) the sound sources were placed in two different positions: the first position in the hall-

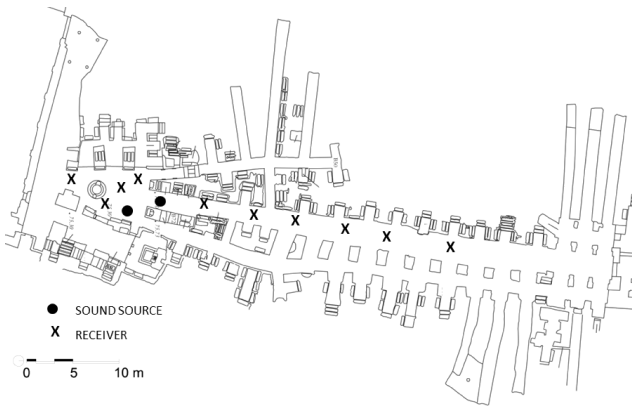

Fig. 4. First level – two positions of sound source and ten receivers.

way, in proximity of the baptismal fountain, and the second position along the principal corridor. At the second level the sound sources were placed inside the "Basilica Adiecta" in two different positions (Fig. 5).

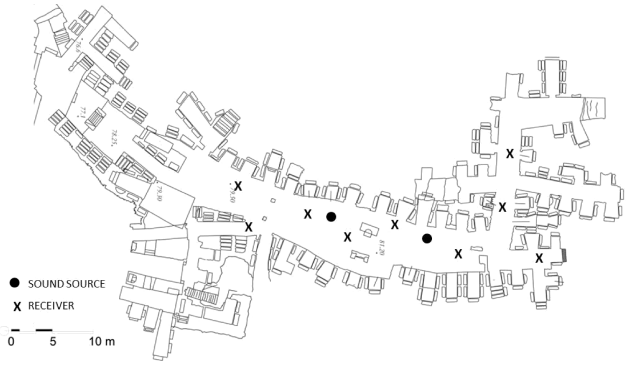

Fig. 5. Second level – two positions of sound source and nine receivers.

For the first level of the catacombs the spatial average values of the acoustic parameters (T_{30}, EDT, C_{80}, D_{50} and STI) were valued and they are shown in Fig. 6, while Fig. 7 shows the D_{50} average spatial distribution, and Fig. 8 shows the C_{80} average spatial distribution at the first level (average values at the frequencies of 500 Hz, 1.0 kHz and 2.0 kHz).

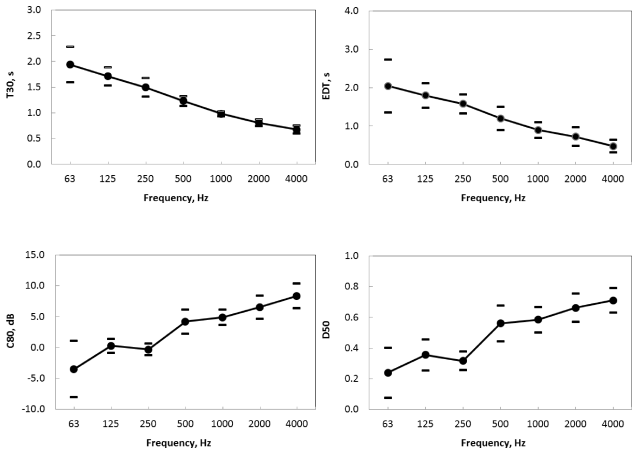

Fig. 6. First level – average values of the acoustic parameters, STI = 0.66.

Fig. 7. First level – D_{50} average spatial distribution.

Fig. 8. First level – C_{80} average spatial distribution.

For the second level of the catacombs the spatial average values of the acoustic parameters (T_{30}, EDT, C_{80}, D_{50} and STI) were valued and they are shown in Fig. 9, while Fig. 10 shows the D_{50} average spatial distribution, and Fig. 11 shows the C_{80} average spatial distribution at the second level.

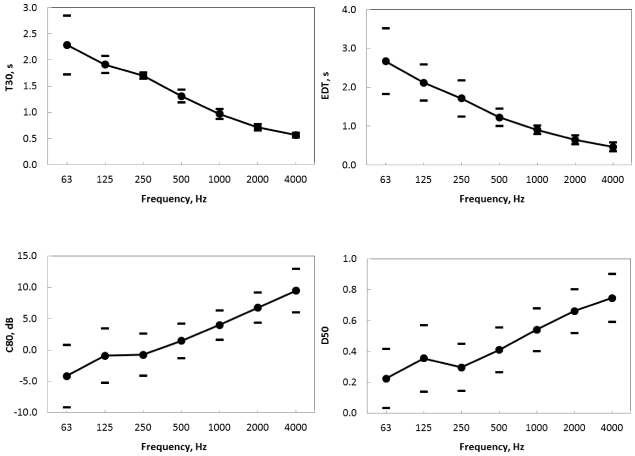

Fig. 9. Second level – average values of the acoustic parameters, STI = 0.60.

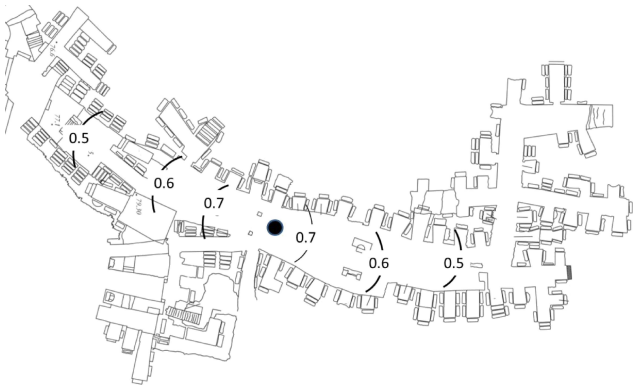

Fig. 10. Second level – D_{50} average spatial distribution.

Despite the ample space of the catacombs inferior and superior, measured acoustic parameters give us an indication that the speech understanding in these environments is excellent: at the frequency of 1.0 kHz

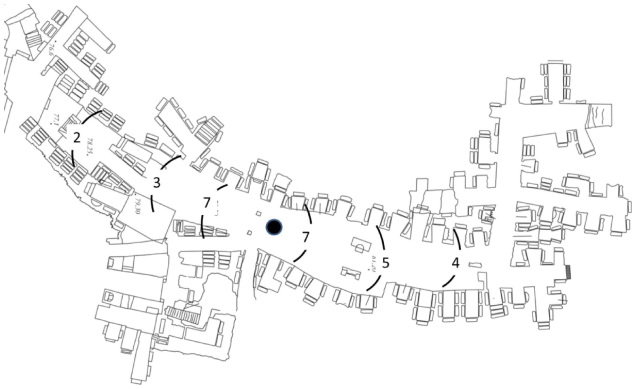

Fig. 11. Second level – C_{80} average spatial distribution.

the value of the reverberation time (T_{30}) is about 1.0 s and the value of the definition (D_{50}) is superior to 0.50 (averaged in the frequency range for speech intelligibility, at the octave bands frequencies of 500 Hz, 1.0 kHz, 2.0 kHz). Furthermore, for the inferior catacombs the average values of STI = 0.66 and for the superior catacombs the average values of STI = 0.60, so the words spoken by a potential orator are correctly understood by the listeners.

For the second level, despite a volume of about 3400 m^3, at the frequency of 1.0 kHz the reverberation time is very low due to the porous surfaces of the tuff walls and floors and the large openings to the outside, and by the scattering surfaces of the lateral niches, but at low frequencies the value of the reverberation time increases leading with a reduction of C_{80} and D_{50} and the average value of the absorption coefficient (a), at the frequency of 1.0 kHz, $a = 0.25$.

2.2. The catacombs of "San Callisto"

The catacombs of "San Callisto" are among the largest and the most important catacombs of Rome (Baruffa, 1992). They appeared around the middle of the 2nd century and they are a part of a cemetery with a network of tunnels almost 20 km long, on different levels reaching a depth of more than 20 m (De Santis *et al.*, 2011). Tens of martyrs, 16 Popes and many Christians were buried there. The catacombs were named after the deacon Callisto who, at the beginning of the 3th century, was appointed administrator of the cemetery by Pope Zefirino, so the catacombs of "San Callisto" became the official cemetery of the Church of Rome (Fiocchi *et al.*, 1999). Figure 12 shows the plant of catacombs of "San Callisto" with the places in which the acoustic measurements were carried out: in the Crypt of Popes and in the Crypt of St. Cecilia (Fig. 13), in the double cubicle, in the corridor, and in the single cubicle (Fig. 14). Table 2 shows the average geometric dimensions of these places.

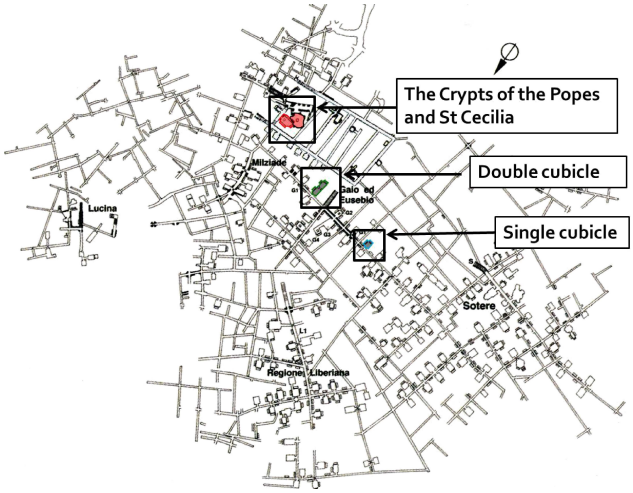

Fig. 12. Plant of the catacombs of "San Callisto", with the places in which the acoustic measurements were carried out.

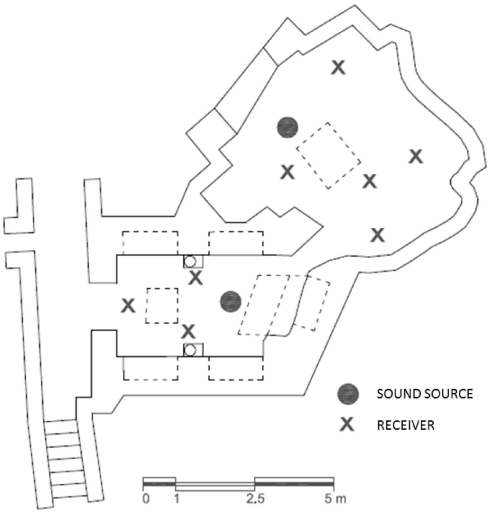

Fig. 13. Plant of the Crypts of Popes and Crypts of St. Cecilia.

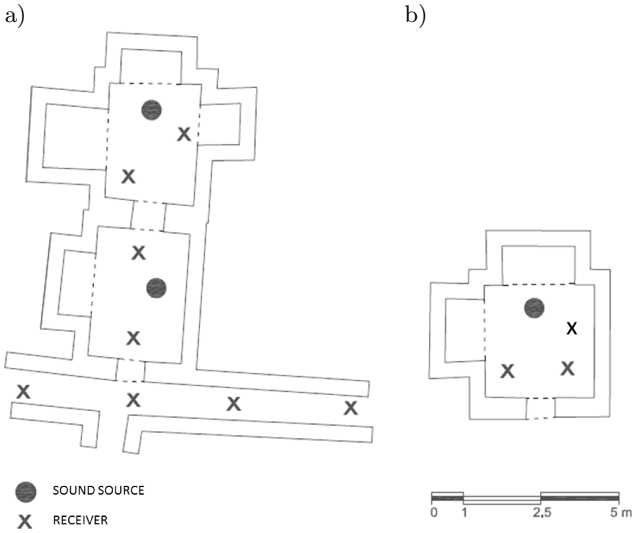

Fig. 14. a) Plant of the double cubicle and the corridor; b) plant of the single cubicle.

Table 2. Average geometric dimensions of the places in which the acoustic measurements were carried out.

Place	Average base area [m^2]	Average height [m]
Crypt of Popes	18	4.5
Crypt of St Cecilia	38	4.5
Double cubicle	26	6.2
Single cubicle	16	2.6

Acoustic measurements in the catacombs of "San Callisto"

The acoustic measurements were carried out in December 2012, with an air temperature of 16°C and a relative humidity of 70%. The spatial average value of the acoustic parameters (T_{30}, EDT, C_{80}, D_{50} and STI) was valued and reported in Fig. 15 for the Crypt of Popes, in Fig. 16 for the Crypt of St. Cecilia, in Fig. 17 for the double cubicle, in Fig. 18 for the corridor, and in Fig. 19 for the single cubicle. Presented acoustic parameters are obtained by the average values of acoustic measurements made in each place. The places are small, in the Crypt of Popes and in the Crypt of St. Cecilia the floor is covered with marble and the walls are made of solid tuff, so the average value of the absorption coefficient (a) at the frequency of 1.0 kHz is $a = 0.27$; in the other places the floors and the walls are made of solid tuff. The values of reverberation time (T_{30}) and the EDT measured in the Crypt of Popes and in the Crypt of St. Cecilia are greater than values measured in the other places, because in these places the floor is covered with marble. The analyzed acoustic parameters show an excellent level of speech understanding; in fact the values of the reverberation time (T_{30}), at the frequency of 1.0 kHz, are less than 1.0 s and the values of the definition (D_{50}) are superior to 0.50; so the words spoken by a potential orator are correctly understood by the listeners.

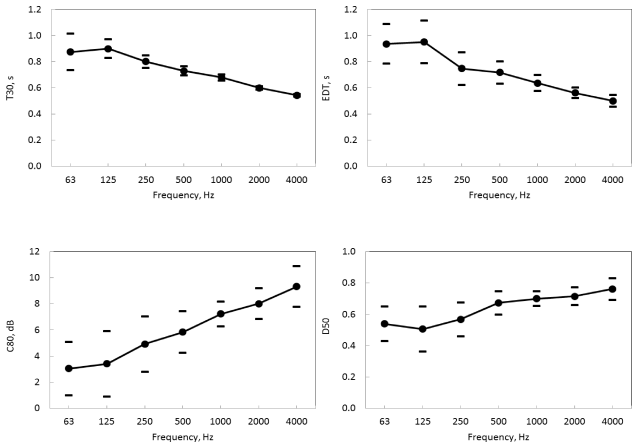

Fig. 15. Crypt of Popes – average values of the acoustic parameters; STI = 0.71.

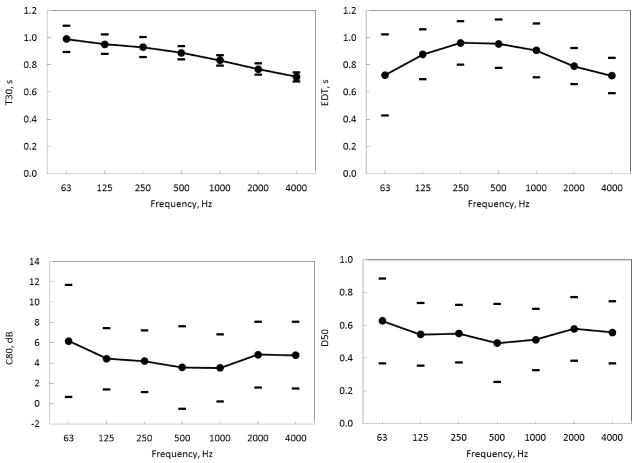

Fig. 16. Crypt of St Cecilia – average values of the acoustic parameters; STI = 0.64.

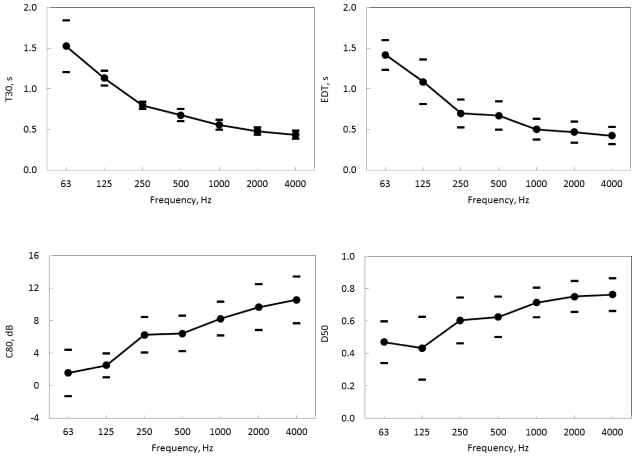

Fig. 17. Double cubicle – average values of the acoustic parameters; STI = 0.73.

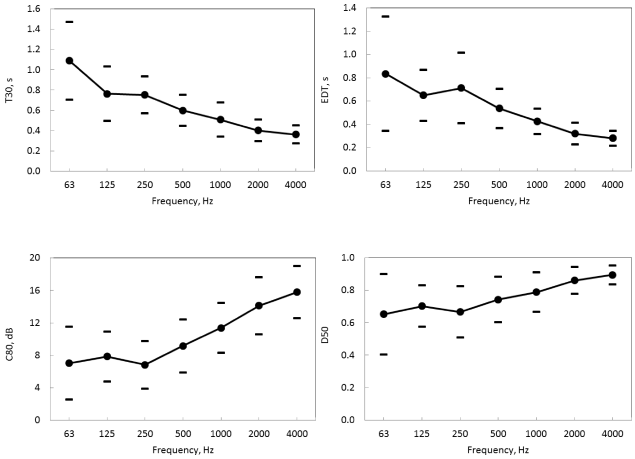

Fig. 18. Corridor – average values of the acoustic parameters; STI = 0.78.

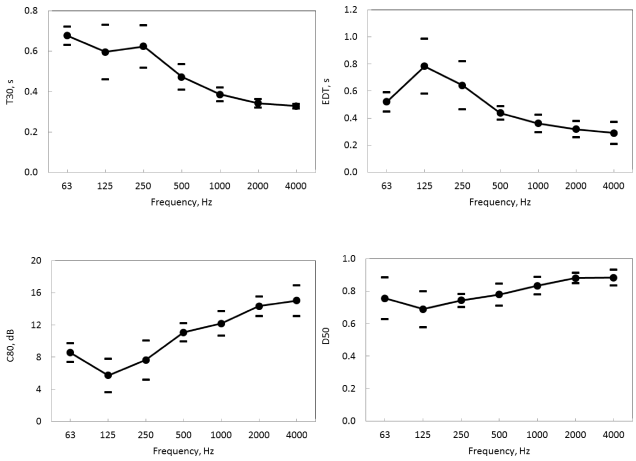

Fig. 19. Single cubicle – average values of the acoustic parameters; STI = 0.78.

Figure 20, for the Crypt of Popes and Crypt of St Cecilia, shows the D_{50} spatial distribution, while Fig. 21 shows the C_{80} spatial distribution. Figure 22,

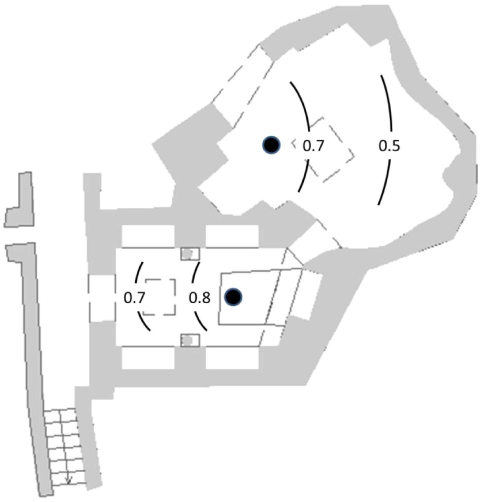

Fig. 20. D_{50} average spatial distribution.

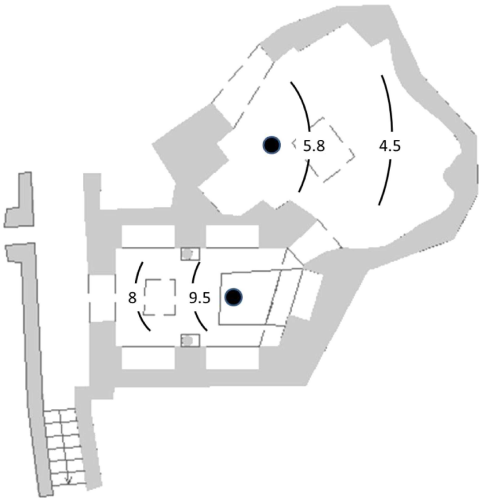

Fig. 21. C_{80} average spatial distribution.

for the double cubicle and corridor, shows the D_{50} spatial distribution, while Fig. 23 shows the C_{80} spatial distribution. For the single cubicle the room is very small so the acoustic parameters are uniformed.

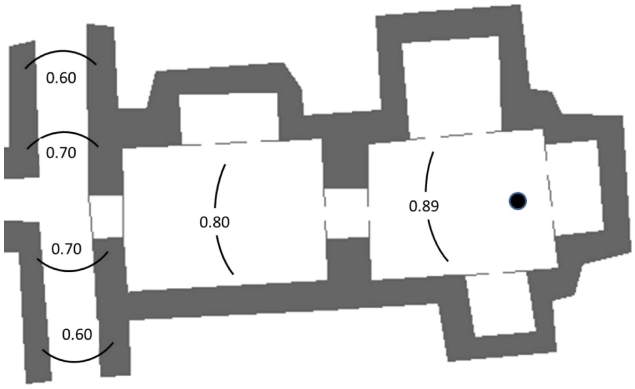

Fig. 22. D_{50} average spatial distribution.

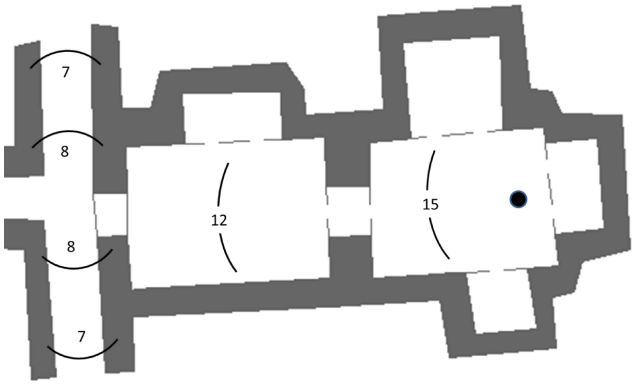

Fig. 23. C_{80} average spatial distribution.

3. Discussion

The average acoustic parameters T_{30}, EDT, C_{80}, D_{50} and STI are reported, these values were measured in the catacombs of "San Gennaro" (Naples) and in those one of "San Callisto" (Rome). This work shows large values of standard deviation at low frequencies (63 Hz and 125 Hz) because in the underground locations there are low frequencies components (Plummer, 1969), while from the frequency of 250 Hz these differences are small. At the frequency of 1.0 kHz the value of the reverberation time (T_{30}) is about 1.0 s, while the value of the definition (D_{50}) is superior to 0.50. The analysis of the acoustic parameters indicates that in these environments the speech understanding is excellent, so the words by a potential orator are correctly understood by the listeners. It is possible, therefore, to hypothesize that in these environments the religious services were mainly based on the liturgy of the word or psalms and maybe an excessive reverberation would have prevented the catacombs from becoming a place of cult, meditation and prayer. It needs to these environments are made up to alive tuff, a porous mate-

rial and therefore fit to absorb the sound that engrave on it. In the catacombs of "San Callisto" the average acoustic parameters measured and the standard deviation are the same as those obtained in the catacombs of "San Gennaro", because in "San Callisto" the volume of cubicles is interconnected environments between them as coupled volumes. It has not been possible to investigate the effects of the sound diffusion between adjacent places, or if in the case of simultaneous functions the same would influence between them in a negative way; moreover, the measurements of the acoustic properties at the band of 63 Hz have been carried out to investigate the reaction of these underground places at the low frequencies.

4. Conclusions

It needs to be taken into account that the acoustic measurements are performed at the actual state of the catacombs, in absence of the closings of the recesses realized in marble or bricks. The religious functions based on the liturgy of the word or psalms were compatible with the acoustic characteristics of the locations. It needs that these locations are made of alive tuff, a porous material that therefore it is fit to absorb the sound that engrave on it, so at the frequency of 1.0 kHz the values of reverberation time (T_{30}) are under 1.0 s, and the values of STI are over 0.6.

References

1. Abela J.S., Rickb J.W., Huanga P.P., Kolara M.A., Smitha J.O., Chowninga J.M. (2008), *On the Acoustics of the Underground Galleries of Ancient Chavin de Huàntar, Peru*, Proceedings of Acoustics'08, pp. 4167–4172, Paris.
2. Baruffa A. (1992), *Le catacombe di San Callisto. Storia, archeologia, fede* [in Italian], Libreria Editrice Vaticana.
3. Barron M. (1993), *Auditorium Acoustics and Architectural Design*, E&FN SPON London.
4. Deichmann F.W. (1993), *Archeologia cristiana* [in Italian], L'Erma di Bretschneider, Roma.
5. de Jorio A. (1839), *Guida per le Catacombe di S. Gennaro de' Poveri* [in Italian], (Reprint).
6. De Santis L., Biamonte G. (2011), *Le catacombe di Roma* [in Italian], Newton Compton Italiana.
7. Fasola U.M. (1974), *Le catacombe di S. Gennaro a Capodimonte* [in Italian], Editalia.
8. Fiocchi Nicolai V., Bisconti F., Mazzoloni D. (1999), *The Christian Catacombs of Rome*, Schnell & Steiner Regensburg.
9. Garbini L. (2012), *Breve storia della musica sacra* [in Italian], il Saggiatore, Milano.
10. Iannace G., Marletta L., Sicurella F., Ianniello E. (2010), *Acoustic measurements in the Ear of Dionysius at Syracuse (Italy)*, Proceedings of 39th International Congress on Noise Control Engineering, paper 580, Lisbon.
11. Iannace G., Ianniello C., Ianniello E. (2012), *Acoustic measurements in underground rooms of Castelcivita Caves (Italy)*, Proceedings of European Conference on Noise Control – Euronoise 2012, pp. 124–129, Prague.
12. Iannace G., Trematerra A., Masullo M. (2013), *The large theatre of Pompeii: Acoustic evolution*, Building Acoustics, **20**, 215–227.
13. Iannace G., Trematerra A. (2014), *The acoustics of caves*, Applied Acoustics, **86**, 42–46.
14. Ianniello C. (2011), *Acustica delle caverne*, Rivista Italiana di Acustica, **35**, 7–22.
15. ISO-3382 (2012), *Acoustics – Measurement of the reverberation time of rooms with reference to other acoustical parameters.*
16. Jahn R.G., Devereux P., Ibison M. (1996), *Acoustical resonances of assorted ancient structures*, J. Acoust. Soc. Am., **99**, 2, 649–658.
17. Jimenéz González N., Picó R., Redondo J. (2008), *The Parpalló Cave: A singular archaeological acoustic site*, Proc. Acoustics'08, Paris.
18. Picó R., Hortelano Piqueras L., Roig B., Redondo J. (2006), *Simulaciòn acùstica de la cueva del Parpallò mediante el metodo de elementos finitos*, Tecniacustica, Gandia.
19. Plummer W.T. (1969), *Infrasonic Resonances in Natural Underground Cavities*, J. Acoust. Soc. Am., **46**, 5, 1074–1080.
20. Reznikoff I. (2008), *Sound resonance in prehistoric times: A study of Paleolithic painted caves and rocks*, Proceedings of Acoustics'08, pp. 4137–4141, Paris.
21. Stevenson J. (1978), *The Catacombs*, Thames and Hudson Ltd, London.
22. Suárez R., Juan J., Sendra J.J., Alonso A. (2013), *Acoustics, Liturgy and Architecture in the Early Christian Church. From the domus ecclesiae to the basilica*, Acta Acustica, **99**, 292–301.
23. Trematerra A., Iannace G. (2013), *The acoustic of the Catacombs of "San Gennaro" in Naples*, Proceedings of International Congress on Noise Control Engineering, Innsbruck.
24. Wallin N.L., Merker B. (2000), *The Origins of Music*, Steven Brown [Ed.], MIT Press.
25. Watson A., Keating D. (1999), *Architecture and sound: an acoustic analysis of megalithic monuments in prehistoric Britain*, Antiquity, **3**, 325–336.