Validation and comparison of Advanced Differential Interferometry Techniques: Murcia metropolitan area case study

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\textbf{A B S T R A C T}

This paper is focused on the analysis of the performance of Stable Point Network (SPN) and Coherent Pixel Technique (CPT), which are Advanced Differential Interferometry Techniques (A-DInSAR) that estimate, among other results, mean deformation velocity maps of the ground surface and displacement time series from a SAR dataset. The test site is the metropolitan area of the city of Murcia (Spain) where a moderate slow subsidence induced by the overexploitation of aquifers is present. SAR data acquired between July 1995 and August 2005 from ERS and ENVISAT sensors have been processed by the SPN and CPT techniques and compared with in situ instrumental measurements assumed as reference. Experimental results have shown that both SPN and CPT techniques provide estimates of the deformation evolution in time with an absolute difference below 6 mm consistently in all comparisons: SPN vs extensometer, CPT vs extensometer and SPN vs CPT. The proposed validation and comparison experiment between both A-DInSAR techniques has been useful to observe their differences and complementarities.

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1. Introduction

Differential Interferometry with Synthetic Aperture Radar (DInSAR) has become, over the last decade, an important remote sensing tool for the estimation of the temporal evolution of ground surface displacements. This technique is able to observe wide areas periodically and at a low cost, monitoring deformation of the ground surface at millimetre level. The standard DInSAR technique, which is based on a single interferogram generated from a pair of SAR images (Rosen et al., 2000), has been improved in the last years by several Advanced DInSAR techniques (A-DInSAR), which are based on the processing of multiple interferograms derived from a large set of SAR images (Ferretti et al., 2000; Berardino et al., 2002; Mora et al., 2003; Arnaud et al., 2003; Werner et al., 2003; Hooper et al., 2004). In this context, several studies have been devised for comparing DInSAR retrieved results against geodetic measurements (see Strozzi et al. (2001) and Colesanti et al. (2003) and Casu et al. (2006) and Crosetto et al. (2008) and Ferretti et al. (2007)). In most of these studies, it is observed that the precision depends mainly on the electromagnetic stability of the pixel, the number of available SAR images and the linearity of the deformation phenomenon itself. The main objective of this work is to validate two A-DInSAR techniques called CPT (Mora et al., 2003) and SPN (Arnaud et al., 2003) with an extensometer network and then to perform a comparison between SPN and CPT techniques.
A specific ESA project, called PSIC 4, for the comparison of A-DInSAR techniques has been already carried out including, among others, the SPN and the CPT techniques. Nevertheless the results were not satisfactory because of the strong non linear movement of the selected test site (Crosetto et al., 2008), combined with the lack of images when the sudden deformation occurred. In this case, the proposed study area site is affected by a slow linear deformation process. Additionally, in this paper, new aspects from both A-DInSAR techniques are addressed in order to improve the interpretation of the estimated deformation values, and also to analyze the existing differences and complementarities between them.

The main differences between these techniques are: the pixel selection criteria, the characteristics of the required images and interferograms, and the features of their deliverables. The SPN technique can operate in different modes both in high resolution (as was the case for Murcia) or in low resolution using multilook coherence to select the stable pixels (SP’s). In high resolution mode SPN selects those SP’s in the single-look complex images that show a stable electromagnetic behaviour in time, and the selection is performed by inspecting their amplitude stability (Ferretti et al., 2000). In the case of the CPT approach, the selection of coherent pixels (CP’s) is based on multi-looked interferograms, and pixels whose interferometric coherence is above a defined threshold for all the stack of interferograms are selected. Note that, due to the multi-look factor, the spatial resolution of the CPT technique is degraded, typical values are 80 × 80 m but it is possible to work with better resolutions depending on the characteristics of the dataset, whereas for the SPN technique it remains at full resolution (20 × 4 m). In principle, both techniques can detect ground deformation with a reduced set of images, (Mora et al., 2003; Duro et al., 2005), and a similar number of SAR images are needed to quantify deformation with high quality. Nevertheless, the requirements for the generation of interferograms, the perpendicular spatial baseline and the relative Doppler centroid difference, are less restrictive for the SPN technique and consequently more interferograms can be generated from the same SAR images dataset. The main products of both techniques for each selected pixel are the deformation rate map, the deformation time series, and the residual topographic error. Due to the better spatial resolution of the SPN technique the residual topographic error is used to achieve a more precise geocoding, with a planimetric precision of 2.5 m in the best cases. Note that the planimetric precision depends on the baseline extent and distribution as well as the number of acquisitions employed for the interferograms generation (Perissin and Rocca, 2006; Crosetto et al., 2008). Associated with these products, the SPN technique provides parameters for checking the quality of the deformation measurement for each selected pixel: quality of the height correction indicator, quality of the linear model movement rate, standard deviation of the time series with respect to a linear model, and amplitude stability. A more detailed explanation of these parameters can be found in Crosetto et al. (2008).

In this study, the test site is the metropolitan area of Murcia City, in SE Spain, which is affected by a slow subsidence induced by the overexploitation of aquifers (Mulas et al., 2003; Aragón et al., 2004; Martínez et al., 2004; Tomás et al., 2007). The temporal evolution of the deformation has been monitored by an extensometer network since 2001 (Peral et al., 2004), and also by the analysis of DInSAR time series in previous works (Tomás et al., 2005). The use of a large number of SAR images of the study area acquired from descending orbits between July 1995 and December 2005 has enabled the estimation of high quality deformation maps. The same dataset has been processed with both techniques, and retrieved results have been compared separately with those available from the extensometer network. As a result of the CPT/extensometers and SPN/extensometers comparisons, a quantitative assessment of both technique performances for monitoring urban subsidence has been provided. Finally, the comparison between SPN and CPT techniques has been useful to observe the main differences and common features of both approaches. The paper begins with a brief description of the deformation phenomenon that has occurred in the study area and an interpretation of the retrieved deformation results of the A-DInSAR analysis performed with both techniques. Section 3 is dedicated to the comparison of SPN/extensometers, CPT/extensometers and SPN/CPT, respectively, and, finally, in the conclusions the achieved results are summarized and compared with those available in literature.

2. A-DInSAR results

2.1. Description of the study area

This study is focused on the Murcia city and its metropolitan area. The city of Murcia, with a population of more than 400,000 inhabitants is the most populated city of the Vega Media of the Segura river Basin (SE Spain) (Fig. 1). The Vega Media of the Segura river basin constitute a multilayer detritic aquifer formed by sediments accumulated by the Segura River from Pliocene up to present. It can reach 250 m of thickness (Cerón and Pulido, 1996; Aragón et al., 2004). The aquifer is constituted by two principal aquifer systems, a superficial aquifer and a deep aquifer. The superficial aquifer is constituted by recent sediments (clay, silt and sands) with poor hydrological parameters. The underlying deep aquifer is composed of a sequence of gravels and sands with good hydrological parameters that has been exploited increasingly in the last decades. The recent sediments, or materials that constitute the superficial aquifer, are the most compressible ones in the zone. On the contrary, the deep aquifer materials are more rigid and represent the geotechnical substratum of the zone, used as the support level for deep foundations.

The subsidence model (Mulas et al., 2003) suggests that when water is pumped from the upper gravels of the deep aquifer, a gradient is created that implies a water flow from upper aquifer to gravels giving rise to a lowering of the water (it was more than 15 m at some points of the Vega Media Basin during 90’s drought period). Consequently, pore pressure on the superficial aquifer falls due to pore water drainage and the soil suffers a consolidation. During the 90’s drought, soil consolidation at Murcia city caused moderate to severe damages at several buildings (approximately 150 buildings) and other structures (sidewalks, roads, walls, etc.). The cost was estimated in 50 million euro (Martínez et al., 2004). As a consequence, the local authorities requested a detailed field study of subsol consisting of a considerable number of boreholes and laboratory and in situ tests. In order to measure the temporal evolution of the deformation in depth, 22 extensometer boreholes were installed, in four suburban areas of in the south and east of the city (Fig. 1). An extensometer consists of a device for measuring the deformation of the ground along a borehole. These extensometers suggest that the first 5 m depth of the superficial aquifer are the more deformed, with an accumulated consolidation varying from 0.5 to 2.8 cm since 2001 to 2005. This fact has been noticed by Tomás et al. (2007) that established that the first 5 m of soils from surface are generally highly consolidated due to water level fluctuations and fall, desiccation and sometimes cementation.

2.2. Data processing and results

Both A-DInSAR algorithms have been applied to images acquired by the European Space Agency (ESA) ERS-1/2 and Envisat ASAR sensors covering the July 1995-December 2005 time interval. A similar crop of about 20 km × 8 km was selected from the
original images, corresponding to the Vega Media of the Segura River (Fig. 1). The CPT algorithm has elaborated 62 interferometric SAR image pairs with a perpendicular spatial baseline smaller than 130 m, a temporal baseline shorter than 900 days and a relative Doppler centroid difference below 250 Hz. The external DEM used to cancel the topographic component of the interferometric phase has a resolution of 25 m × 25 m and belongs to the cartographic numeric database E20 from IGN (National Cartographical Service of Spain). Due to the multi-look operation of 20 pixels in azimuth by 4 pixels in range, the final resolution has been degraded to 80 m × 80 m. The estimation of the deformation was computed in those coherent multi-look pixels selected with an iterative multi-layer process (Blanco et al., 2006) whose coherence was above a threshold of 0.5, 0.4 and 0.3 for more than 50% of the interferograms. During the linear model adjustment those arcs linking to neighbouring pixels not fulfilling the model within a margin are eliminated. In the case of the SPN algorithm, a total of 79 interferograms have been generated with a perpendicular spatial baseline smaller than 800 m, a temporal baseline shorter than 6 years, and a relative Doppler centroid difference below 400 Hz. The Shuttle Radar Topography Mission (SRTM) DEM of the study area has been used. In this case the pixel selection was based on a combination of several quality parameters including low amplitude standard deviation and high model coherence.

The maps of the accumulated deformation in August 2005 (estimated along the line of sight, LOS) obtained by both techniques are presented in Fig. 2. Both deformation maps have been geocoded and superimposed on an amplitude SAR image, which are shown in 6 colours. Note that reliable information is available only on urban areas and rock outcrops. In this sense, displacements are observed mainly on the urban and sub-urban areas of the central part of the valley, corresponding with the zone occupied by compressible sediments. It is clear that both techniques show a very similar performance in the estimation of the total deformation. The South-West and North-East areas of the city of Murcia are affected by total displacements which vary between −1 and −4 cm (a and b in Fig. 2). If the course of Segura River is followed towards the northeast subsidence varies between −3 cm and −9 cm (c in Fig. 2). Note that in this area the deformation estimated by both techniques is not the same. The downtown area towards the North from Segura River has remained almost stable for the whole monitoring period (d in Fig. 2). This area is located, approximately, on quaternary alluvial fan formed by old, coarse and low deformable materials. Finally it has been observed that on the South sub-urban area of Murcia City (e in Fig. 2) there are some punctual absidence spots with displacements varying between +1 and +3 cm. The correlation of deformation estimated with CPT and the aquifer water level variation is found in Tomás et al. (2005).
3. A-DInSAR techniques validation and comparison

3.1. SPN validation with the extensometer benchmarks

In this section, the analysis is focused on the assessment of the SPN performance by comparing retrieved deformations against measurements from the extensometer boreholes. The basic idea is to compare the time series achieved from the SAR data with those available from the extensometer network measurements projected along the LOS. To enable the comparison, LOS-projected extensometer time series have been interpolated via a linear regression within the interval common to the SAR data, i.e. from 2001 to 2005. The comparison with the extensometers has been made using the following methodology: (1) to compare all the SP’s identified in a circle defined around the position of the extensometer; (2) to compare from the previous operation those SP’s located at the ground level; and, finally, (3) to compare from the second step the best match (most similar with respect to the extensometer measurement) among the nearest SP’s (since usually some of them are located at the same distance $\pm 1$ m tolerance).

Regarding the first operation described above, the obtained results are presented in Table 1. The third and fourth columns show the maximum distance and the number of SP’s found within a circle area around each extensometer. The starting radius of the circle was 100 m, but when no SP’s were found it was increased to 150 m and 200 m.
For each selected SP, the mean and the standard deviation of the absolute difference between SPN and LOS-projected extensometer deformation time series were calculated. Subsequently, the mean values of these parameters for the entire population of SP's inside the circle of each extensometer were calculated. The resulting mean values of average and standard deviations for the whole set of extensometers are $\mu = 5.0$ mm and $\sigma = 2.8$ mm, respectively. Note that if we only consider the extensometers with a total deformation greater than 1 cm, from extensometer v8 to v1 in Table 1, these values are $\mu = 6.2$ mm and $\sigma = 3.4$ mm.

In the second step, the residual topographic error has been used to discriminate those SP's that are closer to the ground level. The residual topographic error denotes the difference between the height of the scattering phase centre of the SP and the height provided by the SRTM DEM, which was used by the SPN algorithm. A negative value means that the real position of the SP is closer to the satellite position, whereas a positive value means that the real position of the SP is farther from the satellite. The term ‘closer’ means that the retrieved height (above the reference ellipsoid) of the SP is higher than the height of the DEM at the same position, that is, the SP is above the DEM vertical coordinate. In contrast, the term ‘farther’ means that the retrieved height for the SP is below the DEM vertical coordinate. Taking into account this criterion, the SP’s population is filtered and reduced to approximately 25% of that of the previous analysis that is an average of 4 SP’s around each extensometer. The average value of the minimum residual topographical error of the selected SP’s is 13 m, a value that is very close to the mean maximum value, 16.2 m, showed in Table 1. Consequently it seems that among the whole SP population around the extensometer, the ground level is usually found in those SP’s with a residual topographical error greater than 13 m. In this sense, it is interesting to observe that when the selected SP’s are represented by superposing them over an orthoimage, they are mostly located in sidewalks, park areas and borders of buildings. Therefore, in urban areas the above mentioned parameter can be used to differentiate those SP’s that are not located at the ground level.

Once the selection of SP’s based on proximity to the ground has been performed with the whole set of benchmarks, the absolute difference of the time series is $\mu = 4.5$ mm and $\sigma = 2.6$ mm. Comparing these result with the first one, it seems that the separation of SP’s located on ground level structures from buildings does not bring any benefit on terms of accuracy of the results. Nevertheless, if we only consider the extensometers that measured a deformation greater than 1 cm (from extensometer v8 to v1 in Table 1) the improvement is of $\Delta \mu = 1$ mm and $\Delta \sigma = 0.5$ mm. These values represent 20% of the result achieved after the first operation.

In the next step, the best match from the nearest SP’s has been chosen, starting from the SP’s population selected in the previous step. With the resulting SP’s, the absolute difference of the time series has been reduced to $\mu = 3.2$ mm and $\sigma = 2.1$ mm. Overall, the improvement between the first and the last step of this comparison is $\Delta \mu = 1.8$ mm and $\Delta \sigma = 0.8$ mm. And, if we only consider the extensometers that measured a deformation greater than 1 cm (from extensometer v8 to v1 in Table 1), the improvement is $\Delta \mu = 3.0$ mm and $\Delta \sigma = 1.3$ mm. This represents an improvement of the 50% over the results achieved after the first operation. Consequently, the proposed methodology has permitted to demonstrate that the deformation estimated on the ground level is closer to the measurements of the extensometers than that of SP located on the buildings. This affirmation coincides with other authors (Mulas et al., 2003; Tomás et al., 2005), that stated that there is not a direct relationship between subsidence values and damages in buildings because this depends on the construction quality of the buildings, the kind of foundation used for, and the singularities of terrain under foundation.

In order to enable the comparison of these results with those obtained by previous experiences published in the literature, the standard deviation of the difference between SP and LOS-projected extensometer deformation time series, resulting $\sigma' = 3.0$ mm. Note that 49% and 74% of all the time series differences are included within the ($-\sigma', +\sigma'$) and ($-2\sigma', +2\sigma'$) intervals, respectively.

In Fig. 3, the SP and the LOS projected extensometer time series are superimposed, for those extensometers that measured a total deformation greater than 1 cm (from extensometer v8 to v1 in Table 1). These plots evidence the strong similarity between the temporal evolutions of the deformation for both datasets. Note that plots corresponding to extensometer v1, v6 and v4 exhibit a slight dispersion in the SP time series. This can be explained by a lack of perfect stability of the electromagnetic properties of the SP, which produces a noisy behaviour of the DInSAR phase over the observed period. The SPN technique assesses the quality of each SP through the estimation of two parameters: temporal coherence (also known as multi-image coherence) and standard deviation of the time series with respect to the linear deformation model. Both parameters measure the quality of the estimation with respect to the DInSAR phases (Crosetto et al., 2008). In this case, the low temporal coherences (below 0.5) for the selected SP’s (see Table 1) reflect the high dispersion or fluctuation of the SP time series, which can be explained by the non linear behaviour of the
deformation observed by both extensometers. In this sense, it is important to recall that the non-linearity of the motion affects the dispersion of the SP time series, which is not an error in the estimation but a problem with the chosen model.

### 3.2. CPT validation with extensometer benchmarks

This section is dedicated to present the results of the comparison between the deformation measurements retrieved via the CPT technique and those available from the extensometer network. LOS-projected extensometer retrieved deformation values have also been interpolated via a linear regression within the interval common to the CPT data. In this case the comparison period is one year shorter, from 2002 to 2005, since there is a gap of information in the CPT time series between 2001 and 2002. This gap is due to the poor quality of the ERS-2 SAR images for that time period and the limitation of this technique to exploit interferograms with large baselines. The proposed methodology has been followed: (1) to compare all the coherent pixels (CP) included within a defined circle around each extensometer, (2) to compare the best match (most similar with respect to the extensometer measurement) from the nearest CP’s (since some of them are located at a similar distance $+/- 10$ m tolerance).

In this case, the circle radius used for each extensometer coincides with that employed for the SP validation, and an average of 6 CP’s were selected for all the extensometers. The global statistics of the comparison yield an absolute difference for the whole set of extensometers characterized by $\mu = 4.9$ mm and $\sigma = 2.2$ mm. As in the previous section, the residual topographic error was used to select the CP which is closest to the ground level. Nevertheless, due to the pixel size in the CP algorithm ($80 \times 80$ m), it is not possible to identify which ground surface structure within the CP area dominates the dispersion from the pixel. Furthermore there may not be a dominant reflector but rather the average of many reflectors (especially in an urban environment). Hence, the residual topographic error can help to indicate where the scatterers are located.

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**Fig. 3.** Temporal evolution of the estimated deformation for the best SP match (squares) and the extensometer time series (circles). Each plot show the mean ($\mu$) and standard deviation ($\sigma$) of the absolute difference, and the standard deviation ($\sigma'$) of the difference for each extensometer.
Fig. 4. Temporal evolution of the estimated deformation for the best CP match (squares) and the extensometer time series (circles). Each plot show the mean ($\mu$) and standard deviation ($\sigma$) of the absolute difference, and the standard deviation ($\sigma'$) of the difference for each extensometer.

In this sense, in the second step of the comparison, the proximity of the CP to the ground level has been considered to select the best match from the CP's nearest to the extensometer. After this step, the absolute difference values for all the benchmarks yield $\mu = 3.9$ mm and $\sigma = 1.8$ mm. As in the previous section, the standard deviation of the difference between CPT and LOS-projected extensometer deformation time series was calculated, resulting in $\sigma' = 2.3$ mm. Note that 34% and 60% of these differences are included within the $(−\sigma',+\sigma')$ and $(−2\sigma',+2\sigma')$ intervals, respectively.

Fig. 4 presents the temporal evolution of the deformations measured by the CP technique and by the extensometers (projected along the LOS). A global agreement is evident between both types of measurements, except at the locations of extensometers v6 and v4. In these particular locations, the non-linear deformations shown by the extensometers are not well estimated by the CP technique.

### 3.3. Experimental comparison of SPN and CPT approaches

As it is already discussed in this paper, both DInSAR techniques have been applied to the same SAR dataset, corresponding to the period from 1995 to 2005. Despite the use of the same original images, the data were processed by different groups, in different hardware and software platforms, and by using different ground control points for zero displacement. Therefore, it is interesting to carry out a comparison of the space-time information retrieved by both algorithms. In principle, the comparison is not straightforward because the reference pixels (also known as seeds) employed in both techniques are different. In this sense, the proposed methodology has been followed: (1) to compare the accumulated deformation at the end of the period for the entire SPN and CPT datasets; (2) to compare both deformation evolutions in time at representative locations of the study area.
The analysis is performed by first selecting and evaluating all SP’s included within a circle around the centre of each CP. The radius of the circle is 57 m. The deformation estimated at the CP’s are compared against deformations at all their inscribed SP’s. The first assessment consists of identifying, for the whole 20 km × 8 km study area, the number of CP’s whose accumulated deformation value is within the range of accumulated deformations of their corresponding inscribed SP’s (hereafter the range will be denoted as [SPmin, SPmax]). A tolerance of ±0.2 cm is applied when identifying this set of CP’s. All CP’s whose accumulated deformation is within the range [SPmin – tolerance, SPmax + tolerance] will be identified as Δ = 0. Note that if there is only one SP inside the circle, the range for deciding whether the CP is Δ = 0 will be [SP – tolerance, SP + tolerance]. After identifying all CP’s denoted as Δ = 0, the remaining CP’s are classified by establishing several intervals of 0.2 cm (i.e. the tolerance) above and below the main interval already defined. For instance, a CP whose deformation is 0.3 cm smaller than the minimum SP deformation is marked as Δ = –1, and analogously, but with positive Δ for the CP’s with larger deformations. The general procedure is graphically explained in Fig. 5. A map with the values of Δ is also depicted in this figure for illustrating the spatial distribution of this parameter, which symbolizes the agreement between the estimations delivered by both techniques.

The results of the comparison between both datasets, expressed with the Δ parameter, is shown in Fig. 6. The overall agreement, Δ = 0 between both datasets is 57% (see central bin in Fig. 6). If we only consider the CP’s that have experienced an absolute deformation greater than ±1 cm are considered, the agreement is 55%, and if only the CP’s with an absolute displacement larger than ±3 cm is considered the coincidence is 50%. Hence, the agreement is almost independent of the estimated deformation. However, it is important to note that the population of CP’s with positive Δ is significantly greater than that of negative Δ. This means that the CP technique has estimated less deformation than the SPN technique. Nevertheless, this difference could be reduced if one takes into account the CPT estimated deformation at the location of the SPN reference point. This difference, which will be detailed later, generates an offset between both sets of estimates.

A comparison has been performed between both deformation time evolutions around the extensometers and other representative locations of the study area (see Fig. 7). The CPT benchmarks
selected for this comparison are the same as those selected for the CPT validation, and only in the case that no SP were found within the CP circle area, a nearby different CP is selected. As in previous sections, the absolute difference between CPT and SPN time series was calculated, and also the mean values of all the SP circumscribed within each CP area. The overall absolute difference between both techniques yields $\mu = 6.9$ mm and $\sigma = 3.8$ mm. Nevertheless in a second stage of the comparison, by employing only the best SP match (most similar) around each CP, the resulting statistics are $\mu = 3.7$ mm and $\sigma = 2.4$ mm. Note that retrieved parameters by both techniques around the SP reference point are $\mu = 4.4$ mm and $\sigma = 2.8$ mm, respectively. This dif-

Fig. 6. Distribution of $\Delta$ values of the CPT/SPN comparison.

Fig. 7. Subsidence profiles of the best SP match (circles) and the CP (squares) time series. Each plot show the mean ($\mu$) and standard deviation ($\sigma$) of the absolute difference.
ference may explain the observed offset between both sets of estimates described above. Another explanation may be the nature of the CP size (80 m × 80 m), which does not permit to distinguish if there is a single reflector within the CP area that dominates the SAR backscattering response or if it is the average of many reflectors.

A good coincidence can be observed in Fig. 7 between the temporal evolution of the deformation for both datasets, except for extensometer v4. In this particular location, as it was already noticed in the previous section, the CPT estimated deformation does not coincide so well with the deformation retrieved by the extensometers. In the case of extensometer v8 both dataset are consistent with respect to extensometer monitoring (Figs. 3 and 4), but the SPN accumulated deformation shown in Fig. 3 was −2 cm, whereas the one derived by the CPT in Fig. 6 is close to 0. This apparent inconsistency is due to the range of deformations estimated in the SP’s selected around benchmark v8 (Section 3.1), which vary between 0 and −2 cm.

Following the comparison methodology proposed in this section, two SP’s have been identified within CP1 area (see Fig. 8 left). The topographical error analysis, explained in Section 3.1, indicates that SP2 is closer to the ground level than SP1. This observation is supported by the analysis of the SP’s on the orthoimage, where it can be appreciated that SP1 is located in building “a”, whereas SP2 is located between two roads. Hence, the estimated total deformation of CP1, −0.3 cm, is close to that of SP1, −0.9 cm, and differs from that of SP2 which is −2.1 cm. Consequently, for this particular case, the analysis of the SP’s values within CP1 circle area has permitted to identify that the most probable backscattering structures responsible for the CPT estimation correspond to the building rather than the ground level structures.

This comparison has been extended to other two areas, far from the extensometer benchmarks, where estimated total deformation is greater than in the city of Murcia (around b and c in Figs. 2 and 7). In both cases, a difference of $\mu = 11.7$ and 16.8 mm has been obtained between both CP’s and their respective SP populations. Nevertheless, this difference is reduced to $\mu = 3.5$ and 9.0 mm for the best match SP comparison.

In Fig. 8(right), one of these cases (around c in Figs. 2 and 7) is analysed in detail. The estimated total deformation of CP2 is −6.6 cm, and within its circle area, two SP’s (SP3 and SP4) estimated a total deformation close to −3 cm, and another two about −7 cm (SP5 and SP6). The analysis of the residual topographic error indicates that SP3 and SP4 are closer to the ground level than SP5 and SP6. This affirmation is supported by observing the SP’s location on the orthoimage, which demonstrates that SP3 and SP4 are located in building “b”, and SP5 and SP6 are located at the ground level nearby. Finally, if the best SP match is selected, a good agreement between both time series is observed (bottom right plot in Fig. 7). Note that the circle area of CP3 shares all the SP’s with that of CP2. Nevertheless the estimated total deformation of CP3 is −3.7 cm, value, which is close to the estimated deformation in SP5 and SP6, located in the ground level between both buildings “b” and “c”. Therefore, the analysis of the SP’s values within CP2 and CP3 has permitted to identify that the backscattering structures responsible are the buildings “b” and “c”, respectively.

Consequently, in this section it has been demonstrated a very similar performance of both A-DInSAR techniques and also the possibility to distinguish the nature of the SAR backscattering response of each CP by analysing the SP’s deformation values within each CP circle area.

4. Discussion and conclusion

Both A-DInSAR techniques have observed a maximum total subsidence of 10 cm and the same subsiding areas, showing a clear coincidence in their spatial extent and location. Concerning the spatial density of both techniques measurements, 39 000 SP’s were measured over the 20 km × 8 km test site, with a spatial density of 245 SP km$^{-2}$. This is a considerable amount of observations if one takes into account that over 50% of the study area is occupied by agricultural fields (Gumiel et al., 2001). In fact, if only the 3 km × 3 km urban area of Murcia is considered, the spatial density is 665 SP km$^{-2}$. In the case of the CP technique, about 9000 CP’s were measured over the study area, with a spatial density of 54 CP km$^{-2}$, and 165 CP km$^{-2}$ for the urban area. Note that the size of the CP’s is greater than that of the SP’s, so the spatial coverage is similar, as illustrated in the maps included in Fig. 2. Consequently it is observed that for both techniques, the density of observations is reduced to the 1/3 in non urban areas. Overall, the average density of observations estimated with both techniques has been four times lower than that obtained in Barcelona with the same techniques by Crosetto et al. (2008) and Mora et al. (2003). This shows that not all the urban environments are equal for the application of A-DInSAR techniques, and this depends upon aspects like the availability of images SAR, the size of the city, the width of the streets, the presence of fields and gardens, etc.

The comparison of both techniques with extensometer boreholes has demonstrated their capability to monitor ground deformation evolution in time with millimetre accuracy. When the results of both validation experiments are compared, a similar performance is noticed for both techniques. Table 2 summarizes the
results of the best pixel match compared against the extensometer boreholes measurements. It is observed that the mean and standard deviation of the absolute difference between both techniques is \( \Delta \mu = 0.5 \) mm and \( \Delta \sigma = 0.3 \) mm respectively.

The standard deviation (\( \sigma_2 \)) in Table 2, corresponds to the standard deviation of the mean of the absolute difference and provides information about the dispersion of the total mean with respect to the mean of each extensometer benchmarks. The CPT has double the standard deviation obtained by the SPN technique because the comparisons with some extensometers are distilled from the mean. For instance, in the case of extensometer v6 the mean is 13.5 mm, whereas the mean of v8, v17, v15, e6 varies between 0.7 and 1.9 mm. The errors \( e_1 \) and \( e_2 \) in Table 2 represent the \((\mu - \sigma_1, \mu + \sigma_1)\) and \((\mu - \sigma_2, \mu + \sigma_2)\) intervals and the percentage (% of the absolute differences between the time series included within these intervals. The normal distribution of the absolute differences for the SPN and the CPT techniques with respect to the extensometer benchmarks are found between \((1.7; 4.7)\) and \((0.8; 7.0)\) respectively. The last columns of Table 2 report the standard deviation interval (\( \epsilon^\prime \)) of the difference between the SPN/extensometer and CPT/extensometer deformation time series, and a very similar performance of both techniques is observed. Finally, the absolute difference of the CPT/SPN comparison corresponds to the \((1.3; 6.1)\) interval, which agrees with the range of values shown above.

Table 3 compares the results presented in this paper with the most recent validation experiments available in the scientific literature, demonstrating the realistic numbers achieved in this analysis. A-DInSAR techniques have been compared with traditional geodetic techniques by employing three different approaches proposed by different authors: (a) the comparison of the linear rate of the movement, i.e. the velocity error, which achieves values below 1 mm/year; (b) the comparison of the absolute difference of the deformation time series, which has provided in this study error values below 6 mm; and, finally, (c) the comparison of the difference of the deformation time series, resulting in this case, in an error interval below \( \pm 4.6 \) mm for more than 60% of the comparisons. There are other important aspects that have to be considered when comparing the results of validation experiments. The velocity accuracy depends on the temporal span considered for the A-DInSAR processing since the higher the temporal span (fourth column from the left) the more accurate the velocity estimation will be. The same reasoning can be applied to the spatial distribution of the benchmarks: higher spatial separations mean lower accuracy because of the increase of the distance from the reference points. In the eighth column from the left, the maximum distance between ground truth points is shown for the different validation experiments. In Los Angeles Casu et al. (2006) estimated a variation rate of 0.05 mm/km among 38 benchmarks distributed in a 70 km \( \times \) 80 km. In the present study this aspect has been not considered because the extensometer benchmarks are located within a 5 km \( \times \) 5 km area and therefore the effect of the ground truth separation is minimal.

The presented A-DInSAR analysis in Murcia demonstrates the good performance of both CPT and SPN techniques to estimate the deformation evolution in time. The following aspects can be highlighted:

- The main difference between both techniques is the operative resolution, the SPN technique works at full resolution, 4 m \( \times \) 20 m, and has provided four times a greater density of observations than the CPT technique, which operates at low resolution, 80 m \( \times \) 80 m.
- The average density of the observations estimated with both techniques has been lower than in other urban case studies. This is due to the presence of agricultural fields. This evidences that not all the urban environments are equal for the application of A-DInSAR techniques, and several aspects should be considered, like the availability of SAR images, the size of the city, the width of the streets, the presence of agricultural fields and gardens, etc.
The methodology used to analyze A-DInSAR data has permitted to discriminate those pixels that are closer to the ground level. In this sense, it has been demonstrated that the studied subsidence is a regional phenomenon that affects more intensely ground level structures than buildings. Consequently, this analysis can be especially useful to distinguish regional from local deformation processes in other study areas.

The validation of both low and high resolution A-DInSAR techniques revealed that, even though the SPN technique locates the estimated deformation more precisely, the precision of the estimation of the deformation is very similar. Note that the absolute difference between both A-DInSAR techniques with respect to extensometer measurements is almost inexistent ($\Delta \mu = 0.5 \text{ mm}$ and $\Delta \sigma = 0.3 \text{ mm}$).

Finally, the spatial and temporal comparison of the deformation data estimated with both A-DInSAR techniques has demonstrated a very similar performance and also, the possibility to distinguish the nature of the SAR backscattering response of each CP by analysing the SP’s deformation values within each CP circle area.

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