Subsidence activity maps derived from DInSAR data: Orihuela case study

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First at all we would like to thank referee # 2 for agreeing to review the article. We appreciate the valuable comments as they all have helped us to significantly improve the paper. Before responding in detail to comments we would like to emphasize that the paper has been reorganized in order to improve presentation and to make it more readable. The new version of the paper can be found as a supplementary file. In this document referee's comments are in italic bold font whereas authors' answers are in blue font.

Before the detailed comments, it has to be noted that part of the manuscript has been published by Sanabria et al. in Mathematics of Planet Earth, Lecture Notes in Earth System Sciences 2014, pp 267-270 (*http://link.springer.com/chapter/10.1007%2F978-3-642-32408-6_60****), although it is clear that the latter is only a 4-page long extended abstract from a recent conference (i.e. IAMG 2013, held in Madrid). Probably the authors should cite it and acknowledge the relationship of this paper with the above publication (e.g. by declaring that it is a longer version of the paper already published).***

The reviewer is right. We published a very short (4 pages) paper briefly describing the methodology. The present paper is a considerable improved version of the cited one containing all the details and results for implementing the proposed methodology. In the new version, the short paper has been cited in the introduction.

Comment 1 - The abstract is clear and concise, although the authors do not report quantitative information on the results of their research. The latter would be added value to the paper, so I suggest the authors improve the text accordingly.

Answer 1 - The 100% success rate of the qualitative evaluation of local subsidence activity map has been introduced in the abstract.

Comment 2 - The first paragraph of the Introduction (page 5366, l.18-25) includes a sequence of statements regarding land subsidence and water withdrawal, structural motions, damages and monitoring, which would benefit from the addition of specific supporting references to scientific and technical literature. The sole reference Tomás et al. 2013 seems not sufficient to support the entire set of statements, although this is a review of the subject 'subsidence measured with InSAR'. Please consider related work and include appropriate references.

Answer 2 - New references have been included in this paragraph.

For monitoring the following references were added:

- Galloway, D.L., Jones, D.R., Ingebritsen, S.E. (1999). Land Subsidence in the United States U.S. Geological Survey Circular U.S. Geological Survey, Reston, Virginia, p. 177.
- Galloway D. and Burbey T. (2011). Review: regional land subsidence accompanying groundwater extraction. Hydrogeol J 19(8):1459–1486. doi:10.1007/s10040-011-0775-5
- Poland, J.F., Yamamoto, S. and working group (1984). Field measurements of deformation. In: Poland, J.F., ed., 1984, Guidebook to studies of land subsidence due to ground-water withdrawal: United Nations Educational, Scientific and Cultural Organization, Paris, Studies and reports in hydrology 40, pp. 17-36.

For foundation the following references were added

- Namazi, E., Mohamad, H., 2013. Potential damage assessment in buildings undergoing tilt, Proceedings of the ICE - Geotechnical Engineering, pp. 365-375.Bjerrum L (1963) Allowable settlement of structures. Proceedings of the 3rd European Conference on Soil Mechanics and Foundation Engineering, Wiesbaden, Germany, vol. 2, pp. 135–137.
- Burland JB and Wroth CP (1974) Settlement of buildings and associated damage. Proceedings of the Conference on Settlement of Structures, Cambridge, UK. Pentech Press, London, UK, pp. 611–654.
- Skempton AW and MacDonald DH (1956) The allowable settlement of buildings. Proceedings of the Institution of Civil Engineers, Part III 5: 727–784.
- Boscardin MD and Cording JC (1989) Building response to excavation-induced settlement. Journal of Geotechnical Engineering, ASCE 115(1): 1–21.

Comment 3 - Section 2, Methodology (pages 5368-5369): this section summarizes the entire methodology proposed by the authors to create activity maps for subsidence from PSI data. The section lists the various phases of the methodology, but these are mixed with discussion and results from the specific case study of Orihuela, which are then presented again in the following sections. Although it is undoubtedly useful for the readers to have a summary of the methodology at the beginning of the paper, the current content of section 2 creates confusion with sections 4, 5, 6 and 7, where a more detailed description of the various phases and steps are described, together with results. Please make the link between these sections and the subsequent ones more clear and smooth.

Answer 3 – We completely agree with the reviewer comment. The new version of the paper has been reorganized. Methodology (section 3 in the new version) has been rewritten removing the information regarding the specific study case of Orihuela. Also the methodological content from old sections 4 to 7 has been included in the methodology. For the specific geological and geotechnical information from Orihuela a new section (section 2: Description of the study area) has been added. Additionally, the information related to the application of the proposed methodology to Orihuela has been included in section 4 (Data analysis) and section 5 (Results and discussion).

Comment 4 - Page 5372, l.27 & page 5373, l.1-5: 'The thickness of the soft soils cannot be considered as an additional source of information for improving the displacement data interpolation. Although this fact is apparently contradictory to the results published by Tomás et al. (2010), the observed lack of correlation can be explained considering that the piezometric level variation is also a key variable involved in the consolidation process. The soft soil thickness has a spatial variability, whereas the second one has a spatio-temporal variability.' — please comment further these statements, and use figures or plots to explain the contradiction with the observations by Tomás et al. On the other hand, based on figure 3 it can be noted that motion values seem to be highly correlated with the thickness of soft soils, as opposed to what stated here. Please add further numerical evidences for the lack of correlation, and specify the thresholds for the Pearson coefficient to judge the data as correlated or uncorrelated.

Answer 4 – Geostatistics offers a collection of deterministic and statistical tools aimed at understanding and modeling spatial variability. Hybrid geostatistical procedures that account for environmental correlation have become increasingly popular in recent years because they allow utilizing secondary information that is often available at finer spatial resolution than the sampled values of a primary target variable. If the correlation between primary and secondary variables is significant, hybrid techniques generally result in more accurate local predictions than ordinary kriging or other univariate predictors (Goovaerts, 1999; McBratney et al., 2000; Odeh et al., 1994; Triantafilis et al., 2001).

Simulation between primary and secondary variables needs the use of Cokriging equations. Cokriging is the extension of kriging to more than one variable. Cokriging is most effective when the variables are highly correlated (Collins and Bolstad, 1996; Ashrat et al., 1997; Nalder and Wein, 1998; Apaydin et al., 2004). Because of its feasibility our intention was to use a reduced and modified form of cokriging, collocated cokriging (Wackernagel, 2009), which assumes that there is a linear correlation between the variables. The Pearson correlation coefficient was applied to check the linear correlation between the soils soft thickness and ground displacements along the LOS. This coefficient will help to decide if the soil soft thickness could be included as a secondary variable.

Pearson correlation coefficient is a measure of the strength of a linear association between two variables. Another name for this coefficient is the Pearson product moment correlation coefficient in honor of Karl Pearson who developed it about 1900 (McCullagh and Nelder 1989). Basically, a line of best fit is drawn through the data of two variables; the Pearson correlation coefficient indicates how far away all these data points are to this line of best fit (how well the data points fit this new model/line of best fit).It is not appropriate to analyse a non-linear relationship using a Pearson coefficient. The scatter diagrams between the average displacement and the thickness soft soils are added as appendix A. The resulting Pearson coefficient for each period (-0.22 y -0.52) indicates that the soft soils thickness and the ground displacements along the LOS are not linearly correlated and/or other variables might also be involved. Kaiser (1974) recommended accepting values of Pearson correlation coefficient ≥ 0.5 and described values between 0.5 and 0.7 as mediocre; 0.7 and 0.8 as good, 0.8 and 0.9 as great, and > 0.9 as superb. Therefore, using Kaiser's scale, the values obtained indicate that our variables have a poor linear correlation. Therefore, the soft soils cannot be considered as an additional source of information for improving the displacement using collocated cokriking data interpolation, which requires a linear correlation between the variable to be interpolated and the additional one.

The observed lack of high linear correlation can be explained considering that the ground displacements are the result of the combined and superposed effect of piezometric level changes and the soil thickness deformability that do not follow a linear relationship.

Comment 5 - The PSI data for the test area do not cover homogeneously the monitored area, hence the spatial interpolation of displacement data based on points which are several kilometres away is undoubtedly risky and of little reliability (see Fig.4 and sparse location of PSI data across the river plain). PS points located far away are very unlikely to be correlated with areas of no PS, hence are not significant. Please comment this aspect further, and discuss limits and issues relating to this evidence, as well as how

Answer 5 – The interpolation is based on a variogram model. The variogram model reflects the spatial behaviour of PSI data taken into account the spatial correlation.

The variogram determines the relationship between the distance separating nearby samples and the amount of correlation present. Through the process of variogram analysis, the spatial correlation structures of the variable of interest can be identified and quantified. The variogram, departing from classical statistics, demonstrates that all samples are not equal for estimation purposes. Rather, the usefulness of a sample for prediction purposes is related to its spatial location. Mathematically samples close to an unsampled location being estimated are better estimator than samples farther away. The variogram takes into account that as the distance from known sample locations to unsampled points increases, the uncertainty of or difficulty in estimating these unsampled locations also increases. Whereas variograms provide the assessment of the spatial correlation structure present, the geostatitiscal interpolations and simulations provide the machinery that enables to use more fully information from the variogram. The estimation of the unsampled location has been designed to minimize the error associated with the estimate. Error minimization is a very desirable attribute and a fairly common technique in the statistical world. This explanation has been taken from the book "Geostatistical Error Management: Quantifying Uncertainty for Environmental Sampling and Mapping" by Jeffrey C. Myers (1997).

On the other hand, as is explained in the methodology section, the subsidence activity maps consist on two surfaces. The first one is the interpolation surface with his level of confidence associated. The second one is the variance surface that provides information on the reliability of the interpolation.

Therefore for each point in the analysed area, we obtain a value that takes into account the spatial correlation and by the variance we know the spatial reliability of this value.

Comment 6 - per page 5368, l.18-24, the cumulative displacement values used by the authors refer to the satellite LOS component of motions (i.e. the raw output of the PSI processing), and not to the recomputed vertical values. For the analysis of building displacements and the application of the Serviceability Limit State (SLS) criterion, it is clearly necessary the use of vertical components, and not LOS ones. Please first comment this aspect with regard to civil engineering and geotechnical standards. It is also highly recommended that the authors re-compute all the displacement values from LOS to vertical, and recalculate all subsequent parameters for the various buildings by taking into account this conversion. Results discussed in sections 4, 5, 6 and 7 should be rectified accordingly.

Answer 6 – To more realistic analysis the thresholds set by the literature for the SLS have been projected along the LOS for a direct comparison (see eqs. (2) to (6) and Table 1). The explanation of this change has been introduced in the text (section 3) and the consequent changes in the damage assessment have been also modified in the results section.

Comment -7-the figures with PSI results need to include locations of the reference points for the two datasets. Were these identified at the same location for both datasets, 1995-2005and 2004-2008? If yes, please specify the assumptions made for this location, and the selection criterion for this point. If not, it is clear that the two datasets and results of the methodology would be difficult to compare as they are, and these would need calibration to a common reference point, before any statistical and structural analysis. Please clarify and, in case, calibrate the two PS datasets.

Answer 7 - Both datasets have been processed in relation with reference points located in Murcia City, 20 km west of Orihuela city along the axis of the basin. It is quite difficult to include both cities in a unique figure without losing a lot of detail; this is the reason why reference point has not been shown. Nevertheless, in the new version of the paper a new sentence explaining the location of the two reference points has been included in the text. Note that, although the reference point is not the same for both datasets, the method only requires a stable reference point. The references points were located in nearby areas where no displacement occurred during each of the considered periods. The validation experiments (Herrera et al., 2009a, b;Tomás et al., 2011) performed between SPN displacement measurements and the extensometric network of Murcia, provided a similar cumulative error (± 5 mm) for both periods. On the other hand, the average displacement rate of the PSs included within the stable lithologies (i.e. the mountain ranges) is below 2 mm/yr, which is the common stability threshold adopted in the scientific literature for C-band satellite sensors.

Thus, we can conclude that the two dataset, and their derived results, are comparable even though they don't have the same reference point.

Comment -8- Please specify and discuss geolocation accuracy of the two SPN datasets, including internal precision of the SPN points, accuracy with respect to the SRTM DEM, and final external accuracy of the points after the geocoding to map coordinates. In section 4, the authors should also mention the input pixel size of the satellite data of the two stacks of SAR and ASAR data, and multi-look factors used during the SPN processing. They also may want to relate the latter with the final geolocation accuracy of the points.

Answer 8 - The main characteristics of the processed data stacks required by the reviewer have been included in a new table (Table 2). The geolocation accuracy and its implications are discussed in the answer to comment 9

Comment 9- Section 7, page 5376, l.23-26 & page 5377, l.1-3: the authors use a buffer area of 14m around each building to calculate the angular distortion and differential settlement for the application of the SLS criterion. The authors need to comment about the choice of this size for the buffer areas, in respect of: (i) the resolution of the satellite images (around 30m), the interpolated maps (20m), and the geolocation accuracy of the final SPN results/data (as per comment above regarding accuracy of the geolocation). These aspects and related assumptions are critical, and the above seem a contradiction between the local scale (single building) of the SLS analysis, and the resolution and accuracy of the input satellite SPN data

Answer 9 - ERS and ENVISAT satellites full operative resolution is 4 m x 8 m in orbital coordinates, which represents approximately 4 m x 20 m at ground coordinates. The geolocation accuracy of every PS obtained from the SPN processing is ± 5 m for 1995-2005 period and ± 3 m for 2004-2008 period. Therefore the PS location (± 3-5 m) indicates the most probable ground surface structure backscattering the radar signal more intensely, within the 4 m x 20 m area (Crosetto et al. 2010). Assuming that the ground backscatter is certainly located within the 4 m x 20 m area, the interpolated maps have been generated with a 20 m x 20 m resolution. The 14 m buffer area around each building represents the radius of the circle inscribing every PS, i.e. the "influence area" for each PS (4 m x 20 m aprox.). In this context the number of interpolated pixels selected to perform the SLS calculations for each building varies from 2 to 43 for the 27 historical buildings. Only for two buildings (22 and 23 in Table 5) the SLS are calculated with less than 5 pixels, due to their small area. In these cases, the predictions might not be accurate enough and more resolution would be required.

Comment-10-Section 7.3: at the beginning of the manuscript, at page 5369, l.9-12, the authors state that they have calculated maximum differential settlement and angular distortions for each historical building of the Orihuela city, however, in section 7.3 only the results for a single church (Santa Justa and Rufina church, see section 7.3) are shown and discussed in detailed. Indeed, there are only final statistics about false and true positives and negatives with respect to a 'damage inventory'. To this aim,

please specify and describe the content of the 'damage inventory' (page 5378, l.6-11), i.e. type of information recorded within the inventory. And also the level of completeness of the inventory (at l.5-6, the authors state this is not exhaustive).

Answer 10 – The referred sentence has been removed from the text. In section 5 now it is clear that the maximum differential settlement and the maximum angular distortion are calculated for the 27 historical buildings located in Orihula city. A highly detailed damage report is only available for the Santas Justa and Rufina Church. Thus, a detailed validation of the methodology can be only done in this building. From the 26 remaining buildings, only for 9 of them a brief description of the structural damages is available through literature or fields works. A new table (Table 5) summarizes this information. Consequently, in summary, in the new version of the paper the evaluation of the SLS is performed considering 10 buildings where damages are available and only for one of these buildings a detailed analysis has been performed. For the 17 remaining buildings the expected damage is assessed trough the proposed methodology, although the validation of the results will be performed in the future after the elaboration of damage inventory for these buildings.

Comment - 11-As for the entire set of historic buildings, it would be useful to show and analyse results for all 27 historical buildings, for instance, by creating a comparative table with maximum differential settlement and angular distortions for each building. Please also number and show the location of all buildings in one of the existing figures. The authors should also discuss further these results with respect to the total area of each building, and in relation to the resolutions and accuracies mentioned above. Considering the dimension and areas of these buildings, are the resolution and accuracy of the data of this research suitable? Please comment on the significance and suitability of these data. As per above, there seems to be discrepancy between the spatial scale of the two layers (satellite data vs. building dimensions), with medium resolution data that are used here for a local scale, building specific assessment. Please clarify and rework the text accordingly.

Answer 11 – In the new version of the paper, Table 5 shows a summary of the numerical results derived from the methodology proposed in this work for each of the 27 historical building. As mentioned in the previous comment response, this table also includes the damage description and the information from each building (style, century, etc.). Additionally, according to the reviewer comments, the location and the label of the 27 building is shown in Figures 7 and 8 in the new version of the paper.

A discussion about the resolution vs building dimension can be found in the answer to the comment 9. Also a clarification about this issue has been introduced in the text, at the beginning of section 5.2.

Comment -12-Regarding the analysis of Santa Justa and Rufina church, based on figure 11, it seems that the interpolated motion map is based only on 1 PS, hence the maps used for the SLS analysis and assessment is based on a single point and their reliability appears extremely low. Please clarify and discuss this aspect further, in relation to this building, and all other 26 historical buildings of the city. Show activity maps for some of these buildings, and the number of input SPN points present in their buffer areas. This aspect is very critical for the reliability of the proposed activity maps. Please also add data from the damage survey of the Santa Justa and Rufina church and other buildings, e.g.reported damages, number, aperture and size of cracks.

Answer 12 - As explained in the methodology section, the used SLS are not calculated from the PSs but from the subsidence activity maps. In other words SLS are calculated from the interpolation surfaces (mean and P68). Thus, the buffer in each building includes n pixels. Consequently, these pixel values are then used to calculate the SLS. In the case of Santas Justa and Rufina Church 14 pixels are used for the calculation of the maximum differential settlement and the maximum angular distortion. As for the interpolation, the reliability of SLS is given by the variance. In the case of Santas Justa and Rufina church, the mean variance for the periods 1995-2005 and 2004-2008 are 178 and 117 mm^2, respectively.

The details of Santas Justa y Rufina damages survey can be found in Tomás et al. (2012). In this paper we have made a summary of the damages. As for the other buildings, we do not have an exhaustive inventory, thus this information is only presented in a summarized way in a new table (Table 5).

Other corrections related to presentation.

Describe the meaning, mathematical formulae, symbols, and add specify references and comments regarding the following: (i) Pearson correlation coefficient (page 5372, l.24-27); maximum differential settlement and angular distortions (page 5368, l.3 & page 5369, l.6-7; move SLS formulas and parameters from Figure 8 to the main text).

More in general, some repetitions and duplications of various sentences are present throughout the manuscript (e.g., across the above sections, and the discussion and conclusions). These may cause confusion in the readers, and make the procedure difficult to export to other test areas or to allow reproduction by other scientists. I suggest the authors rework the text to restructured the layout, and reduce the above duplications and increase clearness. Section 3 could also be moved before the methodology, to make the description of the approach flow better and smoothly – with no interruptions by the description of the case study area.

Section 8 'Discussion and conclusions': this only includes conclusions, and duplicates sentences from the previous sections. Please add a specific section with detailed discussion and analysis of the results for the historical buildings.

Figure 3: add location of figure 6, 7, 9, 10, 11.

Figure 4: change colours for the last two classes of points, to make them more distinguishable in the legend and map.

Figure 8: move the bottom of the figure to the text and describe SLS formulas and parameters into detail, to make the method exportable to other sites and data.

Answer – According to the referee comment, the description of the study area has been moved after the introduction paragraph. The discussions are now integrated with the results to increase the clearness of the paper. A specific paragraph is devoted to compare the results of the SLS and the available inventory. The conclusions have been rewritten in order to avoid repetition.

Fig. 3 (in the new version of the paper Fig 4) has been reworked and in the new version includes location of Fig 7, 8 and 9. The location of 27 historical buildings can be found in Figs. 7 and 8.

Fig. 4 (in the new version of the paper Fig 5) has been modified. Different colours have been selected to improve the clearness of the figure.

A reference for Pearson Coefficient has been added and the SLS formulas are now include in the text (eqs. (2) to (6)) to allow the application of the proposed methodology by other scientists.