On the fusion between interferometric satellite data and in situ measurements for the monitoring of built heritage

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Abstract. Over the past decades, earthquakes, and other catastrophic events has highlighted the increasingly growing vulnerability of infrastructures, buildings, and architectural heritage structures. In addition to catastrophic events, often related to climate change, another fundamental aspect is represented by the lack of maintenance and monitoring of the asset. In the field of preservation of buildings and infrastructures, Structural Health Monitoring techniques can effectively contribute to the assessment of the health state of structures.

In the case of structural monitoring using data-driven approaches, since the information depends on the type of data used, a great resource for knowing as much as possible about the structure is represented by the combination of multiple data. Thanks to the integration of different types of data, it is possible to know the conditions of the structure in more detail as different aspects can be combined.

In this context, together with the data obtained from in situ monitoring systems, data obtained remotely, i.e. satellite data, can be used. There are different types of satellite data that can be used to study different aspects, e.g., multispectral data, hyperspectral data, and interferometric data, and they can make different contribution to civil engineering. In this paper, the exploitability of open-source interferometric data is investigated and they are studied for the purpose of their integration with data obtained from a monitoring system installed on a monumental building, in order to monitor and observe structural health.

Keywords: *SHM, Data fusion, In situ data, InSAR data, Built Heritage*

Introduction

Nowadays, Structural Health Monitoring (SHM) techniques are very widespread and they are increasingly establishing as an effective tool for observing and monitoring health conditions of structures. This is also due to the evident fragility and vulnerability of buildings, infrastructures and architectural heritage caused by various types of factors including inadequate maintenance, exceptional natural events, which are recently becoming more and more frequent, and also insufficient knowledge of the assets. Indeed, regarding the last aspect, the information available on a structure often refers to the characteristics it had at the time of design, while information regarding the evolution of the structural conditions over time is rarer. This information can be collected through data from different sources. Firstly, conventional methods entail acquiring on-site data by installing sensors for short-term (one-time or periodic monitoring) or long-term (permanent monitoring systems) durations directly on the structure. This approach is frequently enhanced by gathering environmental data from instruments at meteorological stations situated near the structure of interest. In addition to these methods, the utilization of remotely recorded data has seen a notable rise in recent years, enabling the acquisition of highly precise information about either the surroundings of the structure and the structure itself. Satellite Interferometric Synthetic Aperture Radar (InSAR) [1] data allows to estimate displacements in the order of millimetres along the Line of Sight (LoS). Some first applications of these satellite data for SHM purposes has been implemented in the past to detect anomalies in structures [2], infrastructures [3],[4] or urban areas [5],[6]. Despite these applications, challenges persist when structural monitoring involves the use of InSAR data for SHM activities applied to the built environment, such as seismic monitoring of structures. Hence, further investigations and applications will be necessary.

Beyond some difficulties that may be encountered in the use of InSAr data, the availability of different types of data for the same structure undoubtedly represents a precious source for obtaining information. The combination of such data would enable the gathering of structural knowledge from diverse perspectives, facilitating the achievement of a comprehensive understanding of the structural conditions. Indeed, the procedure of data fusion, realized through the integration of data from multiple sources, has the potential to yield information of greater accuracy, coherence, and utility compared to that furnished by each individual data source.

This paper presents an analysis of different kind of data. The analysed data originates from an in situ monitoring system equipped with dynamic, static, and environmental sensors and from satellite remote sensing. The case study is a monumental structure located in Italy, specifically the Sanctuary of Vicoforte in Piedmont, equipped with a sophisticated monitoring system.

1. Data integration for Structural Health Monitoring of structures

In the context of SHM, when data driven methods are used, the kind of data available represents a fundamental point. The potential lies in being able to incorporate different types of data, allowing to acquire information on various aspects of the structure and get a general perception of its health state. For data fusion it would be useful to have data acquired in situ such as those acquired by static sensors (crack meters, load cells, thermometers, etc.) and dynamic sensors (accelerometers) and perhaps add other types of data that do not require the installation of sensors such as InSAR data. Nevertheless, regarding in situ data acquisition, there is a scarcity of buildings outfitted with such sensors due to their costs.

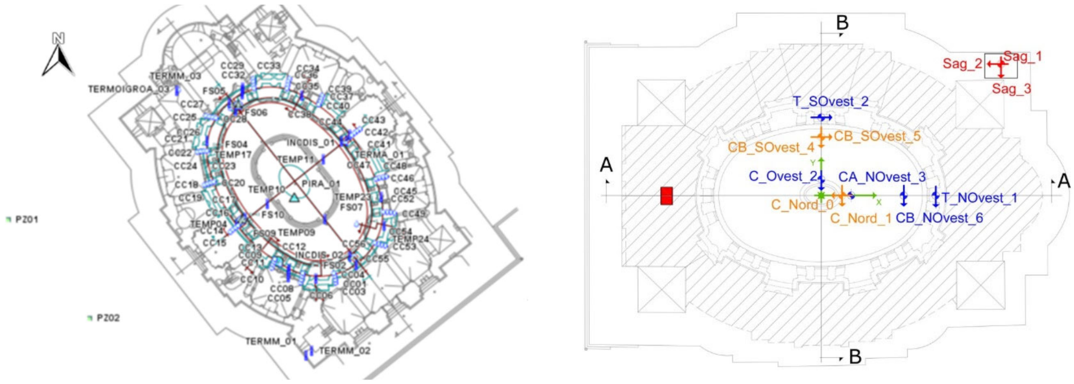
1.1 Case study: the Sanctuary of Vicoforte

(a) *(b)* *(c)*

Figure 1. The Sanctuary of Vicoforte: (a) Top view (Pixelshop - stock.adobe.com), (b) façade, and (c) internal view of the oval dome

Among the few buildings equipped with monitoring systems is the Sanctuary of Vicoforte, an impressive monumental building in Piedmont characterized by the largest masonry oval dome in the world [7]. The building is characterized by both a static system and a dynamic system. The first was installed in 2004 and was restored last year after a few years of lack of data, while the second has been in operation since 2015.

2. Data of in situ monitoring system



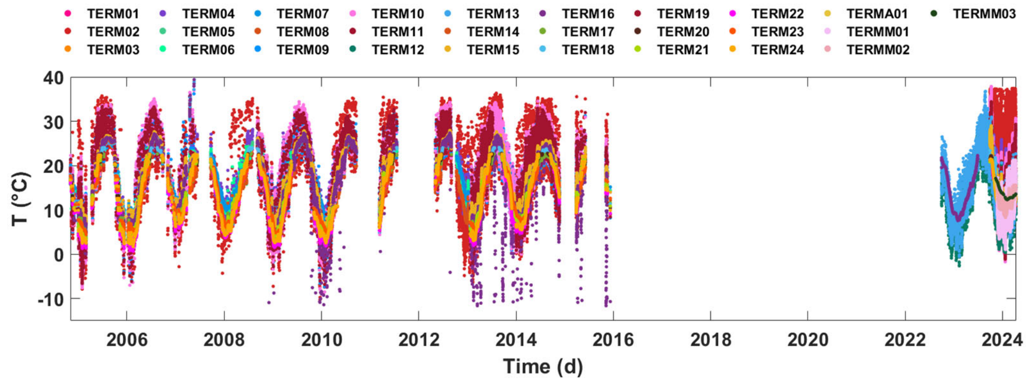
(a) *(b)*

Figure 2. Monitoring system of the Sanctuary of Vicoforte: (a) Static monitoring and (b) Dynamic monitoring

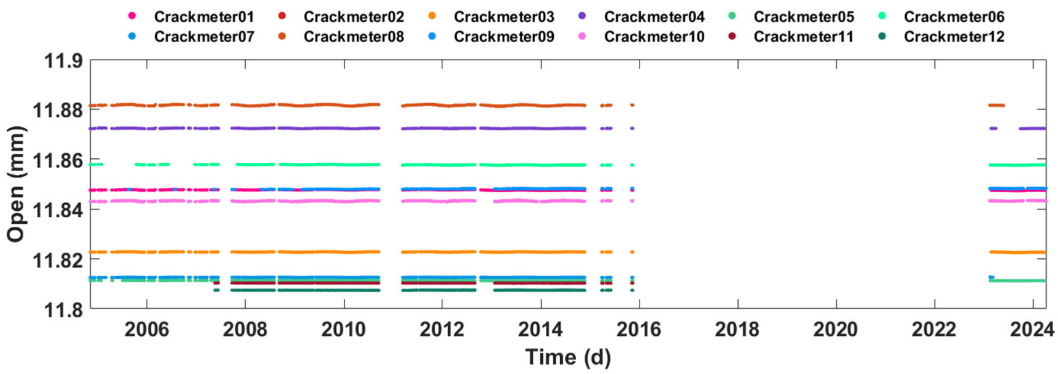
The monitoring system of the Vicoforte of Sanctuary is made up as follows:

- Static system characterized by 28 thermometers, 2 laser distance-meters, 2 distance-meters, 4 piezometers, 20 pressure cells, 56 load cells, 12 crack-meters, 5 thermo-hygrometers, 1 barometer and 1 pyranometer.
- Dynamic system characterized by 12 accelerometers that allow to obtain the natural frequencies of the structure through a process of identification [8].

A fairly complete presentation of the data acquired by these sensors, before the restoration and recent modifications, is presented in [9]. For the sake of brevity, in this paper, only some data currently available are shown and the focus is on static data. The following figure shows the data acquired by thermometers and crack-meters from 2004 until today, after having subjected them to processing and cleaning of outliers.



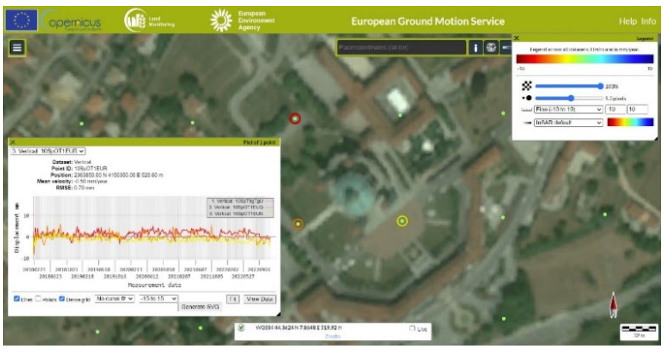
(a)

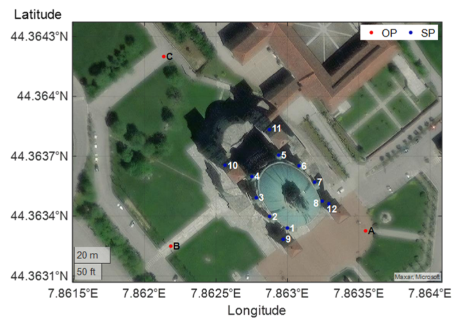


(b)

Figure 3. (a) Time series of temperature, and (b) Time series of cracks opening

3. Open source InSAR data

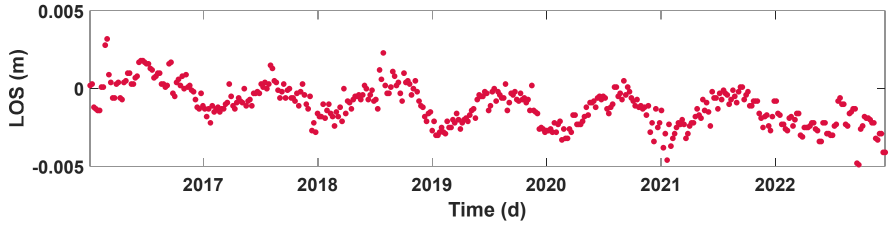




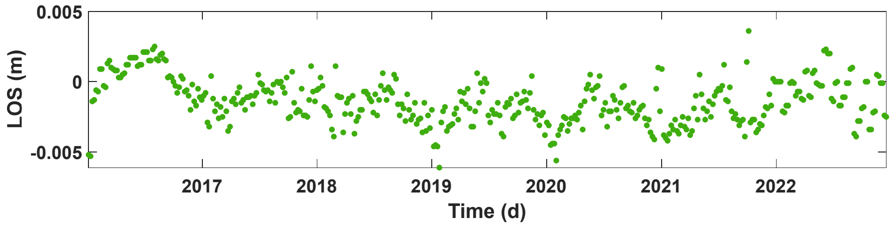
(a) *(b)*

Figure 4. (a) EGMS platform, and (b) Observed Points A,B and of EGMS and Salient Points on the Sanctuary of Vicoforte

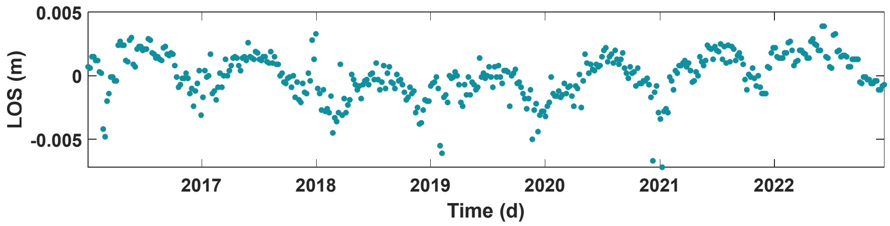
Regarding the InSAR data, they were collected through the European Global Land Service (EGMS) platform, provided by the European Space Agency (ESA), which offers various types of data to users for free. Near the Sanctuary of Vicoforte, the time series of displacements are available for 3 observed points (Figure 4a), indicated as points A, B and C in Figure 4b. These points coincide with street lights (Figure 5), having geometric and material characteristics that facilitate signal reflection; thus, SAR on the satellite is capable of detecting their displacements. In Figure 5 the time series of LOS for the observed points are shown.



(a) *(b)*



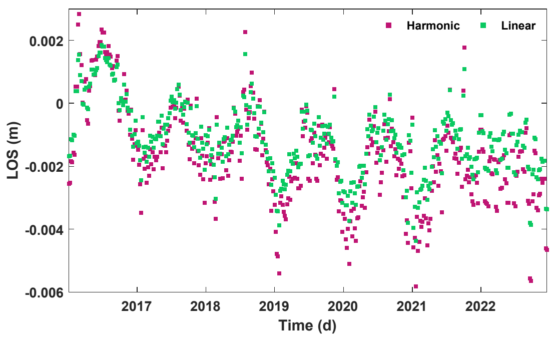
(c) *(d)*



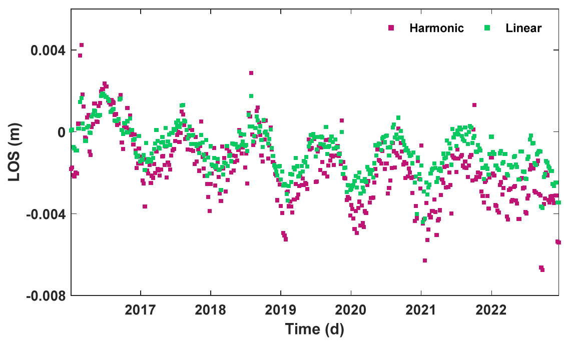
(e) *(f)*

Figure 5. (a) Time series of LOS for point A,(b) Point A,(c) Time series of LOS for point B,(d) Point B,(e) Time series of LOS for point C, and (f) Point C

4. Analysis and results



(a)



(b)

Figure 6. Time series of Salient Point: (a)time series of Salient Point 1 obtained through harmonic and linear interpolation, and (b) time series of Salient Point 8 obtained through harmonic and linear interpolation

After observing the time series of the points close to the Sanctuary of Vicoforte, a linear and harmonic interpolation procedure were performed, corresponding to 12 points on the Sanctuary, as illustrated in Figure 4b. At this point, once the time series of the data acquired in situ and the InSAR data are known, it would be useful to make a comparison between them and a correlation that would allow to partially understand a possible relationship between the phenomena they represent. However, by analysing the periods in which the time series of available data are present, overlapping problems emerge; indeed there are no periods of overlap, at the moment, between the in situ and satellite data. For this reason, it is useful to carry out autocorrelation studies to analyse how much each time series is autocorrelated and therefore similar to itself. Using this method, given the lack of contemporaneity between the data, it is possible to understand whether the available time series can be used and whether they can be superimposed, even if they are not contemporary. Performing an autocorrelation analysis entails examining the presence of periodic patterns, or seasonality, within the dataset. Thus, the sample autocorrelation (ACF) and the partial autocorrelation analysis (PACF) have been performed [10]. The ACF plot shows the correlation of a time series with itself at different lags; this kind of analysis can be useful to understand whether seasonal pattern and trends are present. The PACF is similar to ACF, but it analyses shorter lags respect to the ACF. Assuming a high autocorrelation in the case of temperature data, given the high seasonality of this type of data, it was decided to analyse the data of displacements and cracks opening. In Figure 7 the ACF and PACF plots for the InSAR data are presented, while Figure 8 shows those of cracks opening acquired from some crack-meters (1,3 and 8) installed on the Sanctuary of Vicoforte. Observing the results of the autocorrelation analysis, it is noted that, both in the case of InSAR data and those of crack meters, the ACF values decrease slowly. It decreases more in the case of InSAR data (Figure 7), while in the case of crack openings (Figure 8) the ACF takes on almost constant values; this could be because the data values oscillate in very narrow ranges without large oscillations (Figure 3b). This slow decay in the ACF generally indicates the presence of a trend in the time series.

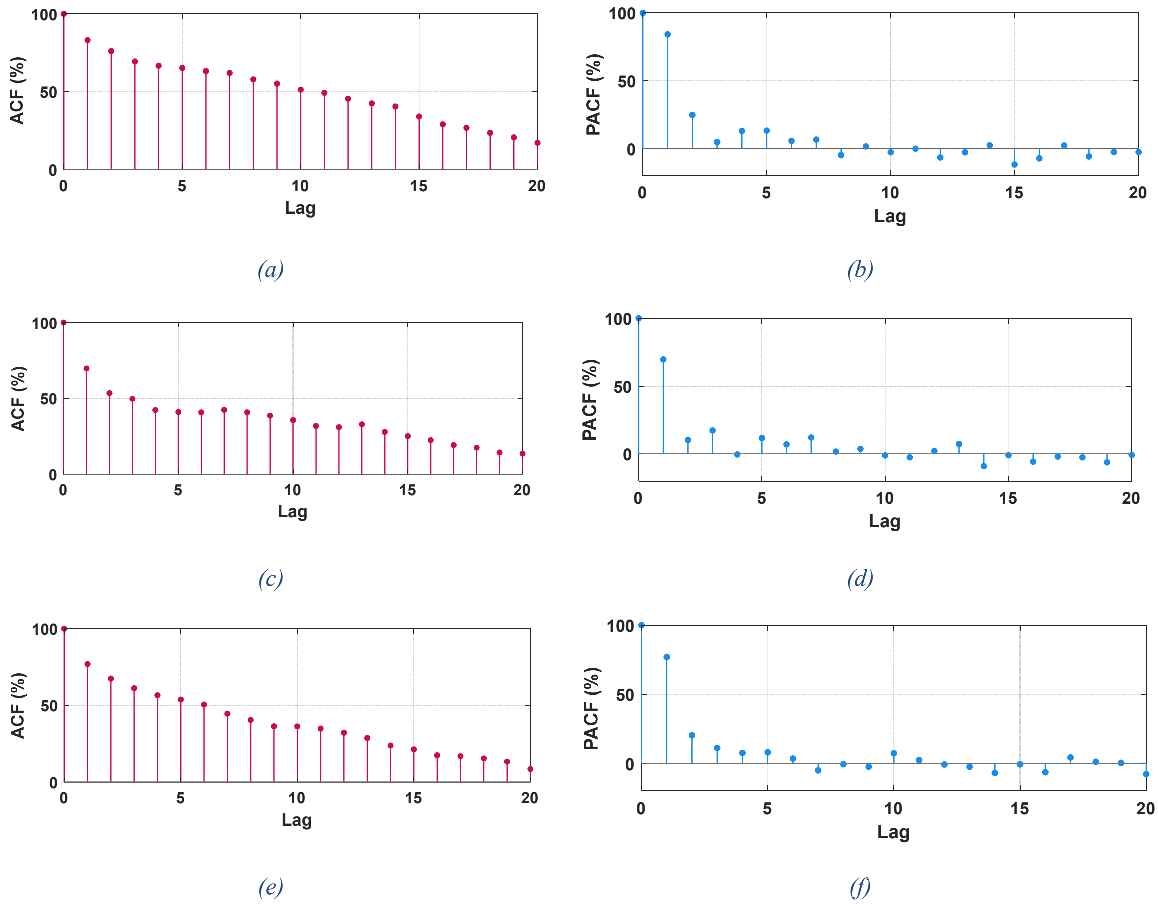


Figure 7. Sample autocorrelation and Partial Autocorrelation Analysis of InSAR time series: (a)ACF of Point A ,(b)PACF of Point A,(c)ACF of Point B,(d)PACF of Point B,(e)ACF of Point C, and (f) PACF of Point C

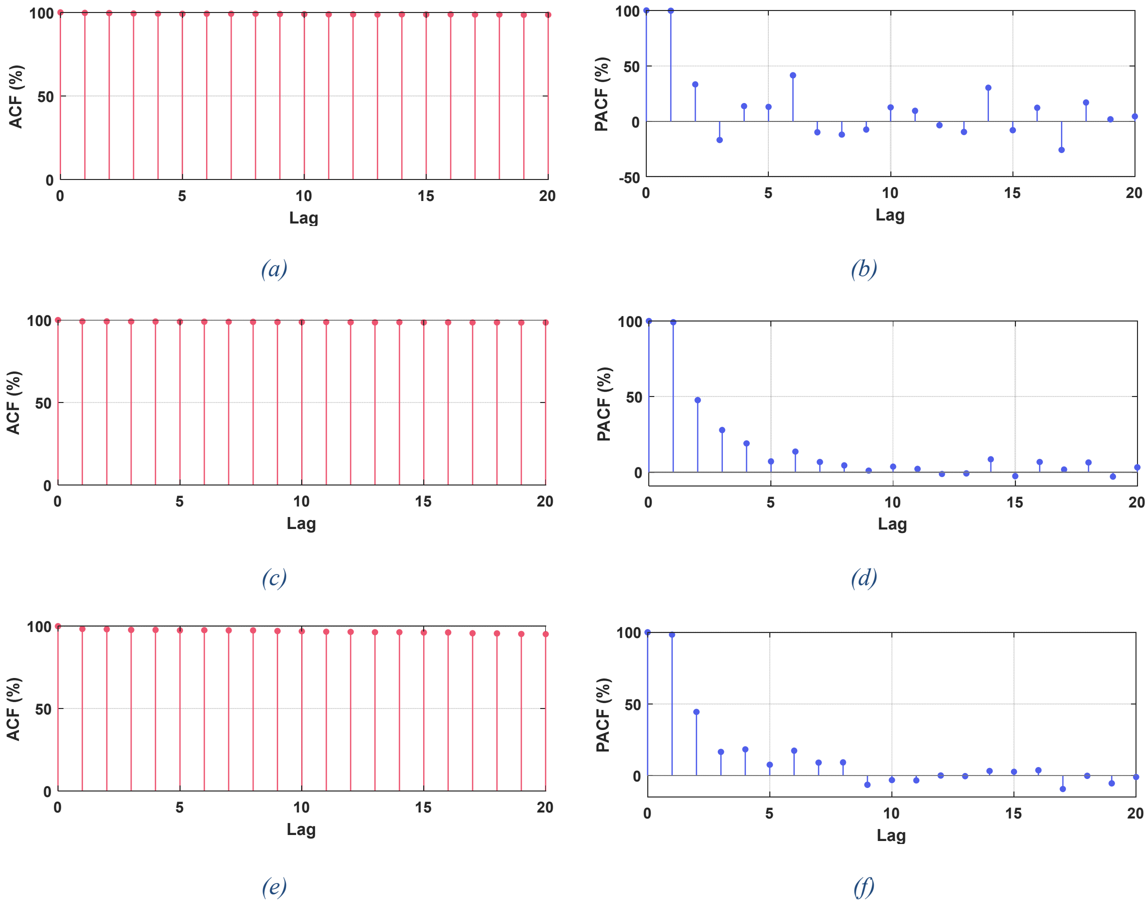


Figure 8. Sample autocorrelation and Partial Autocorrelation Analysis of crack openings time series: (a)ACF of crack meters 1,(b)PACF of crack meters 1,(c)ACF of crack meters 3,(d)PACF of crack meters 3,(e)ACF of crack meters 8, and (f) PACF of crack meters 8

Observing the PACF graphs, it is found the presence of a clear break at lag 1, this represents the presence of periodicity or seasonality in the data. Therefore, it would seem that they repeat with a delay of 1. From these first autocorrelation analyses it could be said that, since the data are periodic, they could be correlated without using contemporary time series.

5. Conclusions

The paper presents the study of different types of data in order to fuse and integrate them to better understand the health state of a structure. This is because by combining multiple types of data it is possible to have a more complete and integrated view of the various aspects. The Sanctuary of Vicoforte, equipped with an in situ monitoring system to which InSAR data obtained from satellite remote sensing are added, is used as case study. However, at present, the data used are not contemporaneous with each other. For this reason, waiting for contemporary data to be collected and then correlated, an autocorrelation study was carried out to observe how much the time series are correlated to themselves, so as to better understand whether they can be combined with each other despite the absence of contemporaneity. From these first autocorrelation analyses it could be said that, since the data are periodic, they could be correlated without using synchronous series.

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