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Interferometric Satellite Data For The Structural Health Monitoring Of Infrastructures

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Abstract

Over the past few years, some catastrophic events have highlighted the vulnerability of Italian infrastructures. Bridges and viaducts are increasingly fragile both due to exceptional events (earthquakes, floods, etc.) but also due to ageing. In this context, Structural Health Monitoring (SHM) systems can effectively contribute to the assessment of the health state of structures because they allow the detection of structural anomalies that may indicate possible damage. However, there are very few structures equipped with permanent monitoring systems. Although their advantages are well known, the high costs have not yet allowed their widespread use. For these reasons, it is important to experiment with new technologies and methodologies in order to study and observe the structural behavior of infrastructures and structures. Since installing permanent monitoring systems in situ is very expensive, new easily accessible and low-cost data sources are being investigated. Among these, satellite remote sensing data have taken on particular relevance. They are often applied to study environmental phenomena (i.e. fires, drought, melting glaciers, etc…) and their application in SHM fields is quite recent. 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 help civil engineering to better understand the health conditions in which the structures are.
In this paper, interferometric (InSAR) data of European Ground Motion Service (EGMS) acquired by Sentinel-1 are used in order to observe and analyze the presence of displacements before tragic events in case of bridges and viaducts.

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1. Introduction

In the last few years, catastrophic events have increasingly highlighted the fragility and vulnerability of the infrastructures, buildings, and architectural heritage structures. With reference to urban areas, entire areas have demonstrate to be particularly exposed to natural phenomena caused by climate change, such as floods and landslides, but also by exceptional events such as earthquakes. This can certainly be attributed to the exceptional nature of the events, but on the other hand, very often, the lack or inadequacy of monitoring and maintenance have also contributed to worsening the situation. In this context, there is an increasing awareness of the need to keep under observation the structures, indeed in Italy new codes regarding the monitoring and maintenance of bridges and viaducts were issued last years, Ministero delle Infrastrutture e dei Trasporti & Consiglio Superiore dei Lavori Pubblici, (2020), and to develop techniques that can allow the health state of structures to be kept under observation and control. From the latter, arises the demand to find new methodologies to integrate heterogeneous data for Structural Health Monitoring (SHM) purposes in order to collect as much information as possible. Among the different type of data, the dynamic monitoring in situ can provide information on the global behavior of the structure, through the estimates of natural frequencies. From the other side, the use of satellite remote sensing data is becoming a considerable opportunity for SHM. In particular, satellite Interferometric Synthetic Aperture Radar (InSAR), Rodriguez & Martin, (1992) information allows the estimate of displacements in the order of millimeters along the Line of Sight (LoS). There are different types of satellite data including multispectral and hyperspectral, as well as interferometric. As regards the latter, they are the most used among satellite data and some first applications of satellite interferometric data for SHM purposes have been implemented in the past to detect anomalies in single structures, Sohn et al., (1999); Tang et al., (2016), or infrastructures, Lazecky et al., (2015); Milillo et al., (2019) or to detect entire urban areas Arangio et al., (2014); Bonano et al., (2013); Cavalagli et al., (2019); Cigna et al., (2014); Lenticchia et al., (2021); Zhu et al., (2018). Despite these applications, since satellite data was created for purposes other than structural monitoring, there are still many challenges when contemplating the synergistic integration of InSAR satellite data and in situ dynamic data for SHM tasks applied to the built environment in monitoring. Although InSAR data are the most used among satellite data, they do not have a low cost, or rather they can only be accessible in certain cases and situations, and a large computational effort is required to obtain them. Most recently, the European Ground Motion Service (EGMS) has activated a platform where it is possible to access and download the InSAR data acquired by the Sentinel-1 (S1) satellite of the Copernicus program for free.
In this paper, EGMS satellite data, Kotzerke et al., (2022), are presented and illustrated, and a study of these data for their application and exploitation for infrastructures is reported. The paper is structured as follows: in Section 2 the EGMS data are presented as well as their general applications. Section 3 reports the method followed by the authors for the application of the data. In Section 4 the application on case study is presented. In Section 5 the results of the study are reported and finally in Section 6 the conclusions are reported.

2. Interferometric data and general applications

EGMS is the latest component of the Copernicus Land Monitoring Service (CLMS) and its baseline is from February 2015 to December 2020. The measured physical data, although elaborated following different levels of processing, is the displacement of a point gathered by satellite. The use of two different orbits allows the LoS displacement to be projected along two directions. The methodology utilises multi-interferogram techniques analysing time series of differential full-resolution Sentinel-1- based SAR interferograms to minimise noise related to different sources and to derive displacements over time and average velocities for individual Measurement Points (MPs), Kotzerke et al., (2022). The data is freely available to anyone interested in ground motion data and can be used for a variety of purposes. Furthermore, they are characterized by high measurement precision. On the EGMS website InSAR data is provided in three different forms: *basic,* it provides InSAR displacement data provided in the satellite Line-of-Sight (LOS), with annotated geo-localisation and quality measures per measurement point; *calibrated,* it is considered the main EGMS product as it serves the needs of most users. It is fundamentally the same as the Basic product but enhanced by the InSAR MPs displacement values being referenced to model derived from Global Navigation Satellite System (GNSS) time-series data, thereby making the InSAR measurements absolute. *Ortho*, it exploits the discrete look-angles provided by the Calibrated product to derive two further layers; one of purely vertical displacements, the other of purely east-west displacements.

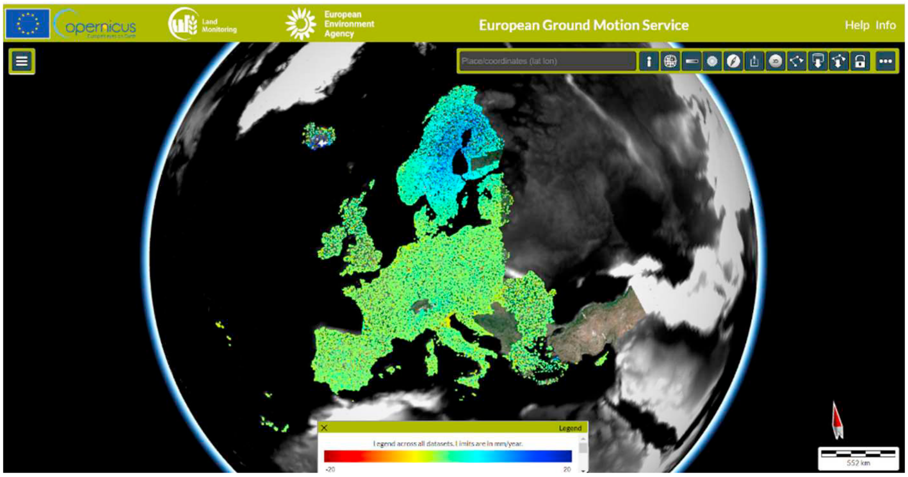


Fig. 1 EGMS platform with points distributed on the whole Europe territory

For the present study, the authors focused their attention on ortho data, and in particular to vertical ones. Data is represented in 100 m x 100 m output resolution cells to provide robustness plus reliability and match other existing CLMS datasets. The ortho products are not available in the case of accentuated topographic reliefs and in these cases there is not 100% coverage. Regarding the time sampling, in general, the temporal sampling of the satellite tracks contributing to the ortho product is not aligned. This happens because calibrated products, from which ortho are derived, exhibit acquisition patterns shifted in times on a track basis. Moreover, there may be holes in the datasets (e.g., missed acquisition, especially in 2015). In order to define a common temporal grid, for the baseline all time-series will start on January 2016 and end on December 2022, with regular six-day temporal sampling with origin on 3-April-2014 (launch date of S1A). A regular sampling will be maintained whenever possible, even if, in correspondence of huge gaps in the calibrated products time series used to generate the ortho level, customized solutions may be adopted. It is possible to use the data presented in the EGMS platform in multiple applications, from the monitoring of landslides, to that of infrastructures, dams, tunnel excavations and architectural heritage.

3. Methodology

EGMS data are a baseline for the investigation of active movements both along linear infrastructure and in their surroundings. They can offer a general overview of those phenomena that may endanger and damage an infrastructure and they can be useful to monitor the surroundings of a critical infrastructures. However, EGMS products are not capable of providing data for structural investigations and may not be accurate enough for specific, individual assessments, Kotzerke et al., (2022). It has always be kept in mind that these data cannot follow any type of engineering operation in real time and has limitations in vegetated areas and may not be accurate enough for the structural assessment of individual structures affected by movement induced by the engineering work. Certainly, they can be useful in the long-term monitoring of phenomena that could put the safety of structures at risk. The EGMS data are available base on the MPs present on the territory and that are able to reflect the signal. For this reason, it is not guaranteed that there will be the specific points wanted to be analyze on a structure or infrastructure. Therefore, two situations can occur: in the first case, the MPs are measured directly on the structure or infrastructure; while, in the second case, the MPs are measured around the structure and therefore they correspond not to it, but to the surrounding soil. In the latter case, the analysis could be based on an interpolation among the MPs which could be able to provide data on points of interest.

4. Application to case study

The case study considered in this paper is the Viadotto Imera I located in Sicily on the A19 highway near Scillato and Caltavuturo (PA) and it extends for 2 km in length. It is constituted by two similar decks, i.e. right and left deck, respectively direction towards Catania and direction towards Palermo. It is sadly known due to the collapse occurred in 2015 due to a landslide in the surrounding area; during which one of the pylons of the right desk tilted, damaging five piers and six spans and collapsing on the left deck. The latter was affected by a reversible displacement, as soon as the spans of the right deck were removed, the left one returned to its original position, but with some defects. Indeed, with reference to pier 9 of the left deck, it is characterized by cracks that run along its entire perimeter. Therefore, the structure observed today is the result of reconstruction work.

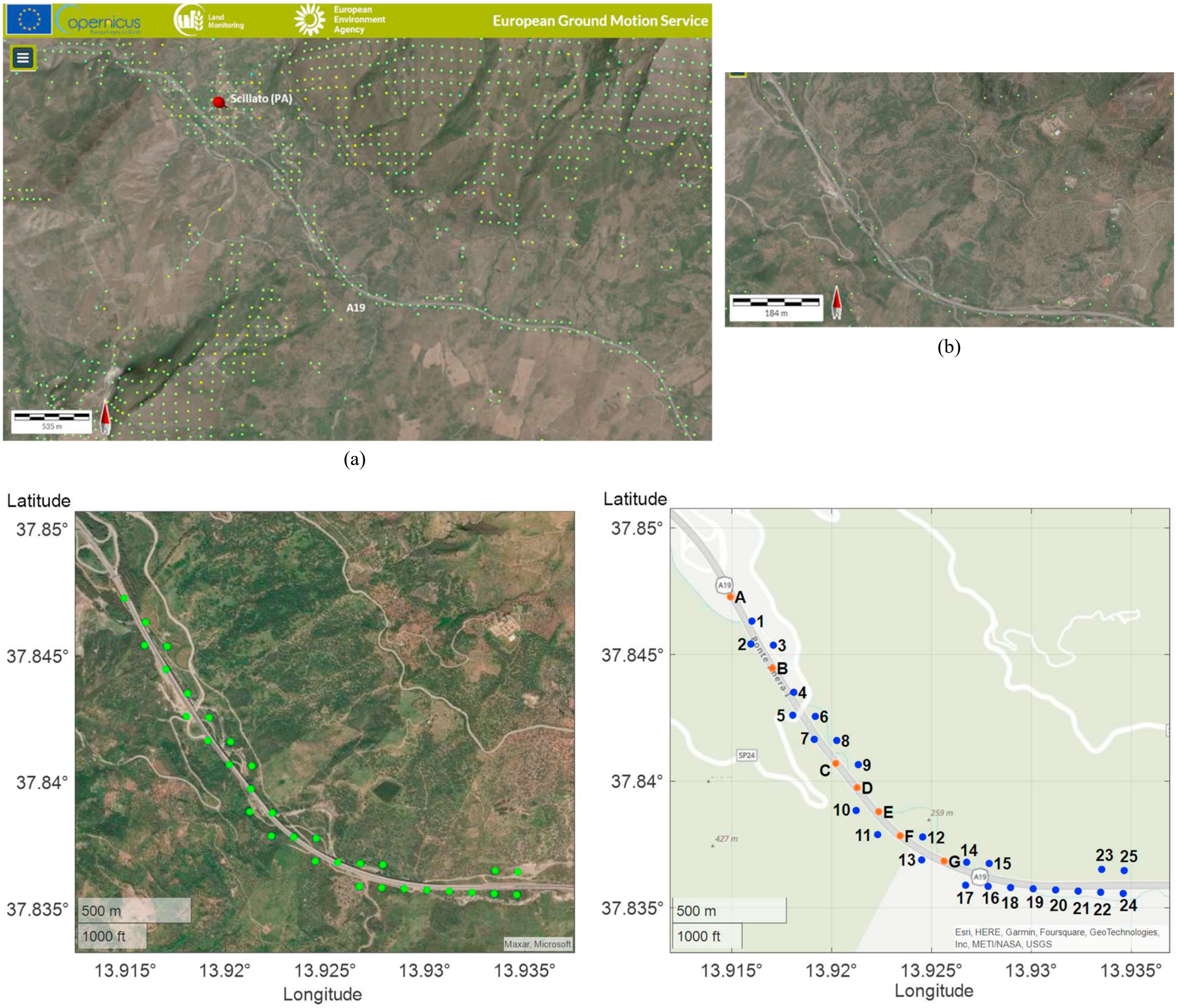
(a)

(b)

Fig. 2 Viadotto Imera I: (a) Right deck, steel construction after collapse; (b) Left desk, pre-stressed reinforced concrete

Nowadays, the viaduct is made up: right desk is constituted pre-stressed reinforced concrete (spans 1-7,11-15 and 18-41), steel beams and pre-stressed reinforced concrete (spans 8-10) and a steel caisson (spans 16-17); while, the left desk is constituted by pre-stressed reinforced concrete (spans 1-18 and 21-44) and a steel caisson (spans 19-20). In the case of the right deck, with the new steel structure it was possible to obtain three spans with a much wider span than the previous six spans. Fig. 2 shows two different part of the desk of the Viadotto Imera, in Fig. 2 (a) it is shown the steel and pre-stressed reinforced concrete structure of the right desk made after the collapse, while in Fig. 2 (b) it is shown the left desk of the viaduct in pre-stressed reinforced concrete. Given the length of the viaduct, EGMS data is available both on the deck and in the surrounding area, most of which corresponds to the latter case. Once the area was searched and the available points observed, they were collected in order to deepen the study. It was possible to collect data relating to 32 points with their time series from 2015 to 2022. Among these points, 7 are acquired directly on the viaduct deck and they are indicated with the letters A-G and belonging to the orange group in Fig. 3d, while the remaining points belonging to the surrounding area are indicated with numbers from 1 to 25 and belong to the blue group in Fig. 3d. Once the available points had been analysed, it was checked whether they corresponded to any specific part of the viaduct. However, the points on the viaduct all correspond to the pre-stressed reinforced concrete part and they are far from the area affected by the collapse. Thus, additional points were selected because they were considered significant for the analysis of the displacements of the structure. Points belonging to the different structural typologies were chosen, therefore pre-stressed reinforced concrete and steel over the entire length of the bridge, and then a point was selected near pier 9 of the left deck. In this way it was possible to analyse the time series of the points belonging to the three different groups, i.e. points on the deck, points in the surrounding area and salient points indicated in Fig. 4 as P1 to P6. Time histories of salient points was obtained by interpolation based on linear model and harmonic model. Before applying the interpolation process, it was taken into account which group the chosen points were closest to.

Consequently, the points P1 P2 P3 P6 were interpolated within the group of points on the surrounding area, while the other two were interpolated on the points acquired directly on the deck. Once data was also available on the salient points, it was possible to carry out a study and a comparison of the time series and the distributions. This made it possible to compare the trends of the points on the deck and those in the surrounding area, so as to evaluate whether the data provided by satellite are able to provide the real displacement of the deck or in any case provides the displacement of the soil and consequently it is as if the structure moved as a rigid block.



(a) (b) (c) (d)

Fig. 3 (a) Area around the Viadotto Imera on EGMS platform, (b) zoom on the Viadotto Imera I in the EGMS platform, (c) Data collected from the EGMS platform and, (d) Data collected by the EGMS platform divided into two groups, points on the deck (orange) and points in the surrounding area (blue)

5. Results

Firstly, the time series of data belonging to the different groups were analysed in order to observe if within the same groups there were similar behaviours. For the sake of brevity, the time series of each points are not reported here.

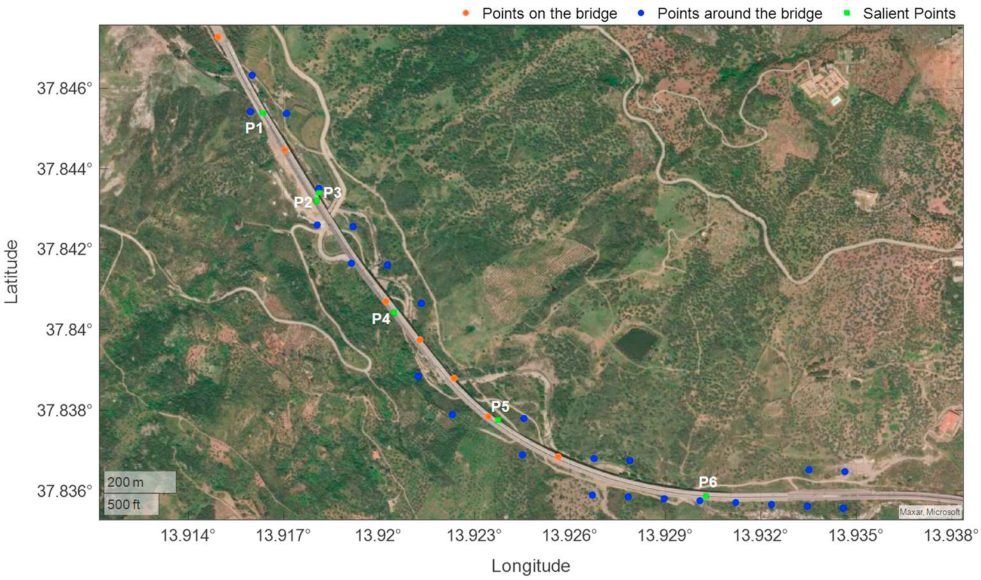


Fig. 4 Location of all points analised: points on the bridge, points in the surrounding area and salient points (in order not to make the figure heavier, here only the salient points are indicated)

Then, a study was carried out comparing samples belonging to the different groups, in order to note differences in the behaviour of each group. From the analysis of the various time series, a specific trend did not emerge based on the different group, but on the contrary the behaviour is very similar (Fig. 5). In this last figure, it is noted the seasonal trend, increasing in the first half of the year and then decreasing in the second half. This aspect is confirmed by Kotzerke et al., (2022) where the seasonality is highlighted; it characterises the magnitude of seasonal displacement over the period of one year and the sinusoidal oscillations are the results from cyclic processes over the year. It can be related to rainfalls or temperature variations between winter and summer. The magnitude of this oscillation is dependent on the type the surface or the object and its response to temperature variation. In the graph, it is not possible to distinguish particular trends because they are all similar, except for some values. It seems that the structure is moving rigidly following the displacements of the underlying soil. Even in the case of the displacement distributions (Fig. 6), it can be observe that distributions are very similar characterized by different value of mean and standard deviation based on different group of points and different points. In addition, it would seem that the first points of each group, which are located in the same area, are characterized by less high peaks. Finally, in the last figure (Fig. 7) the slope of the displacements measured in mm/yy is displayed. They are all in the range between - 0.2 mm/yy and - 0.8 mm/yy, only in some points does it reach higher values. Among these, the point near pier 9 of the left deck, i.e. the one cracked along the entire height, particularly stands out. Corresponding to it, there is an increase in the slope up to -1.8 mm/yy and it is the point indicated in red in the figure. This higher value than the others is also confirmed by the time series, in fact an increase in displacement has been noted in the last year, reaching -15 mm in mid-July 2022 that are out of the range that is usually between -10 mm to 10mm. Since the point is located in the area surrounding the viaduct, it could be excluded that these movements are due to the damaged pier. Rather, what could be kept under observation is whether a possible increase in this displacement could lead to a worsening of the conditions affecting the pier, also bringing with it risk for the structure above.

6. Conclusions

This paper presents the use of InSAR satellite data freely available on the EGMS platform. This data is able to provide displacement information of the order of mm. For this study the ortho data present on the site were used so it is possible to analyse the vertical component of the displacement. The latter allows to evaluate any subsidence of the structures or the underlying soil. However, this type of data is not able to provide direct and specific information on the health state of the structure. Indeed, from the analyses it would seem that no difference emerges between the movements recorded on the ground and those recorded on the deck. Nevertheless, it is necessary to deepen the study of such data and also to thicken their use because only in this way will it be possible to improve their exploitation and the knowledge that could be gained from them.

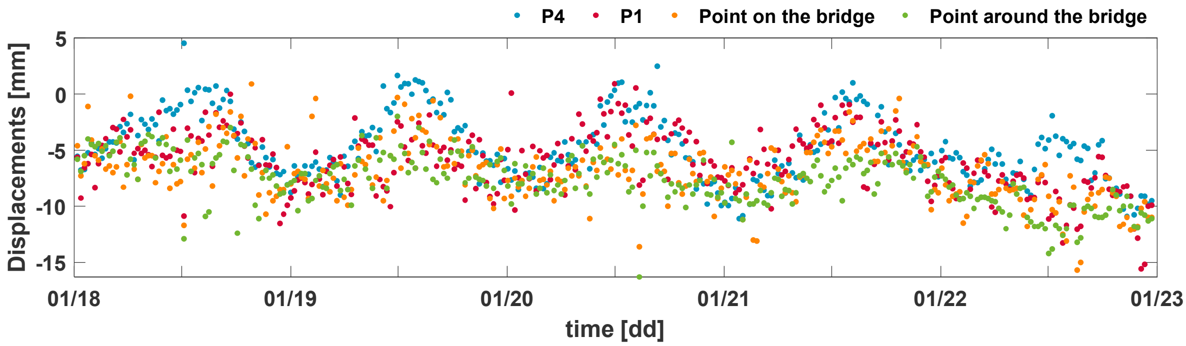


Fig. 5. Overlapping time series of point obtained from interpolation on bridge (P4), point obtained from interpolation on surrounding area (P1), point on the bridge and point around the bridge.

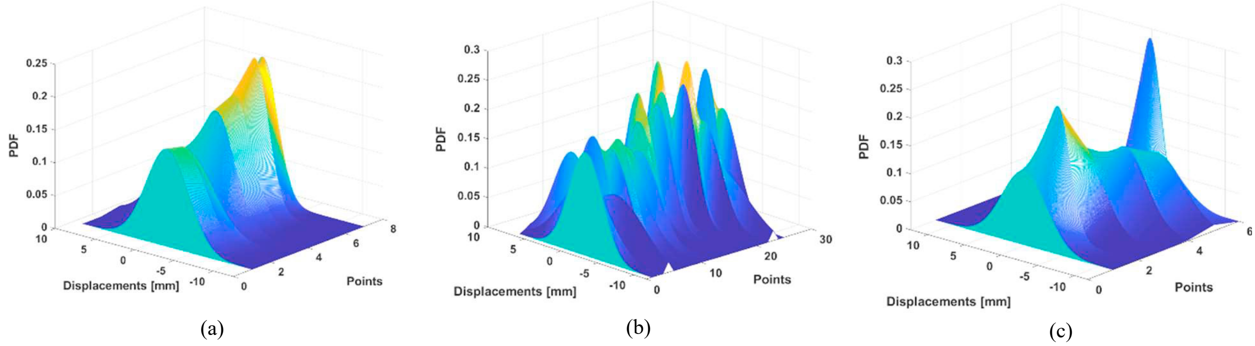


Fig. 6. Distribution of displacements: (a) points on the bridge, (b) points on the surrounding area and (c) points obtained from the interpolation

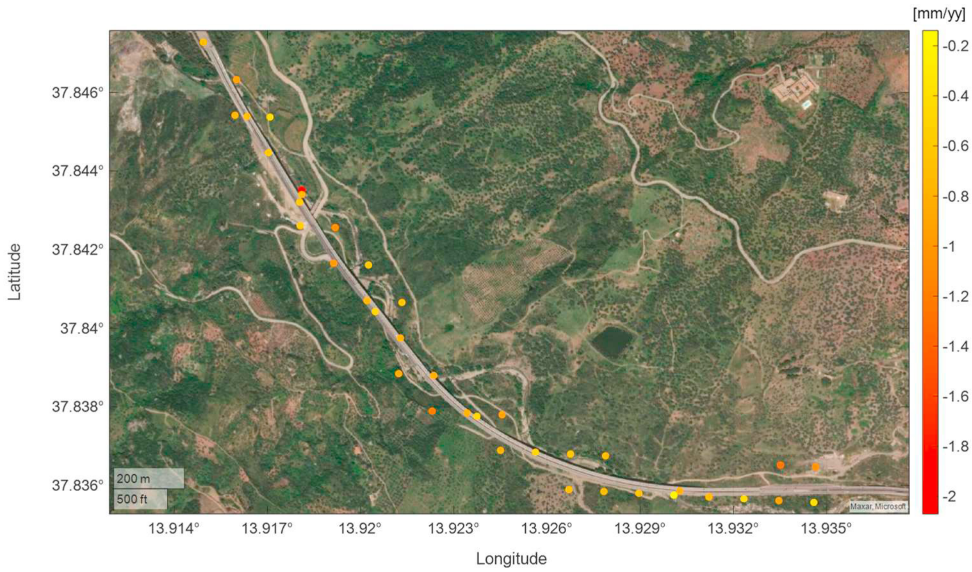


Fig. 7. Slope [mm/yy] of displacements of all points considered in the analysis

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