Correlation between Acoustic Emission and Seismicity in the Sacred Mountain of Varallo Renaissance Complex in Italy

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Abstract In this work, we examine an application of AE technique for a probabilistic prediction of the time and place of earthquakes, in order to preserve the inestimable Italian Renaissance Architectural Complex named “The Sacred Mountain of Varallo”. This historical site is composed of 45 Chapels, some of which are isolated, while others are part of monumental groups. The Chapels contain over 800 life-size wooden and multicoloured terracotta statues, which represent the Life, Passion and Death of Christ. The site is considered the most notable example in the group of Sacred Mounts of Piedmont, a complex that has been included in the UNESCO World Heritage List since 2003.

The structure of the Chapel XVII of this Renaissance Complex is at risk for its poor structural health and on account of the intensity of the stresses it is subjected to, due to the level of regional seismicity. For the reliability and safety of this masterpiece of cultural heritage, a life-time assessment should take into account the evolution of damage phenomena. Therefore a continuous AE monitoring is performed to assess the structural behavior of the Chapel.

Earthquakes always affect structural stability: the amount of energy released in a seismic event can cause catastrophic damage in a wide variety of ways. Beside this well-known point of view, in this paper it is claimed that the structures of the “Sacred Mountain of Varallo” behave as sensitive earthquake receptors, since the stress propagation through the Earth’s crust, which can be considered as an earthquake precursor, can be effectively monitored by means of the AE technique.

In some works, a burst of AE activity is considered as representative of a large amount of stress which is crossing some large crustal area surrounding the AE recording site. Such AE crises are observed some time in advance compared to the earthquake, leading to consider AE records like earthquake precursors.

During the monitoring period, a correlation between peaks of AE activity in the masonry of the “Sacred Mountain of Varallo” and regional seismicity is found. These two classes of phenomena, AE in materials and earthquakes in Earth’s crust, though they take place on very different scales, are very similar due to the release of elastic energy from localized sources inside the medium: opening microcracks and hypocenters of earthquakes.

Keywords Acoustic Emission, Structural Monitoring, Cultural Heritage, Earthquake, Seismic Precursors.

1. Introduction: The historic site of the Sacred Mountain of Varallo

The Sacred Mountain of Varallo is located in the italian province of Vercelli. Set on a cliff above the town of Varallo, it is the oldest and most important Sacred Mountain of the Alps (Fig.1). His story began in the late fifteenth century when the Franciscan friar Bernardino Caimi of Milan, returning from the Holy Land where he was guardian of the Holy Sepulchre, decided to reproduce in Varallo the holy places of Palestine [1].

The "New Jerusalem", as it is called the Sacred Mountain, initially intended to represent the distant sites of the Christian tradition for all those people who could never go there (Fig.2). Inside these places are, instead of pictures, paintings and sculptures to evoke the corresponding event in the history of the life of Christ. Already in the early sixteenth century, thanks to the work of the painter sculptor and architect Gaudenzio Ferrari, the scenes inside the chapels are represented in an ingenious and innovative merging of painting and sculpture, with a strong sense of reality, so that the devotee could feel himself deeply involved by the depicted scene of the Christ's Life and almost part of it (Fig.3). The work of Gaudenzio Ferrari will be taken as a model in the construction of many other Sacred Mountains. In the era of the Counter-reformation, the Sacred Mountain of Varallo assumed the appearance of a path, real but at the same time mystical, that the pilgrim completes following the telling of the story of Christ's Life. The Sacred Mountain is composed of a basilica and forty-five frescoed chapels, populated by over eight hundred statues. For the completion of this extraordinary monument worked important Piedmontese artists, among which there are Bernardino Lanino, Tanzio da Varallo, brothers D'Enrico, Morazzone, and Dionigi Bussola [1].

Fig.1. The Sacred Mountain of Varallo, Italy. Overview.

Fig.2. The Sacred Mountain of Varallo. The Square of Tribunals.


Fig.3. Chapel XXXIII. *Ecce Homo.*


Fig.4. Chapel XVII. *The Transfiguration of Christ on Mount Tabor.*

2. Chapel XVII monitoring set-up

The Acoustic Emission monitoring is conducted on the frescoed masonry walls of the Chapel XVII of the Sacred Mountain of Varallo: the Chapel of the Transfiguration of Christ on Mount Tabor (Fig.4). The construction of the Chapel XVII began in 1572, but the structure was completed only in 1647. In 1664 was built the lantern top as crowning.

The purpose of monitoring by means of AE sensors applied to the frescoed wall, is to detect the possible Acoustic Emission signals from a vertical crack and from a region of the wall in which the frescos show a detachment of plaster. The operations necessary for the AE sensors bonding to the wall are carried out by a group of restorers, which have prepared a film of Japanese paper, on the surface of which is coated a thin layer of "Paraloid".

The "Paraloid" is an acrylic resin (methyl acrylate soluble in ketones, esters, hydrocarbons and chlorinated hydrocarbons) and is used in the field of restoration as a consolidant at low concentrations (2,4%) or as an adhesive at higher concentrations. It allows an excellent waterproof performance and has the advantage of being reversible and long-term stable. The layer of "Paraloid" forms a good protective base for the AE sensors bonding with silicone glue. The sensors are applied to monitor both the vertical crack and the detachment of the plaster (Fig.5).

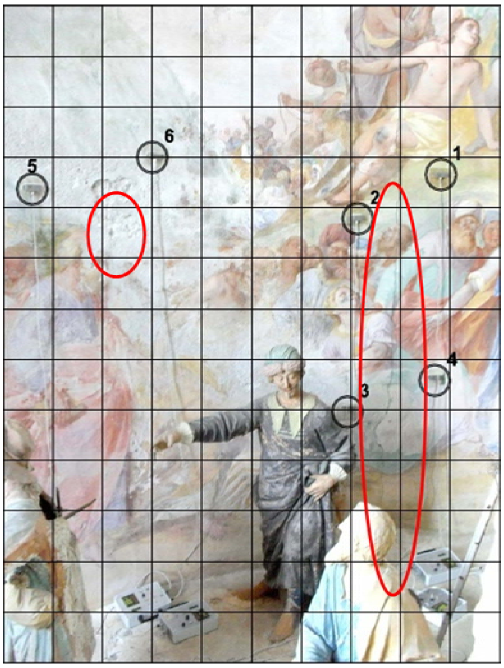

Fig.5. Chapel XVII. View of the Monitored Areas. Left Side: Sensors 5, 6, and the Frescos Detachment. Right Side: Sensors 1-4 and the Vertical Crack.

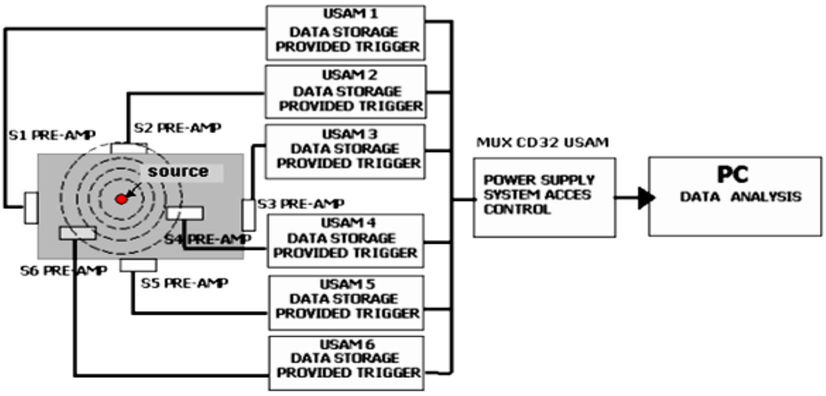

Fig.6. AE Acquisition System.

The Acoustic Emission acquisition system is shown schematically in Fig.6.

The piezoelectric transducers (PZT) are calibrated over a range of frequency between 50 kHz and 800 kHz. The USAM acquisition system consists of 6 pre-amplified sensors, 6 units of data storage provided of triggers, a central unit for the synchronization operations, internal clock and a trigger threshold. The obtained data are: progressive number of each signal, acquisition time, intensity, duration, number of oscillations over the threshold value [2,3].

4. AE and seismic events

Non-destructive testing methods are currently used to evaluate structural damage phenomena and to predict their development over time. In particular, the evaluation of damage in historic buildings is often a complex task [4,5]. It is essential to distinguish between stable damage patterns and damage in evolution toward a catastrophic collapse. Some structural damage can be triggered by events such as earthquakes. Furthermore, the limited ductility of the masonry, combined with the large size of this type of construction, provides a structural behavior rather fragile [6]. For these reasons, the damage evolution in time can be effectively evaluated by means of the Acoustic Emission technique [7,8,9,10].

Moreover, the statistical distribution of earthquakes shows a complicated behavior space–time, that reflects the complexities of the Earth's crust. Despite this complexity, there is a scaling law universally valid: the statistical distributions of frequency-magnitude of an earthquake provided by the Gutenberg-Richter (GR) law [11].

On the other hand, AE in materials and earthquakes in the crust are very similar and correlated in time, even if they are phenomena that occur at different scales [12]. In both cases there is a release of elastic energy from a source located in the medium: respectively the opening of micro cracks and the seismic hypocenter [13]. This similarity suggests an interpretation in which the seismic events and the AE events can be related in space and time. In this view is therefore possible to search for a correlation between the parameters related to AE and the regional seismicity. As a matter of fact, this approach can be used to identify the warning signals that precede a catastrophic event for a structure since, in many cases, these warning signals can be detected well in advance with respect to the time at which the undesired event will occur [14,15].

Most earthquakes have precursors, ie phenomena that in the short or long term change their activity before the earthquake. In the past, many precursors have been proposed but it is still not clear what is really reliable. Surely any operative scheme of prediction must be based on a combination of more clues. Recently, major efforts in the field of earthquake prediction have focused on the fluctuations of the physical parameters of the crustal rocks of the seismically active continental areas, and on regular intervals in the space-time distribution of earthquakes [16]. The variation in the rate of the regional seismicity is considered as a precursor in the long term. A region which had a small earthquake activity for a remarkable number of years is called "seismic gap". The "seismic gaps" are considered as potential sites for major earthquakes. On the other hand, the increasing pressure in the rock surface in the region of the epicenter produces numerous cracks before the final collapse and, as a result, it causes changes in the properties of rocks. Therefore, the drop in speed of seismic waves caused by the expansion of the rock becomes a significant precursor. Other precursors linked to the expansion of the rocks and the opening of cracks are the crustal tilt and elevation changes, the decrease of the electrical resistivity of the rocks, and the release of radon gas in the atmosphere, which requires small pores to propagate. As the process of damage develops, the water diffuses from the surrounding rocks in pores and micro cracks of increasing size, which in the meantime are forming. The moment the water fills the cracks, the speed of seismic waves grows, the soil lifting stops, the emission of radon from the new cracks is relieved, and the electrical resistivity decreases. The next stage is the beginning of the earthquake, which is immediately followed by several aftershocks in the surrounding area [7,16].

When a crack in the Earth's crust increases, the corresponding AE show progressively lower frequencies, up to abandon eventually the ultrasound field reaching the sonic range: this represents the well known phenomenon of seismic roar. Thus, AE techniques have the potential for effectively monitoring the spread of tensions through the earth's crust. In fact, Italian researchers collected continue AE recordings for many years in the Gran Sasso massif. It was noted a peak of the AE about 400 km away from the epicenter, many months before the occurrence of the earthquake in

Assisi [14,15]. Progressively lower frequencies of detected AE seemed consistent with the theory that high-frequency AE can be associated with the progress of small lesions of the crust, which later coalesce to form defects growing bigger and bigger. In order to correlate the peaks of AE activity to seismic precursors mentioned earlier, it was observed that the fumes of radon occur almost simultaneously with the AE peaks about 7-8 months before the earthquake. Therefore, the potential of earthquake prediction related to the AE monitoring appears promising, since the AE signals may be picked up in advance [14].

4.1. Correlation algorithms between AE and seismic events

Among the various studies on the earthquakes space-time correlation, there is a statistical method that allows to calculate the degree of correlation both in space and time between a series of AE and the local seismic recordings, collected in the same period. This analysis is based on the generalization of the space-time correlation known as the integral of Grassberger-Procaccia [17], defined as follows:

$$C(r,\tau) \equiv \frac{1}{N_{EQ}N_{AE}} \sum_{k=1}^{N_{EQ}} \sum_{j=1}^{N_{AE}} \Theta(r - |x_k - x_j|)\Theta(\tau - |t_k - t_j|) \tag{1}$$

where N_{AE} is the number of peaks of AE activity registered in site and in a defined time window, N_{EQ} is the number of earthquakes recorded in the surrounding area during the same time window, and Θ is the step function of Heaviside ($\Theta(x) = 0$ if $x \leq 0$, $\Theta(x) = 1$ if $x > 0$). The index k refers to the recorded seismic events $\{x_k, t_k\}$, while the index j refers to the recorded AE events $\{x_j, t_j\}$.

Therefore, between all possible pairs of recorded AE and seismic events, the sum expressed by the integral of Grassberger-Procaccia is valid for those having the epicentral distance $|x_k - x_j| \leq r$ and the temporal distance $|t_k - t_j| \leq \tau$. Hence, $C(r,\tau)$ is the probability of occurrence of two events, an earthquake and an AE event, whose mutual spatial distances are smaller than r and mutual temporal distances are smaller than τ.

Anyway, this approach does not consider the chronological order of the two types of event. Since the AE time series and the earthquake sequences are closely intertwined in the time domain, the problem of the predictive ability of the AE peaks is still open, and the records of noise could be the consequences of the progressive development of micro damage. However, a probabilistic response sought by considering the first AE events as precursors and later as aftershocks of an earthquake is utilized. This analysis is performed by using a modified correlation integral [7]:

$$C_{\pm}(r,\tau) \equiv \frac{1}{N_{EQ}N_{AE}} \sum_{k=1}^{N_{EQ}} \sum_{j=1}^{N_{AE}} \Theta\left(r - |x_k - x_j|\right)\Theta\left(\tau - |t_k - t_j|\right)\Theta\left(\pm\left(t_k - t_j\right)\right) \tag{2}$$

where "+" and "-" in the Heaviside function are used to take into account that the AE events could be respectively seismic precursors and aftershocks.

5. AE as seismic precursors in The Sacred Mountain of Varallo

5.1. AE monitoring periods

The AE collected data are grouped into two different time windows. The first time window starts from May 9, 2011 and finishes June 16, 2011. The second time window starts July 5, 2011 and finishes September 5, 2011. Both time windows shown in the following involve the monitoring of the vertical crack and of the frescos detachment [2,3].

5.2. Recognizing impending earthquakes by means of AE

In this section, referring to the theories introduced above, we obtain a correlation between seismic and acoustic events through the application of the modified integral of Grassberger-Procaccia.

The data series of AE analyzed are those related to the time periods listed above. The seismic events, taken from the website http://iside.rm.ingv.it/iside/standard/result.jsp?page=EVENTS#result (seismic catalog of INGV, National Institute of Geophysics and Volcanology), are selected introducing search parameters relating to the defined AE monitoring periods and to a radius of 100 km, close to the site of Sacred Mountain of Varallo (Fig.7).

Looking at the temporal distribution of earthquakes in relation to the cumulative AE trend, it can be seen a certain correspondence between AE peaks and earthquake events (Fig.8,9). By applying to the data series the modified correlation integral of Grassberger-Procaccia, we obtain the cumulative probabilities, depending on the radius of interest *r* and on the interval of occurrence *t*, considering the peak of Acoustic Emission both as earthquake precursor and as aftershock (Tables 1,2,3,4).

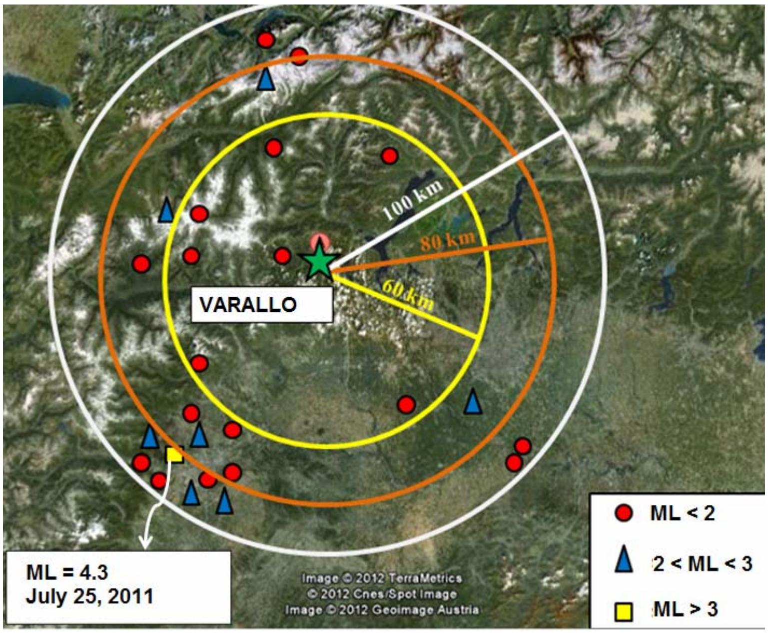

Fig.7. Seisimic Events around Varallo (Italy) from May, 2011 to September, 2011.

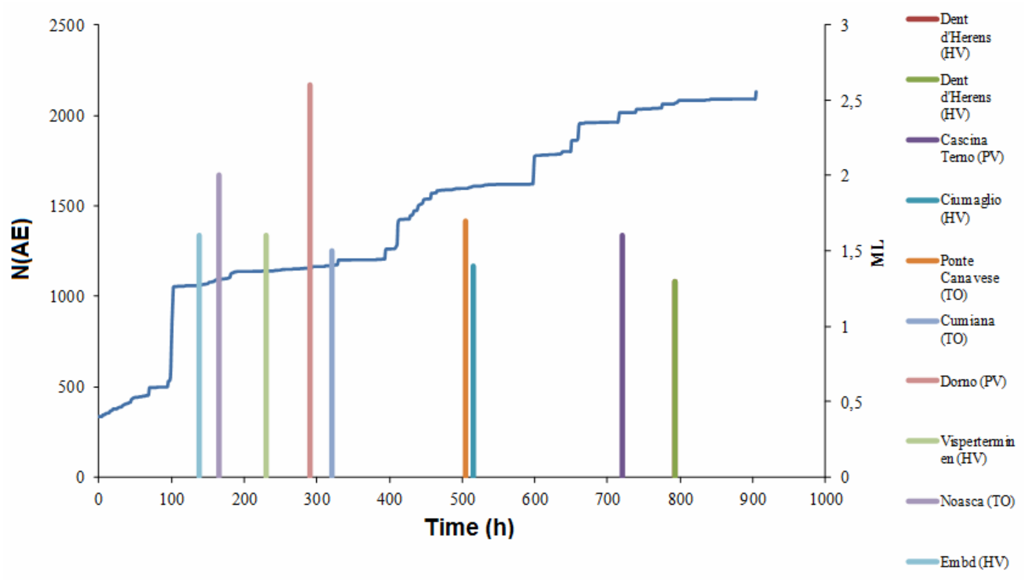

Fig.8. Sacred Mountain of Varallo: Cumulated AE and Seisimic Events from May 9, 2011 to June 16, 2011.

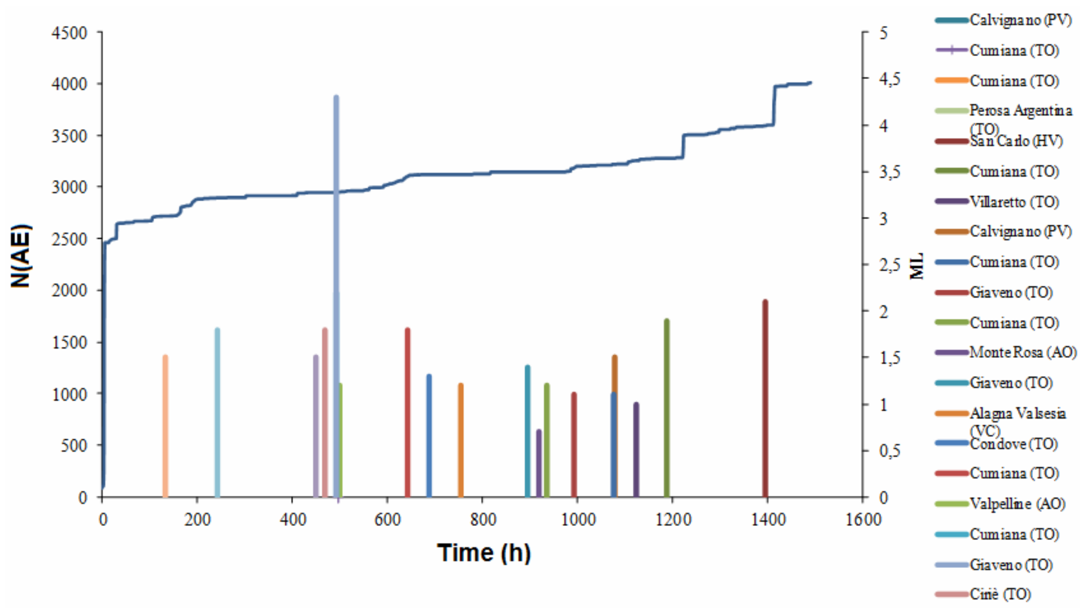

Fig.9. Sacred Mountain of Varallo: Cumulated AE and Seisimic Events from July 5, 2011 to September 5, 2011.

	60 km	**80 km**	**100 km**
1 week	0.0339	0.1121	0.2018
2 weeks	0.0772	0.2130	0.3661
3 weeks	0.1228	0.3018	0.4875
4 weeks	0.1487	0.3661	0.5549
5 weeks	0.1630	0.4321	0.6210

Table 1. Cumulative Probability C^{+}: AE as Precursor from May 9, 2011 to June 16, 2011.

	60 km	80 km	100 km
1 week	0.0254	0.0732	0.1437
2 weeks	0.0357	0.1196	0.2629
3 weeks	0.0371	0.1509	0.3362
4 weeks	0.0371	0.1652	0.3732
5 weeks	0.0371	0.1665	0.3768

Table 2. Cumulative Probability C^-: AE as Aftershock from May 9, 2011 to June 16, 2011

	60 km	80 km	100 km
1 week	0.0075	0.0278	0.0846
2 weeks	0.0184	0.0552	0.1896
3 weeks	0.0239	0.0833	0.3222
4 weeks	0.0346	0.1040	0.3841
5 weeks	0.0498	0.1210	0.4435
6 weeks	0.0557	0.1268	0.5130
7 weeks	0.0557	0.1268	0.5497
8 weeks	0.0557	0.1268	0.5607
9 weeks	0.0557	0.1268	0.5657

Table 3. Cumulative Probability C^+: AE as Precursor from July 5, 2011 to September 5, 2011

	60 km	80 km	100 km
1 week	0.0045	0.0298	0.1192
2 weeks	0.0132	0.0465	0.1916
3 weeks	0.0234	0.0717	0.2592
4 weeks	0.0301	0.0970	0.3251
5 weeks	0.0313	0.1114	0.3737
6 weeks	0.0313	0.1246	0.4164
7 weeks	0.0313	0.1299	0.4283
8 weeks	0.0313	0.1336	0.4333
9 weeks	0.0313	0.1341	0.4338

Table 4. Cumulative Probability C^-: AE as Aftershock from July 5, 2011 to September 5, 2011

Comparing the probability values obtained for the period May-June, it can be seen that, regardless of the distance and of the correlation time, the probability that a seismic event follows a peak of Acoustic Emission is always greater than the probability that the same AE peak is an effect of the damage caused by the earthquake (Tables 1,2). In practice, we see that the monitored structure behaves as a good seismic receptor.

It is interesting to note that, for both monitoring periods, within a radius of 60 km from the monitored site, the AE signal still plays its role as a seismic precursor. On the contrary at 80 km and 100 km, the AE behavior follows the variation of the time windows (Tables 3,4). In particular, we can observe a clear reversal of the AE signal behavior from precursor to aftershock for the second monitoring period (July-September): at 60 km there was a tendency for AE to anticipate earthquakes even though they are effectively correlated only in the long term; at 80 km they are precursive signals only in the short term; at 100 km we see immediately the reversal outlined above, from precursor behavior to aftershock.

In any case, it is worth of the further investigations distinguishing environmental contributions to AE activity on the Chapel XVII due to crustal trembling (external source) from contributions due to structural damage (inner source).

To investigate the nature of these results, true progress can be realistically achieved by discriminating the signals recorded on the basis of a predetermined threshold both in frequency and amplitude, consistently with the physical nature of Acoustic Emissions detected by the sensors. Looking at the USAM data stored, a good choice to discriminate the signals nature, is setting a threshold frequency −for example 30 kHz, which divides the field VLF (Very Low Frequency) from the field LF (Low Frequency)− and a purposeful threshold signal amplitude.

It seems reasonable even from a theoretical point of view, that low frequencies allow the diffusion of the elastic waves in the masonry bulk, both intact or damaged. On the other side, low amplitudes are reasonably related to the fact that an event captured by AE sensors on the monitored structure may have originated from a source physically distant from the site monitored (seismic hypocenter) and therefore is subject to the laws of amplitude damping.

6. Conclusions

Besides the canonical use in Non-destructive Tests, the heuristic potential of AE monitoring of civil structures for earthquakes prediction appears very intriguing. Starting from the assumption that any structure should not be regarded as separated from its environoment, a method of correlating AE activity on the Renaissance Complex of the Sacred Mountain of Varallo subjected to a long-term monitoring with regional seismicity is investigated. Two qualitatively very similar phenomena such as Acoustic Emission and earthquakes become two aspects of a unique phenomenon which looks self-similar.

Furthermore, in this work by applying the modified Grassberger-Procaccia correlation algorithm −with the aim of explaining the correlation between regional seismicity and Acoustic Emission emerging from the Chapel XVII of the Sacred Mountain of Varallo− it is observed that the structure is a good sensitive receptors for earthquakes occurring within a radius of about 60 km.

In any case, it is worth of the further investigations distinguishing environmental contributions to AE activity on the Chapel XVII due to crustal trembling (external source) from contributions due to structural damage (inner source).

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