ASSESSING LEVELLING AND DInSAR FOR DEFORMATION MONITORING IN SEISMIC REGION

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ABSTRACT:

Carrying out monitoring surveys in seismic regions is good practice both for the assessment of land deformation and the evaluation of building structures standing on it. In this work, topographic levelling and DInSAR techniques have been used for displacement measurement. These geomatic techniques are rarely applied in the same context and attempts are made to combine the results obtained for having a complete analysis of the site. The proposed work analyses, compares and discusses topographic levelling and advanced multi-temporal DInSAR techniques used to detect and measure ground deformation when the occurrence of seismic events might have played a role in the displacement. The area of interest had already been under observation through ground-based monitoring surveys, by means of metal bolts attached to façades of buildings detected by topographic level, from 1998 to 2021. The DInSAR analysis was carried out exploiting Sentinel-1A/B data acquired during the period 2014-2021. The goal of the DInSAR processing stage of the procedure is to derive the deformation map of the area of interest from SAR data. A zero date has been set for both survey methods in order to define similar time series for comparison analysis. The results showed that ground displacements measured by levelling and DInSAR have similar trends. On the geomorphological aspect, the same distribution map of terrain subsidence is found in both techniques.

1. INTRODUCTION

Carrying out monitoring surveys in highly seismic areas is good practice both for the assessment of land deformation and the evaluation of building structures standing on it.

The most accurate and widespread technique for measuring ground displacement is topographic levelling. This is a point-wise survey methodology that typically allows the acquisition of dozens of discrete sub-millimetre displacements in situ measurements per squared kilometre (Sabuncu et al., 2014; Di Stefano et al., 2020). Levelling is a relative measurement technique that is based on one or more fixed points, whose data of elevation and position are known. The accuracy of the measurement is case sensitive. The periodicity of the measurements varies in intervals from days to years depending on project-related aspects.

Another approach widely used for ground deformation detection and monitoring is the DInSAR (Differential Interferometric Synthetic Aperture Radar) technique, which is based on SAR images acquired from orbiting satellites. The use of advanced multi-temporal DInSAR techniques, which are based on large stacks of SAR images, offers improved performance. The accuracy of the measurements is influenced by several factors such as wavelength of the Radar, number of images analysed, type of targets measured and the influence of atmospheric phenomena. The quality of the measured targets depends on their response over time to the microwaves sent by space-based SAR sensors. Examples of recognisable targets are man-made objects, e.g. buildings and infrastructures, but also immovable natural features such as rock surfaces: for this DInSAR provides a dense set of measurement points. This remote sensing technique, compared to levelling, can provide higher spatial point density, wider spatial coverage, and cheaper acquisitions (Ager, 2021).

Levelling and DInSAR are rarely applied in the same context and attempts are made in this work to compare the results for having a complete analysis of the site of interest. These techniques are widely used, as documented in the literature, for monitoring geohazards such as landslides (Peduto et al., 2019; Solari et al., 2020) and coastal erosion (Al-Husseinawi et al., 2018) or for assessment and health monitoring of manmade infrastructures such as the construction of new underground tunnels for which a particular excavation activity must be carried out (Serrano-Juan et al., 2017) or ariport runway assessment (Gagliardi et al., 2021). DInSAR based techniques allow monitoring areas from regional/national scale up to very detailed scale such as single buildings, providing a high number of displacement measurements at low cost (Crosetto et al., 2016; Gheorghe at al., 2018). Applications are also reported for post-seismic analysis (Caputo et al., 2015; Saganeiti at al., 2020), which can serve as input for geotechnical and geomechanical survey techniques (Wang et al., 2021).

The comparison between levelling and DInSAR is useful and necessary in an urban environment in order to analyse and estimate ground displacements over time. By comparing both techniques and determining their suitability, it is possible to measure the displacements that occur following seismic events. The main difference between the two techniques is that they are based on different principles of target measurement. Levelling

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is a ground-based technique that measures the relative displacement of metal bolts attached to existing building and structures, whereas DInSAR captures scenes from space, and it is an opportunistic deformation measurement method, i.e. the final measurement points are not known before processing. Besides, there are more differences as, for example, the type of measurements: DInSAR results are based on Line-Of-Sight (LOS), on the other hand, levelling reported the scalar value of vertical displacements.

The proposed work analyses, compares and discusses topographic levelling and DInSAR methodology used to detect and measure ground deformation when the occurrence of seismic events might have played a role in the terrain displacement.

2. MATERIALS AND METHODS

2.1 Case study

The area of interest under monitoring is Madonnetta neighbourhood (Municipality of Pioraco, Italy), built in the 1960-70s. This neighbourhood, with an area of approximately 24,000 m^2, was built in a partly excavated rock recess. This means that the houses on the edge, close to the rock cliff, were erected on rock while those adjacent to the valley lay on a soil of alluvial clay deposits, about 50 m deep (Figure 1). The buildings were constructed of reinforced concrete and the elevations range from 2 to 5 floors.
The area has been affected by several seismic events and, currently, the municipality of Pioraco is included in the list of municipalities forming part of the seismic crater (defined by Civil Protection, https://mappe.protezionecivile.gov.it/it/pagina-base/mappe-terremoto-centro-italia) following the earthquakes that struck central Italy in the years 2016-2017.

Figure 1. Site plan of the area of interest. Contour lines are shown in yellow.

This area had been under observation through ground-based monitoring surveys since 1998 (following the previous seismic event in 1997) until 2021. The DInSAR analysis was carried out exploiting Sentinel-1A/B data during the period 2014-2021. The goal of the DInSAR processing stage of the procedure is to derive the deformation information of the area of interest from SAR data.
The Persistent Scatterer Interferometry chain of the Geomatics (PSIG) Research Unit of the CTTC has been used in this study. A "zero date" has been set for both survey methods in order to define similar time series for comparison analysis.

2.2 Topographic levelling

The first levelling campaign was carried out in 1998. It was necessary for an initial data collection to monitor the area following the earthquake in the central Apennines (Marche-Umbria) in 1997. A total of 49 levelling surveys have been carried out since then, the last one dating back to January 2021 (Figure 2). As can be seen from the list of surveys carried out, in the first 4 years (between 1998 and 2001) monitoring operations were constant with a total of 31 surveys. From 2002 onwards, surveys were carried out occasionally and mainly following the major seismic events that hit the regions of Central Italy in 2009 and 2016-2017.
The monitoring campaigns were carried out by technicians who, using the topographic level, detected the targets, in the form of metal bolts, attached in the corners of building façades. Two fixed markers (indicated with no. 1 and no. 23), attached on the closer rock face, are the reference system to monitor the variations of other 172 targets (Figure 3).

No. survey	Date	No. survey	Date	No. survey	Date
1st and 2nd	17-18/08/1998	18th	07/04/2000	34th	03/10/2005
3rd	21/09/1998	19th	10/05/2000	35th	09/11/2005
4th	19/10/1998	20th	12/06/2000	36th	06/12/2005
5th	27/11/1998	21st	18/07/2000	37th	30/01/2006
6th	04/01/1999	22nd	18/08/2000	38th	27/03/2006
7th	21/02/1999	23rd	18/09/2000	39th	21/07/2009
8th	02/04/1999	24th	23/10/2000	40th	07/01/2010
9th	17/05/1999	25th	26/11/2000	41st	20/07/2010
10th	20/06/1999	26th	10/01/2001	42nd	04/10/2010
11th	27/07/1999	27th	19/02/2001	43rd	30/12/2010
12th	01/09/1999	28th	26/03/2001	44th	29/06/2011
13th	17/10/1999	29th	15/05/2001	**45th**	**04/01/2012**
14th	26/11/1999	30th	29/06/2001	**46th**	**28/09/2016**
15th	28/12/1999	31st	03/11/2001	**47th**	**05/11/2016**
16th	01/02/2000	32nd	22/07/2002	**48th**	**13/02/2017**
17th	28/02/2000	33rd	29/06/2005	**49th**	**29/01/2021**

Figure 2. List of topographic levelling network surveying

Figure 3. Targets of the topographic levelling network with identification of the two fixed markers (in yellow).

2.3 DInSAR

In order to compare and complement the topographic levelling data, a DInSAR analysis was carried out with SAR images acquired by the Sentinel-1 polar-orbiting satellites of ESA (https://sentinel.esa.int/web/sentinel/missions/sentinel-1). The processing of these SAR images makes it possible to estimate the velocity map and the time series of deformation of some points detected in an area of interest. To proceed with this type of analysis, data collection was first carried out, which involved downloading images at a predefined time interval. Sentinel-1A and B satellites were launch in 2014 and 2016, respectively, therefore the analysed images cover the period 2014-2021. The images were obtained from the Copernicus open-access platform (https://scihub.copernicus.eu/dhus/#/home).
A total of 324 SLC (Single Look Complex) Sentinel-1(A and B) images were collected with a minimum revisit period of 6 days. Table 1 provides information concerning the Sentinel-1 dataset

processed in this work. Ascending trajectory was selected due to the exposure of the area of interest, which is near rocky slopes, to avoid shadow or layover effects.

Satellites	**Sentinel-1 (A-B)**
Acquisition mode	Interferometric Wide Swath (IW)
Period	Oct. 2014 – Mar. 2021
Minimum revisit period [days]	6
Wavelength (λ) [cm]	5.546
Polarization	VV
Full resolution (azimuth/range) [m]	14/4
Orbit	Ascending
Incidence angle of the area of interest	36.47° - 41.85°

Table 1. Summary of the dataset analysed

The methodological process of SAR image acquisition and processing is outlined in the following diagram (Figure 4). The goal of the DInSAR processing stage is to derive the deformation map of the area of interest from SAR data. The Persistent Scatterer Interferometry chain of the Geomatics (PSIG) Research Unit of the CTTC described in (Devanthery et al., 2014) has been used in this study.

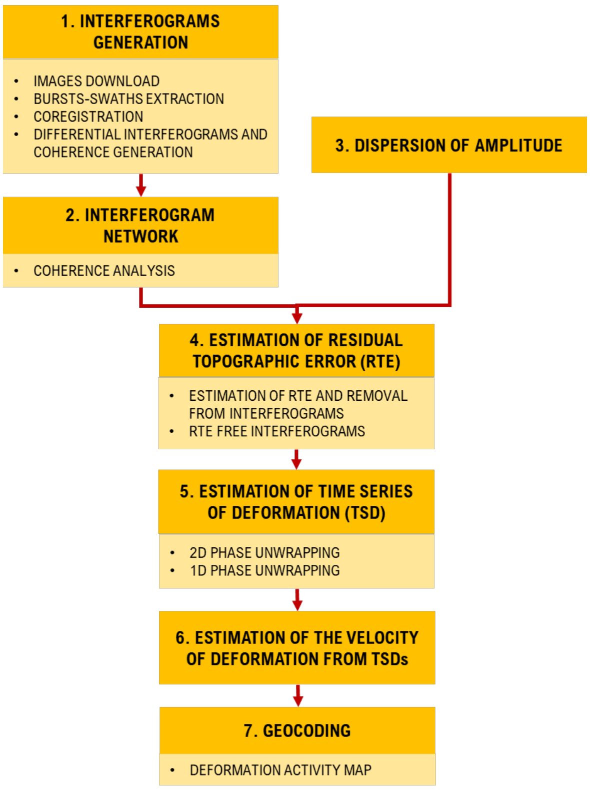


Figure 4. Flowchart of the PSIG chain used in this work

As a first operation, a DTM (Digital Terrain Model) was obtained from Earth Explorer (https://earthexplorer.usgs.gov/) platform, which provides to know the morphology of the area of interest to be analysed and acts as a support for the visualisation of the SAR images.
Then, the DInSAR processing carried out in this study is resumed in these steps:

(i) Interferogram generation: after downloading the images, the processing of the DInSAR images started with the identification of the master (reference) image. The first image downloaded in the temporal order (20 October 2014) is considered as the master image, all others to follow are considered as slave images (until 27 February 2021). A SAR image acquired in IW mode consists of 3 swaths (SAR acquisition amplitudes) and each swath is composed of 9 bursts (horizontal stripes). For subsequent processing and analysis operations, the swath and burst that identify the area of interest were extracted from each SAR image, corresponding to those identified in the master image. This first step leads to the generation of differential interferograms and coherence.

(ii) Interferogram network selection performed with a statistical evaluation of the coherence of the study area in order to locate and remove those interferograms characterized by low coherence (e.g., snow periods in mountain areas). A filtering operation was performed in eliminating from the temporal analysis those months that fall in the winter season; the presence of snow on the ground can lead to interferometric coherence errors.

(iii) Selection of points based on the dispersion of amplitude.

(iv) Estimation of the residual topographic error (RTE) and subsequent removal from original single-look interferograms. Data processing continues with a first estimate of the linear velocity and specific filtering operations. Although it is a remote sensing technique and acquires data beyond the atmospheric surface, the microwaves transmitted and received by satellites are able to pass through the presence of clouds; moreover, being direct light sources, they can operate even in the hours when there is no sunlight.

(v) 2+1D phase unwrapping of the redundant interferograms which generates a set of N unwrapped phase images, which are temporally ordered in correspondence with the dates of the SAR images processed, hereafter referred as time series of deformation (TSD).

(vi) Estimation of the velocity of deformation from the TSDs.

(vii) Geocoding of the results. The result of interferometric processing is the generating of geocoded points which compose the deformation activity map. These points have been identified semi-automatically by the overlapping of the SAR images on to the master image and located on a reference system (UTM-WGS84). Approximately 200 geo-coded points were obtained and about 50 fall within the area of interest. Geocoded points are found in correspondence with elements that remain fixed over time. Since the observation is made from above, they are identified as edges or protrusions of the roofs of buildings, road elements and exposed rocks.

3. RESULTS

3.1 Analysis of levelling data

For what concerns the coordinates of levelling points, they are georeferenced on WGS84-UTM zone 33N (EPSG 25833). The targets were mapped in QGIS. The ground subsidence was elaborated basing to the time series of levelling monitoring, shown in Figure 5, relating to the most significant periods connected to the recent seismic events (2016-2017) that have affected the area of interest. The values reported in the legends, referring to the intervals (5 ranges are displayed) of vertical displacements, are expressed in millimetres.

a.

b.

c.

Figure 5. Ground displacements, expressed in millimetres, from topographic levelling: a. in the period 04/01/2012 to 28/09/2016 (earthquake on 24th of August 2016) b. in the period 28/09/2016 to 05/11/2016 (earthquakes on 26th and 30th of October 2016) c. in the period 13/02/2017 to 29/01/2021 (earthquake on 18th of January 2017).

Figure 6. Deformation velocity map (processing period 2014-2021) with corresponding legend with 5 ranges of terrain displacement values expressed in millimetres.

3.2 Output of DInSAR processing

The output of the DInSAR processing is a deformation activity map composed of a set of selected geocoded points, called Persistent Scatterers (PSs), with information on the estimated LOS velocity of deformation and the accumulated deformation at each Sentinel-1 image acquisition time, i.e. TSDs.
These PSs can be displayed in QGIS environment (Figure 6) in overlay to an orthophoto of the site.

3.3 Comparison between levelling and DInSAR

3.3.1 Global analysis

As stated above, topographic levelling surveys started in 1998. In order to compare the data with those point measurements identified with DInSAR and, considering that the Sentinel-1A mission started in 2014, it has been decided to consider the data acquired in the same temporal period. Therefore, the topographic levelling carried out in 2012 (survey no. 45, Figure 2) is considered as the new "zero date" for subsidence analysis (Figure 7).

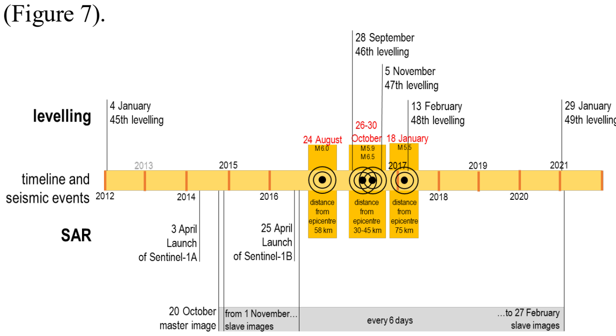


Figure 7. Determination of the “zero date” of the temporal analysis for the topographic levelling-DInSAR data comparison

It should be remembered that we are comparing two systems that give results on different components of ground subsidence: the data obtained from topographic levelling concern only the scalar vertical displacement; the subsidence recorded by SAR data is measured in LOS.
In determining the ground subsidence rate based on SAR points, “stable points” encoded by the SAR images were identified, indicated in green in Figure 6. A check is made for the presence of SAR points (range of values close to zero) near the fixed points of the topographic levelling. Close to the topographic levelling reference point no. 23, there are no SAR points; on the other hand, regarding the topographic levelling reference point no. 1, several SAR points are present at a short distance on the rock relief (Figure 8).

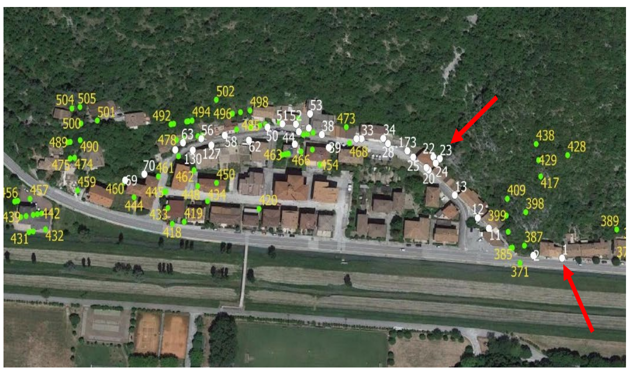
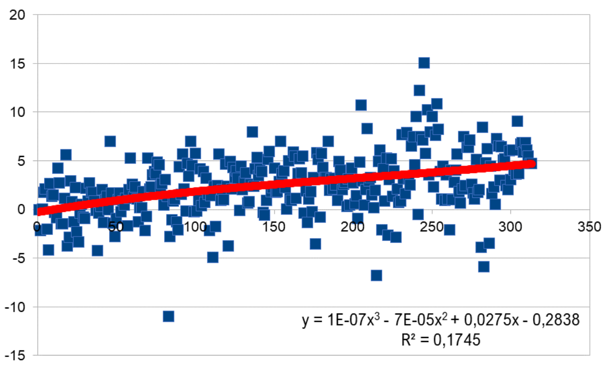


Figure 8. Map of “stable points”, in white from topographic levelling (reference points are indicated by the red arrow) and in green from DInSAR.

In order to identify the "stable points" among the DInSAR geocoded points, a statistical analysis was carried out based on the calculation of polynomial regression and the analysis of dispersion index with respect to the mean value curve.
The graph showing the ground subsidence values of each geocoded point has along the x-axis the number of processed DInSAR images in temporal order and along the y-axis the ground subsidence values over time, in millimetres. From this graph, the third-degree polynomial curve is drawn, and the squared regression coefficient value (R^2) associated to the trend of this curve is calculated. In addition, R^2 for the linear curve was also computed. Both values of R^2 are used for comparison. Some points displaying clear evidence of phase unwrapping errors were discarded from the analysis.
This analysis was first carried out for those DInSAR points close to the reference or immovable points (less than 1 mm of vertical displacement) of the topographic levelling. Searching among mapped DInSAR points, about 3 "stable points" were identified.
Once the graph of values is obtained, the third-degree polynomial curve is generated, and the regression values are calculated (Figure 9). If the third-degree polynomial curve shows an almost linear trend, parallel to the linear curve, with a value of both regression closer to 0, the point is considered "stable". The dispersion of the values with respect to the curve is also verified by visual analysis with the graph obtained.
For example, DInSAR point no. 438, close to reference point no. 1 of topographic levelling, is the one with rather similar regression values (Figure 9). It should also be noted that there are some values in the graph that are beyond the dispersion amplitude. These are considered outliers and discarded from the analysis as they present incorrect results following data processing.



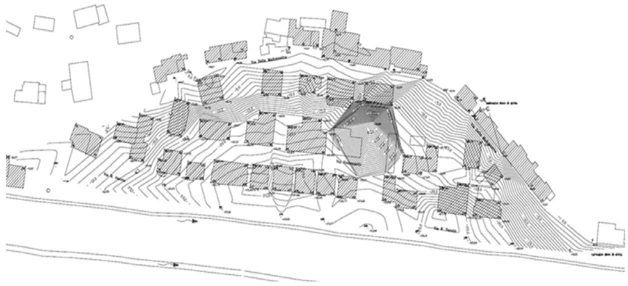
a.

Regression Model	Linear
LINEST raw output	
0,01470169	0,203463996
0,001827397	0,33102117
0,172265928	2,921167549
64,724536	311
552,3086954	2653,831374
Regression Statistics	
R^2	0,172265928
Standard Error	2,921167549
Count of x-variables	1
Observations	313
Adjusted R^2	0,169604404

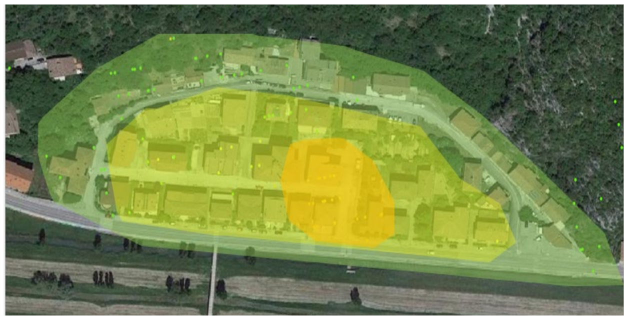
b.

Figure 9. a. Graph of values referring to point no. 438, third-degree polynomial curve, equation and its regression. **b.** Linear regression referring to point no. 438.

The comparison of the analysis, made on QGIS software, showed that ground displacements measured by levelling and DInSAR have similar trends in the results. On the geomorphological aspect, the same distribution map of terrain subsidence is found in both techniques (Figure 11).



a.



b.

Figure 10. a. Map of the subsidence curves generated from the analysis of topographic levelling data. **b.** Heat map of the terrain subsidence from the elaboration of DInSAR data.

3.3.1 Pointwise analysis

In addition, a pointwise analysis was carried out to specifically examine this comparison between topographic levelling and DInSAR. For this purpose, the following time periods were considered:

- Topographic levelling from 2012 to 2016 (45th and 46th survey);
- DInSAR from 2014 to 2016 (until after the seismic event of 24th August 2016).

In this phase, several points measured with levelling and located in the proximity of DInSAR ones were compared in order to make a first assessment. The operation was carried out on 10 points that gave the same feedback. Figure 11 shows the points taken, as an example, to compare the terrain subsidence: no. 99 from topographic levelling and the proximal no. 411 from DInSAR.

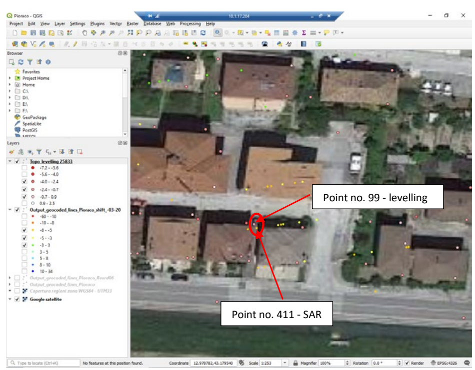


Figure 11. Identification of points for pointwise analysis: no. 99 from topographic levelling and the proximal no. 411 from DInSAR

This comparison produced the following results:

- point no. 99 shows a subsidence of more than 20 mm.
- point no. 411 has a maximum subsidence value of the order of 10-12 mm (in LOS, almost vertical), which is lower than the value of the proximal levelling point (no. 99).

As a first consideration it can be stated that terrain subsidence is highlighted in both results. The different subsidence value between the two surveys (about 10 mm) suggests that in the time interval 2012-2014, previous to SAR survey, there might have been a subsidence phenomenon not related to seismic events. Maybe some geological or geo-mechanical phenomenon may have occurred due to the fact there are a fault, a surface water table, and the clay component of the soil.

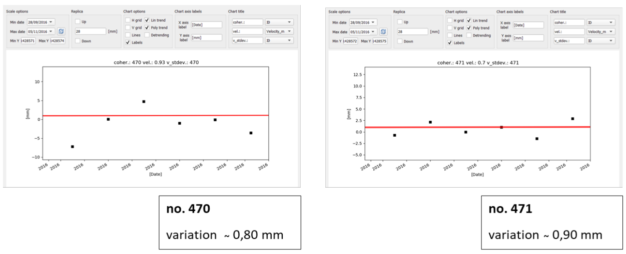
Further validations were performed to verify that both survey techniques give a similar response based on subsidence values. The same post-earthquake period, September-November 2016 (after seismic event of 24th August 2016), is analysed and therefore we have:

- Topographic levelling: 46th survey of 28th September 2016 and 47th survey of 5th November 2016
- DInSAR: images from 28th September 2016 to 3rd November 2016 (the master image is that of the date 20 October 2014).

"Stable points" are defined as those points that did not show a significant variation in subsidence. So-called "moving points" are those that have registered subsidence values greater than 1 mm. The analysis between "stable points" have showed same trend in the variation of terrain subsidence between topographic levelling and DInSAR (Figure 12). Similar trend is confirmed also from the comparison between "moving points" of both survey techniques (Figure 13).

a.

b.

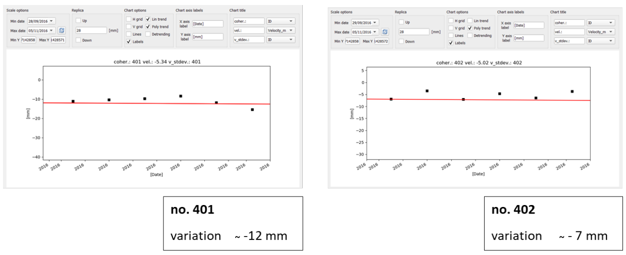


c.

Figure 12. Post-seismic pointwise analysis between "stable points". **a.** Identification of points on map; **b.** Points from topographic levelling **c.** Points from DInSAR.

a.

b.



c.

Figure 13. Post-seismic pointwise analysis between "moving points". **a.** Identification of points on map; **b.** Points from topographic levelling **c.** Points from DInSAR.

It is worthwhile remarking that in the last comparisons just described, in the post-earthquake period of 24th August 2016, the DInSAR data have as reference period the same master image (20th October 2014). DInSAR "stable points" have not changed in values: they remain around the 0 value. From the graphs of the variations referred to DInSAR "moving points" the values oscillate around the -10/-5 mm value. It means that these points have also moved in the period before the 2016 earthquake, between October 2014 and August 2016. This displacement is not detectable by topographic levelling due to a lack of data. As stated before, this subsidence could be related to geological or geo-mechanical phenomena.

4. DISCUSSION AND CONCLUSION

The aim of this contribution is to illustrate and compare geomatic techniques used for monitoring purposes through the analysis of subsidence in a specific area that has been affected by seismic events.

Topographical levelling is confirmed as a surveying technique that allows accurate data to be obtained thanks to the degree of precision of the instrumentation used and the possibility of performing the survey in situ, i.e. at close range with the fixed markers installed (metal bolts) on the façades of buildings. This surveying operation must be at least repeatable with a certain frequancy in time to have an interpretative overview of the variation of subsidence affecting the terrain. This action requires a series of factors that depend on the operator's availability to carry out the survey and the definition of the economic plan that guarantees the execution of the survey itself.

The processing of topographic levelling data is a relatively simple operation. To better analyse the variation of terrain subsidence, for example following seismic events, is required to identify time series and define the most significant ones in terms of subsidence.

Data processing from SAR interferometry (DInSAR) from Sentinel-1 satellites provides results that can be trusted for monitoring purposes. They cannot be as accurate as those from topographic levelling due to the fact that the accuracy is lower. Unlike topographic levelling, SAR data are continuously acquired at the same interval that corresponds with the minimum revisit period of 6 days. Therefore, the images are always available and downloadable. As can be seen from the temporal analysis of the comparison of the two techniques, DInSAR provides continuous data. Due to the lack of continuity of the topographic levelling operations, time gaps were created which can be covered by DInSAR data.

One factor of difference between the two survey techniques concerns the data processing. Topographic levelling data are obtained directly and catalogued in database form. DInSAR data processing is quite complex and requires specific knowledge and skills, but it is a low-cost operation that is carried out in the laboratory. The methodology starts from the download of images in the temporal period to be analysed, followed by the generation of interferograms and the analysis of coherence to the estimation of time series of deformation (TSD) and velocity of deformation for the points identified, and ends with the geocoding process (Figure 4).

Another factor to consider is the type of measurement obtained from the two surveys. The study of terrain deformation from topographic levelling is based on one direction, in the scalar vertical component only. DInSAR measurements are taken in the LOS and the terrain subsidence is calculated through the estimation of the velocity vector for each point identified.

Finally, the displacements of the points that are evaluated based on fixed targets, as reference monitoring system, used to compare the values of subsidence through both techniques. The reference points of the levelling are already known and fixed on elements considered to be stable, such as the rock face close to the urban area. On the contrary, the reference points for the estimation of the subsidence by means of DInSAR are to be identified and are determined according to different factors including the statistical analysis of the square regression of the distribution of the value of the subsidence for each point.

The monitoring of terrain subsidence, particularly in seismic region, is an issue that concerns all sub-disciplines of the geosciences. As a further activity to analyse in detail the case study examined, it is possible to integrate data from the geomatic survey with data from geological and geo-mechanical studies.

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