Validation and intercomparison of Persistent Scatterers interferometry: PSIC4 project results

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1. Abstract:

This article presents the main results of the *Persistent Scatterer Interferometry Codes Cross Comparison and Certification for long term differential interferometry (PSIC4)* project. The project was based on the validation of the PSI (*Persistent Scatterer Interferometry)* data with respect to levelling data on a subsiding mining area near Gardanne, in the South of France. Eight PSI participant teams processed the SAR data without *any a priori* information, as a blind test. Intercomparison of the different teams' results was then carried out in order to assess any similarities and discrepancies. The subsidence velocity intercomparison results obtained from the PSI data showed a standard deviation between 0.6 and 1.9 mm/yr between the teams. The velocity validation against rates measured on the ground showed a standard deviation between 5 and 7 mm/yr. A comparison of the PSI time series and levelling time series shows that if the displacement is larger than about 2 cm in between two consecutive SAR-images, PS-InSAR starts to seriously deviate from the levelling time series. Non-linear deformation rates up to several cm/yr appear to be the main reason for these reduced performances, as no prior information was used to adjust the processing parameters. Under such testing conditions and without good ground-truth information, the phase-unwrapping errors for this type of work are a major issue. This point illustrates the importance of having ground truth information and a strong interaction with the end-user of the data, in order to properly understand the type and speed of the deformation that is to be measured, and thus determine the applicability of the technique.

2. Introduction

Repeat spaceborne Interferometry is a well known technique to assess the displacement of the ground surface. It measures the displacement in the sensor's Line-Of-Sight direction from the phase of the signal measured by Synthetic Aperture Radar (SAR) onboard a satellite (Goldstein et al., 1988, Massonnet and Rabaute, 1993).

In order to understand the limitations of the technique and to separate the different components (deformation, height, atmosphere) of the interferometric signal, a group of methods named Persistent Scatterers Interferometry (PSI) was developed in the late 1990's (the PSInSAR^{TM} algorithm, Ferretti et al., 2001). The method aims to extract the information from radar interferometry on a large set of images by taking advantage of the large data archive acquired over the last decade (mainly with the ERS satellites, Envisat and RadarSat satellites). The main idea behind the method is that some bright radar targets retain their phase and amplitude stability for a period of months or years. The phase information of these targets (here denoted Persistent Scatterers or PS) can be exploited to interpret otherwise uncorrelated long time-scale interferograms. Other alternative methods, which use a quality indicator based on the temporal coherence on sub-sampled SAR data are restricted to small baseline pairs (Small BASelines subset technique, Bernardino et al., 2002) or to points showing both a spatial and temporal coherence (Coherent Target Monitoring, Van der Kooij, 2005). In all the cases, the objective is to statistically separate the different components of the interferometric phase of points, where the phase is reliable for the whole data set, to provide a precise assessment of the ground surface deformation.

End-users outside the radar community have little experience in utilizing the products delivered with PSI methods. Thus, some concerns about PS data quality, trustworthiness and how to interpret them arose. This issue was clearly identified during the 2003 FRINGE Workshop (http://earth.esa.int/fringe03/Fringe_reco3.pdf). ESA (European Space Agency) which decided to initiate this validation project, named PSIC4 (Persistent Scatterer Interferometry Codes Cross Comparison and Certification for long term differential interferometry), in order to assess the performances of PSI for land deformation monitoring.

Eight PSI teams, from business or academic organizations, participated in the project: Altamira Information (Crosetto et al., 2008), DLR (German Space Agency, Adam et al., 2003), Gamma-RS (Werner et al., 2003), IREA-CNR (Institute for Electromagnetic Sensing of the Environment National Research Council of Italy, Berardino et al., 2002), TRE (TeleRilevamento Europa, Ferretti et al., 2007), TUDelft (Delft University of Technology, Kampes, 2005), UPC (Catalonia Polytechnics University, Mora et al, 2003), and Vexcel (Van der Kooij et al., 2005). 107 ERS and 10 Envisat ASAR images were delivered to each of the teams by ESA for them to produce their own PSI deformation products. Their results were then analysed by an independent validation consortium (BRGM, BGS, TNO, IG) as an anonymous procedure so the validation consortium received the data without any identification, except for a random number assigned to each one of the teams.

Past validation tests (e.g. Ferretti et al. 2007) were based on controlled displacements of corner reflector points perfectly identifiable as a PS on the SAR data set, which proved the indisputable precision (better than the millimetre) of the technique in ideal conditions. In contrast, this test aimed to address issues more oriented towards the end-user who plans to use PSI products for helping in the management of deformation hazards in a real operational situation. In particular, there is no a priori coincidence between the ground measurement points and the PS. A similar context is presented in Casu et al. 2006. The issue is addressed in section 4.1 based on the spatial characteristics of the deformation field.

This current work aims to give an insight on the information that the end user can expect from PSI. For this purpose, the project has to address some of the following key questions:

- How well does PSI describe the land deformation field, spatially and temporally?

- How accurately, and how precisely, does PSI describe the land deformation field?

- How consistent are the PSI results between the different teams?

These questions are addressed by the validation and intercomparison activities, where the results of each team are compared both against reference ground-based data and against each other in a series of tests designed to give an extended view of the performance of the PSI methods.

This paper describes the work performed during PSIC4 activities. In this project, six of the eight PSI teams used different implementations of the Persistent Scatterers technique, while the other two teams used alternative concepts (basically two coherent-based approaches). In this paper, the eight PSI teams were asked to process the SAR data according to their own PSI methodology without any *a priori* information about the type and location of deformation in the chosen test area. In addition to this paper, an extensive description of the project is available in the PSIC4 final report (Raucoules et al., 2007).

3. Test site

The test area was selected by ESA from several proposed by the validation group, who considered not only the characteristics of the deformation (size, rate) but most importantly, the availability and quality of levelling data for the 1992-2004 period.

The area of interest is located near the town of Gardanne (Bouches-du-Rhone, France) in the sedimentary basin of "l'Arc" between the Sainte-Victoire Mountain and the cities of Marseille and Aix-en –Provence (figure 1). The area of Marseille-Aix is the second biggest urbanized area in France (with more than 1.4M inhabitants).

[insert figure 1]

Figure 1: Gardanne mining area. The location of the exploited panels is shown.

The coal field (lignite) here has been mined since the Middle Ages Exploitation stopped in February 2003. Different mining techniques were used in the area. For the period of interest (1991-2004), the observed ground subsidence is associated with the coal mining exploitation using long wall mining technique at nearly 1000 m below the surface (figure 2). This technique has particular consequences in terms of size (the width of a panel is 250m) and evolution (almost immediate) of the deformation compared to older mining techniques. The older methods include chamber and pillar extraction with localised subsidence occurring over a longer time-scale.

Typically, when a long-wall panel is mined, half of the displacement (hundreds of metres wide) is produced in the first 2 months with the residual deformation occurring over the following 3 years (Arcamone, 1980). A point on the surface may be influenced by several mined panels extracted at different periods causing the deformation to last for longer periods.

[insert figure 2]

Figure 2: Detailed plan of the underground mine panels. Isolines indicate the depth of the exploitation panel.

The monitoring of land deformation effects associated with coal mining exploitation of the Gardanne area was performed through spirit levelling surveys by the French coal mining authority (CDF – *Charbonnages de France*).

The *in situ* data of the Gardanne test site have been acquired at more than 1000 points over the past decades in order to monitor the deformation effects on the surface associated with the coal mining.

[insert figure 3]

Figure 3: Gardanne mining area, levelling network . This map shows the names and locations of the levelling lines and the positions of the mining works (in gray).

Since 1990, levelling surveys have been carried out with an automatic electronic level (Leica Wild NA3003) whose bar code specified precision performances (Dommanget J.M., 2004) are:

Standard deviation of height measure error, measured point-to-point = ± 0.7 mm

Standard deviation of height error on a 1 km one-way levelling = ± 1.5 mm

4. Pre-processing

4.1 Previous corrections of the data

Although we tried hard to not modify the PSI data (in order not to add involuntary biases to the test), we observed two main problems with the data needing modifications: shifts in the geolocation and biases on the estimated velocities.

The only way to carry out the data comparison was to adjust those shifts to make the data comparible. We observed geocoding shifts by overlaying the PSI data on an ortho-rectified (in the local Lambert III Sud cartographic projection) aerial photograph. The geocoding discrepancies ranged between 5m and 80m depending on the team. After correction, the residual geocoding shifts estimated on other control points were between 3m and 23m. It is important to note that these residual errors include the error made in the identification of the radar features on the ground. A linearly varying shift would probably have provided a better final geolocation. However, we assumed that the constant shift we applied to the data was sufficient for the purpose of this study.

More generally, we emphasize the fact that for many applications where the deformation is of very small extent (e.g. shrink-swelling, cavity collapses, small landslides etc.), the geocoding issue is very important for a potential end-user. It is essential to produce data that can be overlaid with sufficient accuracy on reference maps to allow a correct interpretation. During the processing an interaction with the end-user is recommended.

The fact that the different teams did not chose the same reference point for deformation computation produced biases on the assessment of the deformation, making direct comparison impossible. We carried out a stable area adjustment based on the levelling information and the knowledge of the end-user (CDF) and chose the stable area outside the influence of the mining works. The objective is to be sure that all the PSI datasets are referenced against the same stable area as the levelling network in order to have comparable data. In a general case, the choice of a reference stable area can be critical for the measurement. In operational use we think that the reference should be selected in agreement with the end-user in order to better respond to his needs.

Once we selected the stable area (figure 4), we calculated the average deformation rate value for those PS included in the stable area and for all the teams. In this area, where the velocity should be zero and the time series should be flat, PS average velocity and time series highlighted either a subsidence or an uplift. We assume that the non-zero velocity values can be considered as a bias on the velocities affecting the whole dataset due to bad reference choices. We therefore used the computed average deformation rate values to force both the PS average velocities to be zero and time series to be flat within the stable area. In practice, we first corrected the average velocity estimations on the whole PSI dataset by subtracting the calculated stable area values from the dataset. Secondly, we corrected the time series by removing a linear trend derived from the previous velocity correction estimation.

[insert Figure 4]

Figure 4: The selected stable area (white frame) is located around the five stable levelling points identified by their codes. The triangles correspond to the levelling points, circles to PS provided by the team T4.

4.1 Interpolation of the data

The major issue for the comparison between levelling data and the PSI results comes from the fact that the spatial and temporal sampling of the PS-field and Time Series and the levelling lines do not coincide. The levelling frequency is about twice a year whereas the PSI data correspond to the sensor acquisition rate which is on average every 40 days (taking into account a gap in the acquisitions during 1994). The number of levelling points are fewer than the number of PSI points. The objective of interpolation is to define which value derived from the SAR data can be compared with a given value derived from the levelling.

The option we applied in this study was the following. We interpolated temporally the levelling data to the SAR acquisition dates and we interpolated spatially the PSI deformation values to the levelling point positions (using a limited radius of 50m around the levelling points).

The basic justification is that the studied phenomena have sufficient spatial extents to justify a spatial interpolation in a 50m radius. In fact, in this area, the subsidence bowls due to the mining works spread over hundreds of metres (Arcamone, 1980).

Now, with the selected procedure, each levelling point with given geographic coordinates can be associated to the deformation Time Series corresponding to the eight participant teams and to the levelling measures.

Our choice for the temporal interpolation of the levelling instead of the SAR data was decided in order to avoid excessive smoothing of the time series. Smoothing could hamper the assessment of the quality of the PSI time series. An additional reason is that, due to the nature of the levelling dataset, which is the compilation of 17 lines measured independently at different dates and frequencies, we were not able to define a unique temporal sampling for the levelling.

All the Time Series (SAR and interpolated levelling) were set to ‘0 deformation’ using 15/07/1992 as the reference date. This date corresponds to the oldest image used by all the teams.

We interpolated the levelling by ordinary kriging. This allowed us to retrieve an interpolation error. So, for the PSIC4 exercise, we kept only the values with an interpolation error lower than 3.5mm.
For the spatial interpolation, because the PSI results were massively oversampled with respect to levelling, a spatial kriging computation was performed for each image with a 50 metres search neighbourhood in order to reject possible variability on longer distances.

5. Intercomparison

The intercomparison activities aimed to identify relative differences between the teams. The initial objective of the exercise was to check if the different methods provided equivalent results and to assess any discrepancies. Among the tested indicators, the most relevant are: 1) the average deformation rate; 2) the density and distribution of the PS.

1) Average deformation rates.

To estimate the discrepancies between the teams' results in terms of velocity maps, we resampled the data included in a common area to a 50m by 50m grid containing the velocities of each of the teams.
Using the ISATIS™ software, we carried out a comparison by pairs of teams: for each pair of produced PSI sets, we assessed the mean of the differences, the correlation value and the standard deviation of the differences on the cell occupied by the two compared teams.
The main indicator is the standard deviation that reflects the discrepancies between teams. It ranges from 0.6 mm/yr to 1.86 mm/yr.
The mean of the differences can show possible biases, although these values have been partially affected by the stable area correction and are therefore less relevant as a performance indicator. These values range from -0.84 mm/yr to +0.44 mm/yr. The following table shows the full set of velocity intercomparison values.

Team	T1 (889pts)	T2 (5100pts)	T3 (4169pts)	T4 (6552pts)	T5 (2511pts)	T6 (1269pts)	T7 (6360pts)	T8 (17081pts)
T1		**1.57 (0.79)**	**0.85 (0.85)**	**0.88 (0.85)**	**1.23 (0.83)**	**0.84 (0.72)**	**0.96 (0.83)**	**1.44 (0.85)**
T2	**-0.26**		**0.87 (0.89)**	**1.06 (0.85)**	**1.19 (0.86)**	**0.99 (0.71)**	**1.01 (0.85)**	**1.86 (0.73)**
T3	**-0.14**	**0.12**		**0.63 (0.94)**	**0.87 (0.91)**	**0.73 (0.83)**	**0.71 (0.90)**	**1.40 (0.72)**
T4	**-0.46**	**-0.13**	**-0.24**		**1.01 (0.89)**	**0.74 (0.81)**	**0.76 (0.89)**	**1.46 (0.72)**
T5	**0.11**	**0.27**	**0.20**	**0.44**		**1.08 (0.71)**	**0.99 (0.87)**	**1.71 (0.73)**
T6	**-0.34**	**0.06**	**-0.05**	**0.20**	**-0.21**		**0.81 (0.77)**	**1.06 (0.64)**
T7	**-0.32**	**0.02**	**-0.1**	**0.14**	**-0.32**	**-0.10**		**1.33 (0.72)**
T8	**-0.82**	**-0.41**	**-0.56**	**-0.25**	**-0.84**	**-0.47**	**-0.40**	

Table 1: intercomparison of velocities. The upper right triangle contains for the teams corresponding to the rows and columns, the standard deviation of the velocity differences and the correlation (in parenthesis). The lower triangle contains the mean of the velocity differences. The number of cells occupied by each team is indicated in the first raw of the table.

2) Density and spatial distribution of the PS

PS distributionsshow large variations. For example, some teams have no PS selected in the deformation area whereas team T8 seems to have a larger density in those areas. Such differences are probably the consequence of the use of different coherence thresholds on the selection of the points.

The figures 5 and 6 show the two extreme cases observed: team T6 rejected practically all the points of the deformed area and team T8 kept a large density of points.

[insert figure 5]

Figure 5: density of PS for Team 6. The location of the main deformation (derived from conventional interferometry) is showed (blue contour).

[insert figure 6]

Figure 6: density of PS for Team 8. the location of the main deformation (derived from conventional interferometry) is showed (blue contour).

6. Validation results

The validation in this study is the comparison of the interpolated PSI data with the corresponding levelling measurement.

The first test is a semi-quantative comparison. We selected the more representative levelling line ("AXE" – located on figure 3 - it crosses the main deformed area) and visually compared the PSI data versus the levelling data along it. Figure 7 shows the spatial variation of the cumulative deformation within the period from 1992 to 1998 for each of the teams.

Most of the teams (except team T6) spatially localised the deformation. We observed dissimilarities with the levelling and between PSI teams. In particular, the PSI results seem to underestimate the higher deformations.

[insert figure 7]

Figure 7a): cumulative deformation between 06/05/1992 and 31/10/1998 along the “AXE” levelling seen by the different PS Teams and the levelling versus distance to first point. The frame corresponds to section magnified in figure 7b). We can observe important discrepancies in the area of higher deformation.

Figure 7b): Zoom of the profiles along “AXE” line in a section with moderate (less than 3cm) deformation. This gives a first insight on the relative variability between the different teams. The PSI results globally follow the levelling profile but with fluctuations (respect to levelling and other teams) of about 10-15 mm; a more precise estimation is given below.

The RMSE (root mean square error) of the PSI time series against the levelling time series are reported in table 2. The values are represented by average velocity classes (estimated on levelling). We can observe a dependence of the RMSE with respect to the velocity value (figure 8). The values range on average from 1.5 cm for the lower velocity class (less than 5 mm/yr) to 10 cm (for the larger movements (more than 15 mm/yr).

velocity (mm/yr)	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
>0	12	10	9	11	14	14	9	20
[0; -5]	18	14	14	18	14	22	9	22
]-5;-10]	38	41	38	46	32	58	25	27
]-10; -15]	108	97	90	85	86	86	75	69
<-15	93	97	151	112	106	85	99	91

Table 2. Average RMSE (mm) per velocity class and per processing chain

[insert figure 8]

Figure 8: RMSE per velocity class and per processing chain

A last indicator consists of comparing the estimation of the velocity obtained by PSI versus the levelling. The following figures show the velocity values derived by linear regression on the deformation time series, from both the levelling and the PSI on the location of the levelling points.

This allows a visual examination of the discrepancies in the area of major deformation (in agreement with the previous observations).

[insert figure 9]

Figure 9: Vertical velocities estimated from levelling data resampled at SAR acquisition dates

[insert figure 10]

Figure 10. Vertical velocities derived from PSI resampled at levelling points location. Teams T1-T4.

[insert figure 11]

Figure 11. Vertical velocities derived from PSI resampled at levelling points location. Teams T5-T8.

Table 3 gives a quantitative assessment of the discrepancies. In the conditions of the experiment (characteristics of deformation and land-use) the standard deviation of the velocity differences is about 6 mm/yr.

Team	**Number of points**	**Mean of**	**Standard deviation**

		(|Ti – Levelling|)	of (Ti – Levelling)
T1	158	2.8	5.3
T2	478	4.4	7.2
T3	328	3.9	6.6
T4	447	3.7	6.3
T5	348	3.6	6.8
T6	136	3.2	5.1
T7	417	2.6	5.7
T8	817	4.7	6.7

Table 3: Overall differences between PS and levelling velocities (in mm/yr): mean and standard deviation of difference between PSI and levelling.

To complete this comparison we have to highlight that the number of points associated with levelling is very variable between the teams (158 to 817 in the same area). For instance, team T8 produced points on most of the levelling line lengths. Therefore, the discrepancy with levelling is more affected by the effect of the underestimation of the higher deformations. The quantitative comparison is then less favourable to those who provided points in the higher deformation area, but they provided a better qualitative description of the deformation.

7. Discussion

• The PSIC4 exercise was conceived as an inter-comparison and validation of PSI data computed by eight different teams. The aim of this exercise was to evaluate the performance of eight different PSI methodologies by comparing the results with ground based observations and by inter-comparing the results from the eight processing chains. The results of this study provide an assessment of the absolute (validation) and relative (inter-comparison) performance of the PSI techniques. The PSIC4 exercise is a blind test, carried out on a mining site characterised by different magnitudes and evolutions of deformation and variable land cover. It is worth emphasising that the PSIC4 project represents a unique experiment for the number of PSI teams involved and for the quality of the available ground truth, which involve more than 1000 levelling benchmarks measured once or twice per year.

However, it is important to underline that the deformations of the PSIC4 test site, especially those of the mining area of Gardanne, where the majority of the ground truth are located, represent a difficult case for the PSI techniques. In fact, the deformations range from a few centimetres up to some decimetres, and most of the deformation occurs in a few months, a rather short period for the (at most) monthly SAR acquisitions.

Therefore, in PSIC4 the performances of PSI techniques were tested at the very edge of their capability, as the PS interferometry processing is performed in the less favourable conditions and is evaluated upon the strongest criteria.

When going through the results of the PSIC4 exercise, one should keep in mind the following issues in order to properly interpret the outcome of the study:

1. The eight teams had no knowledge of the type of deformation occurring on the test site, i.e. information such as the linearity/non-linearity of the deformation, the driving mechanism, the location of the deformation, when it started and when it ended, and the expected deformation magnitude. In general, the teams received no information about the deformation signal of interest and. the goal of the PSI analysis was not clearly specified. In contrast, the validation was focused on a specific deformation phenomenon, i.e. the deformation associated with the mining area of Gardanne. This point is important because PSI data processing has different parameters that can be adjusted for a specific application goal. For instance, the processing can be modified to take into account a priori knowledge of fast displacements.

2. The PS measurements were evaluated against the strongest criteria. For the first time the validation of PSI against levelling data was performed quantitatively to the millimetre level. Some of these criteria can be non relevant in specific applications.

The results show that the PS technique is not invalidated, but the outcomes of the PSIC4 project should be used to improve PS interferometry performances for the critical application cases.

• The main indicators investigated during the project were the following:

Time Series validations. A comparison of the spatio-temporal profiles of the levelling data and PSI data along two levelling transects show that, for this case, the stretch along the line experiencing most subsidence was not well sampled by seven out of eight teams and an underestimation of subsidence velocity was shown by all teams.

A comparison of the PSI time series and levelling time series shows that if the displacement is larger than about 2 cm in between two consecutive SAR-images, PS-InSAR starts to seriously deviate from the levelling time series. Since, for the Gardanne site, a large number of the levelling time series show large displacements for two consecutive SAR-acquisition dates (35% in excess of 2.8 cm and 70% in excess of 1.4 cm) validation results are therefore negatively biased. This also explains the low number of cases for which PS-InSAR time series and levelling time series could be tested to belong to the same population. If one only compares those time series having a maximum displacement of 1.4 cm or less for two consecutive SAR-acquisition dates, then the current study *shows average RMSE between levelling time series and PSI time series of 7 mm to 25 mm*. One has to compare this with validation studies performed on artificial scatterers which show standard errors of the time series of 2 mm. From this it can be concluded that for those locations for which phase unwrapping ambiguities do not exist, at least some of the processing chains obtain results in line with previous studies, which mainly took place under controlled circumstances. In all cases reviewed, the team's results did underestimate the subsidence rate in areas showing moderate to fast subsidence. The main reason suggested for this is the character of the subsidence process in the study area. As a result of mining activities in this area, the subsidence takes place over a relatively short time-span. The strong correlation between RMSE and magnitude of displacement for two consecutive SAR-acquisition dates, suggests that the results have certainly been affected by phase unwrapping ambiguities, leading to a systematic underestimation of the subsidence rates.

Velocity validation. The comparison of the PS-InSAR velocity with the ones derived from levelling shows an average absolute difference with standard deviations between 5 and 7 mm/yr. Again, the standard deviations are strongly dependent on the absolute value of the actual displacement of the measured point. It can reach more than 15 mm/yr on the main deformed area but generally less than 2 mm/yr on stable levelling points.

Spatial distribution intercomparison. The highest densities related to urban areas, where many scattering objects exist. Surprisingly, some teams were able to find points in areas of forest or agriculture (Team T8 in particular). Some teams (such as Teams T1 and T8) did succeed in finding PS within a rapid ground motion zone in urban areas. Other teams were not able to identify as many points in these areas. The PSIC4 exercise shows that for the case under consideration, the main area of subsidence could not, or could only partly, be assessed and identified by seven out of eight teams. The main reason for this has been the low density of Persistent Scatterers in the area of interest thus masking the actual subsidence bowl. Nonetheless, improvements are possible taking into account that one team did find a high distribution of Persistent Scatterers within the subsidence area.

Velocity intercomparison. Velocity is the basic deformation parameter derived from PSI techniques, as it is obtained by assessing a linear regression on the phase history. A very high precision was therefore expected. However, the inter-comparison results show discrepancies, in terms of standard deviation, between 0.6 to 1.9 mm/yr.

Geocoding comparison. Significant differences occur between teams, with magnitudes of 'average geocoding difference' between 6 and 80 metres before correction. Improvements can be considered and a better use of prior cartographic information (such as high resolution ortho-photos) might help.

To conclude this discussion, we will present some key outcomes resulting from the responses of the participant teams to open questions addressed after the analysis of the PSI products.

1) One of the most important conclusions of the project concerns the characteristics of the mining test site of PSIC4, which include abrupt nonlinear movements with magnitudes that range from a few centimetres up to some decimetres. These are severe characteristics from the viewpoint of C-band PSI with the temporal acquisition capabilities of ERS and Envisat. Why are the deformation characteristics so important? Because in principle, PSI can measure surface displacements with millimetric precision, but this can only be achieved under the following conditions:

- The right model to describe the deformation is adopted. This is difficult to accomplish with abrupt nonlinear movements.
- The aliasing due to low PS density and/or low temporal sampling with respect to deformation, which may cause phase unwrapping errors, is controlled. This is difficult or impossible with strong deformation magnitudes.
- The assumptions to separate the atmospheric contribution from deformation are correct. This typically fails in presence of nonlinear motion.

Most of the results of PSIC4 can be understood in the context of the above conditions: none of them is fully accomplished in the mining area of Gardanne in the context of this study.

2) It is worth underlining that the above consideration of "strong deformations" holds for C-band PSI with the current temporal acquisition capabilities of ERS and Envisat. They cannot in principle be extended to other types of SAR missions based on different bands and more frequent SAR acquisition capabilities.

3) The PSIC4 project was conceived in a specific framework, where the teams worked under "blind conditions", with no a priori information on deformation type, driving mechanism, deformation magnitude, etc. Furthermore, they had no information about the exact deformation signal of interest, i.e. the goal of the PSI analysis. By contrast, the validation was focused on a specific deformation phenomenon, *i.e.* the deformation associated with the mining area of Gardanne. This point is important because it played a key role in the PSI processing. In fact, instead of tailoring the processing to a specific objective of the analysis, the teams used a standard approach and processing which is feasible with reasonable resources. It is worth emphasising that the area covered by most of the teams is considerably larger than the 100 km^2 area used for the validation. None of the PSI teams has performed an advanced or refined PSI analysis, because neither the area of interest nor the goal of the refinement was defined. This again explains most of the PSIC4 results, e.g. the lack of PS in the mining area "of interest".

4) It is worth analysing a specific consequence of the above point, which explains the different densities achieved by the teams. The PS densities are different because there is no "definition" of what exactly is a PS. The teams used their standard PSI approach (instead of an advanced or tailored one) and delivered the PS only where both velocity and time series could be extracted with reasonable reliability. Unfortunately the validation area represents a difficult area, where phase unwrapping errors represent the main problem. Due to the high probability of this type of error, many teams did not deliver reliable information. Note that this did not occur outside the mining area, i.e. in the great majority of the covered areas, see point six.

5) Considering the above points and the results achieved in the Gardanne mining area we can say that PSIC4 has clearly demonstrated that the PSI limitations are real, i.e. that PSI is not applicable everywhere. Though this was already clear to many PSI specialists, this evidence has now been widely documented.

6) To conclude, the limitations of PSI over deformation areas with similar characteristics to Gardanne open a series of important issues for the future. The first one is the importance of a feasibility study before running a PSI analysis. This may help in avoiding false expectations and disappointing results.

A second issue concerns the appropriate ways to inform the PSI users of the limitations of the technique, especially in those cases where PSI is employed under the non-ideal conditions. Then it is interesting to investigate the possibility of using alternative techniques to PSI, like DInSAR which could provide useful information in difficult applications like mining areas.

8. Acknowledgement

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For D. Tragheim and L. Bateson, this paper is published with permission of the Executive Director, British Geological Survey.

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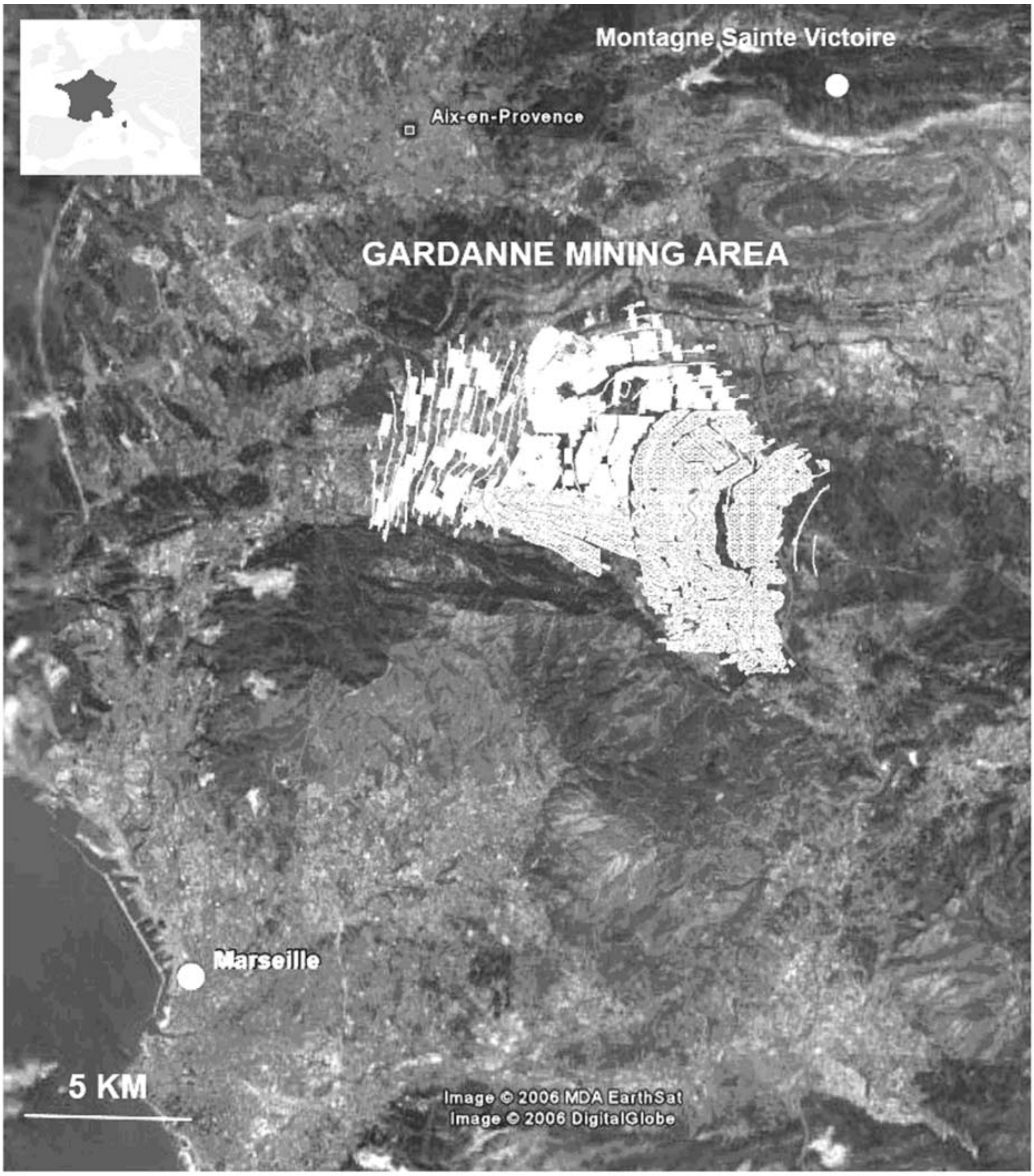

Montagne Sainte Victoire
Aix-en-Provence
GARDANNE MINING AREA
Marseille
5 KM
Image © 2006 MDA EarthSat
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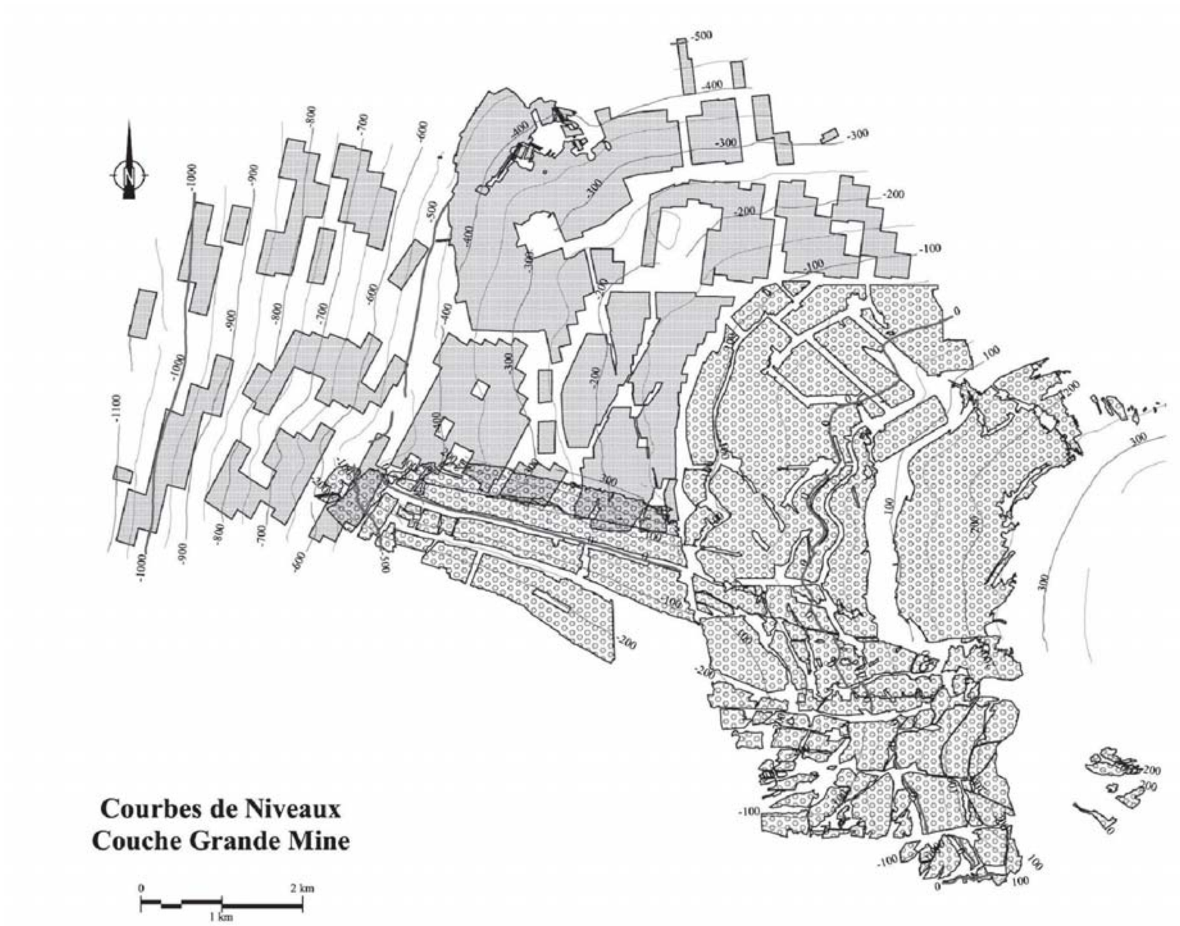

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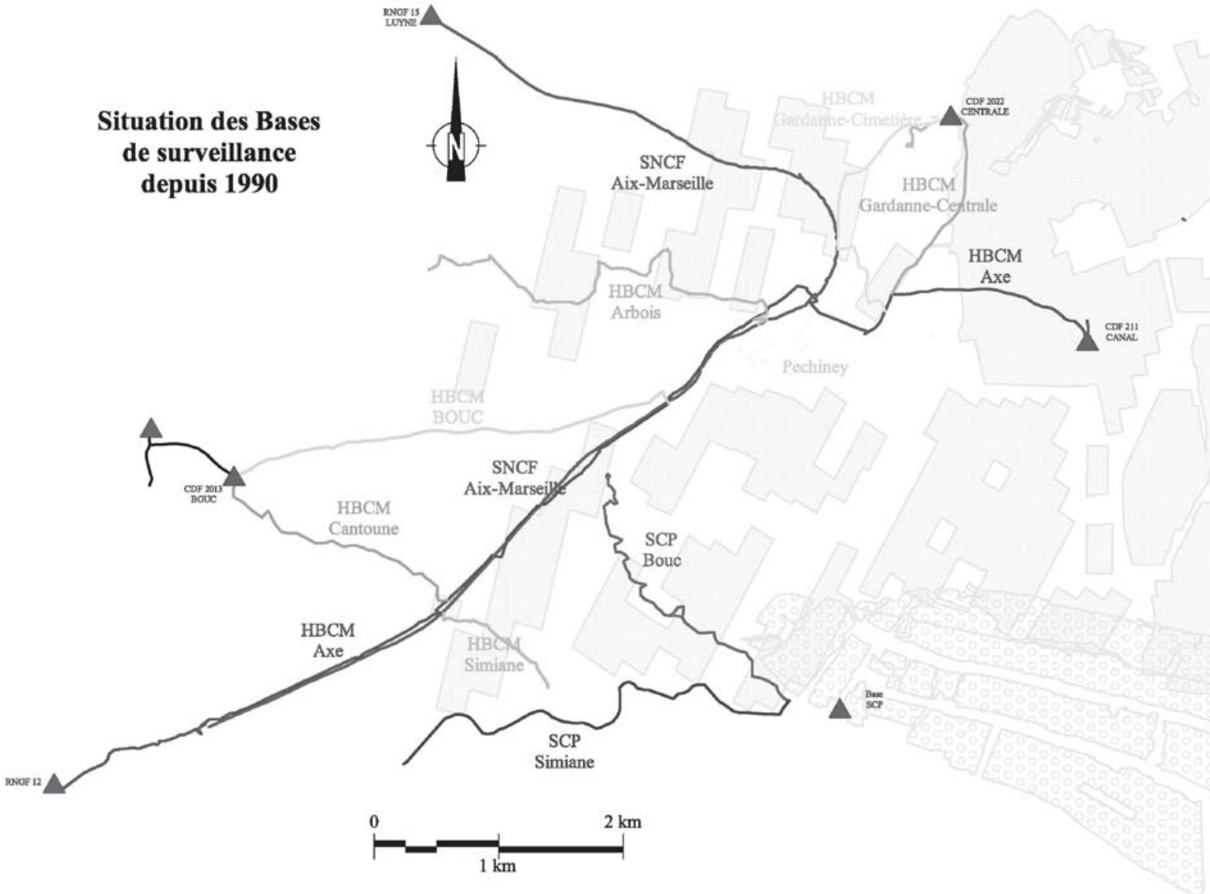
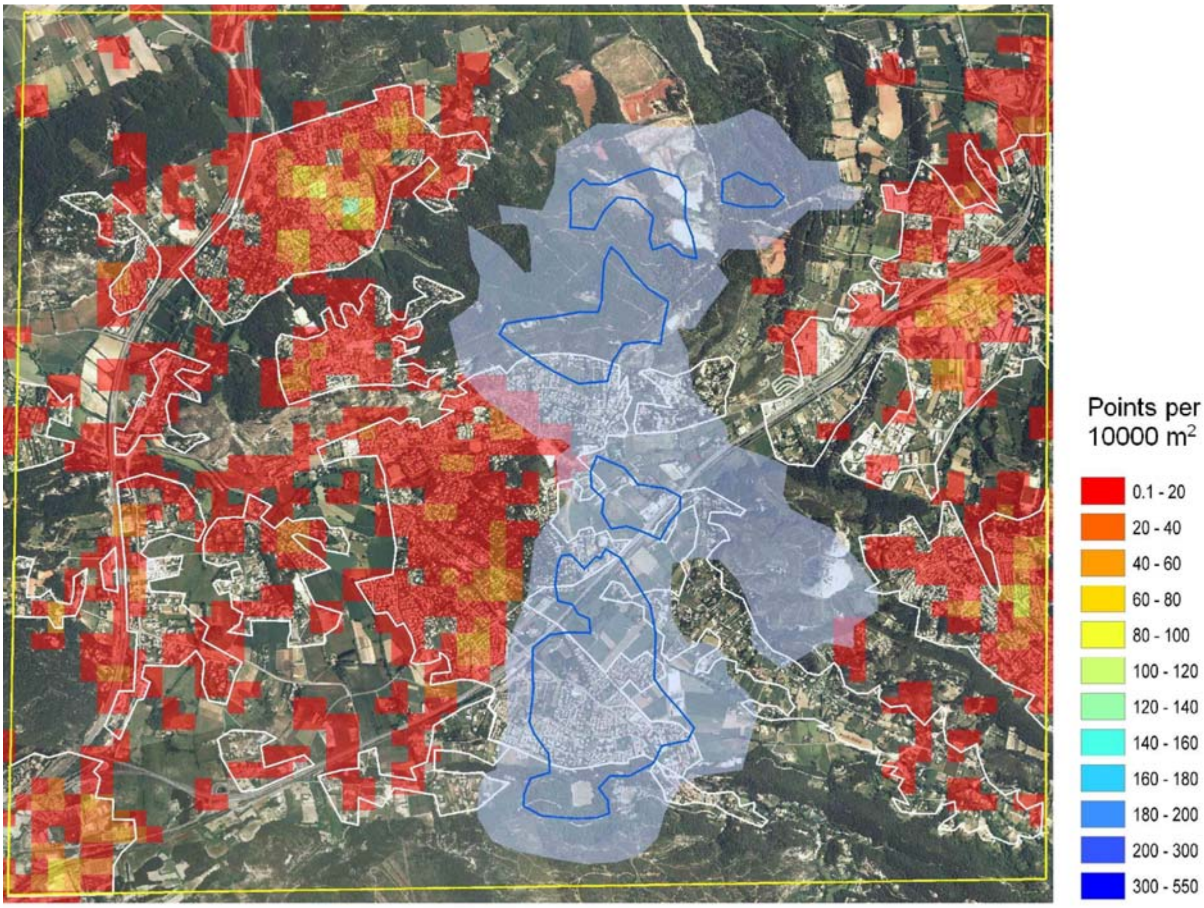

Situation des Bases
de surveillance
depuis 1990
RNGF 15
LUYNE
HBCM
Gardanne-Cimetière
CDF 2022
CENTRALE
SNCF
Aix-Marseille
HBCM
Gardanne-Centrale
HBCM
Axe
HBCM
Arbois
CDF 211
CANAL
Pechiney
HBCM
BOUC
CDF 2013
BOUC
SNCF
Aix-Marseille
HBCM
Cantoune
SCP
Bouc
HBCM
Axe
HBCM
Simiane
Base
SCP
SCP
Simiane
RNGF 12
0
2 km
1 km

599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40 - 60
60 - 80
80 - 100
100 - 120
120 - 140
140 - 160
160 - 180
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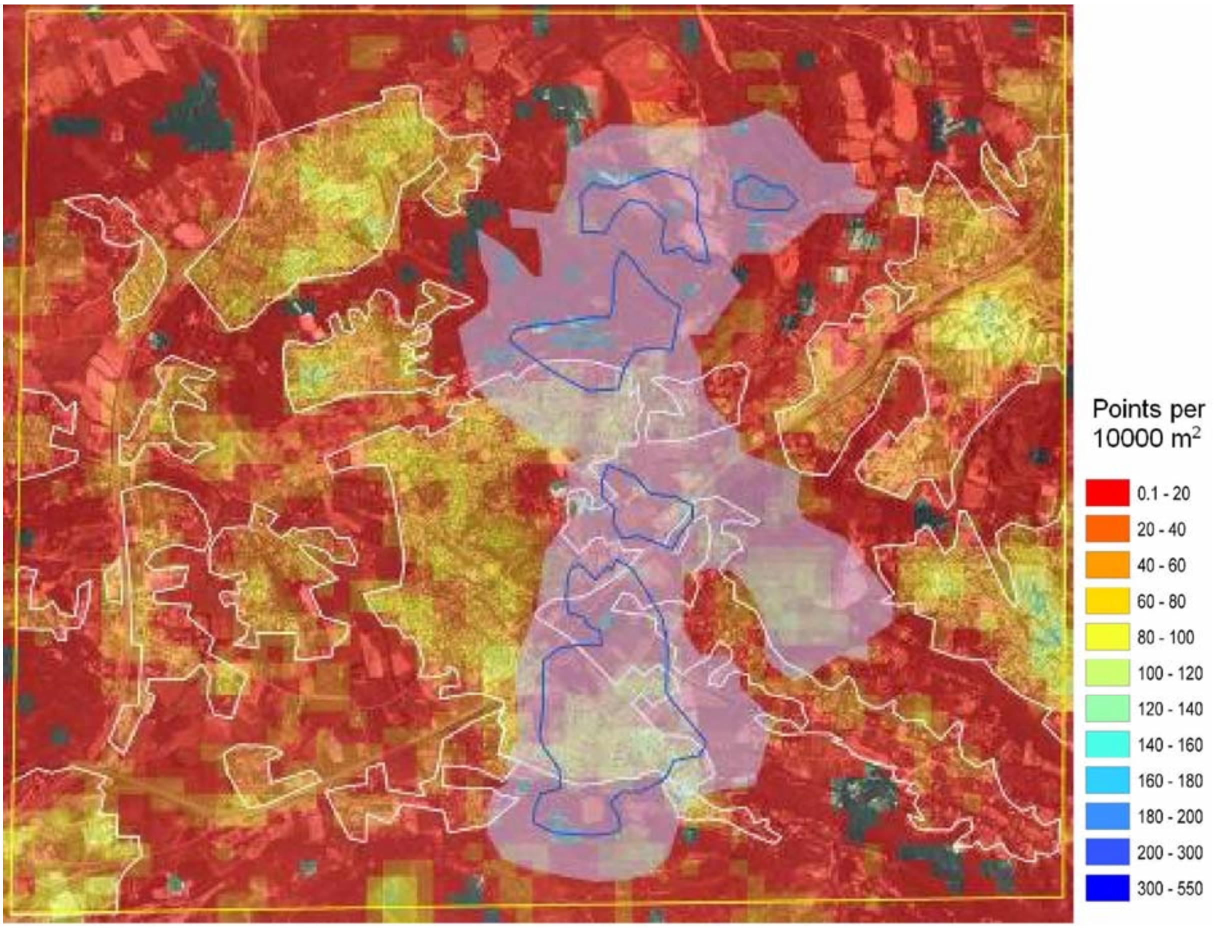
200 - 300
300 - 550

600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0.1 - 20
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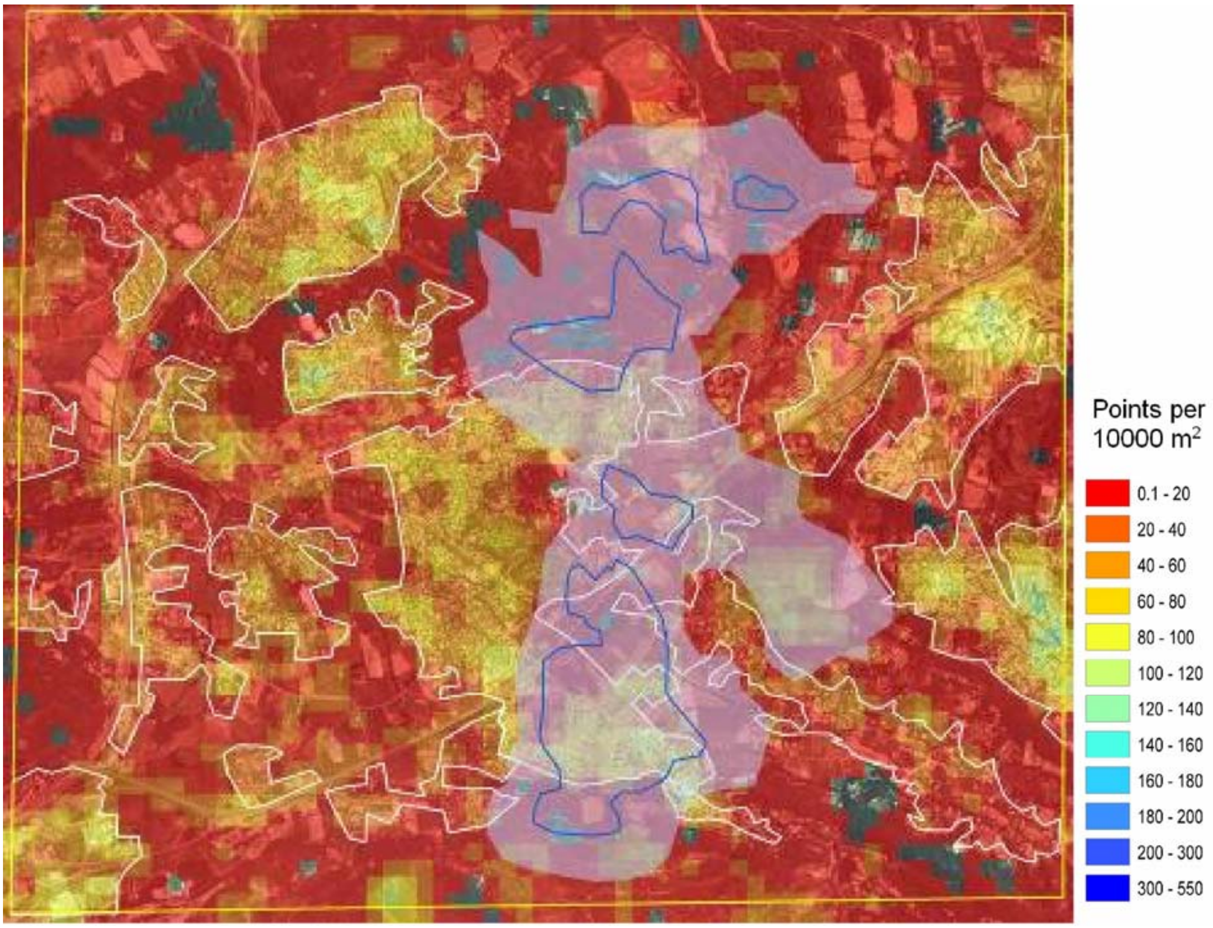
200 - 300
300 - 550


Points per
10000 m^2
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160 - 180
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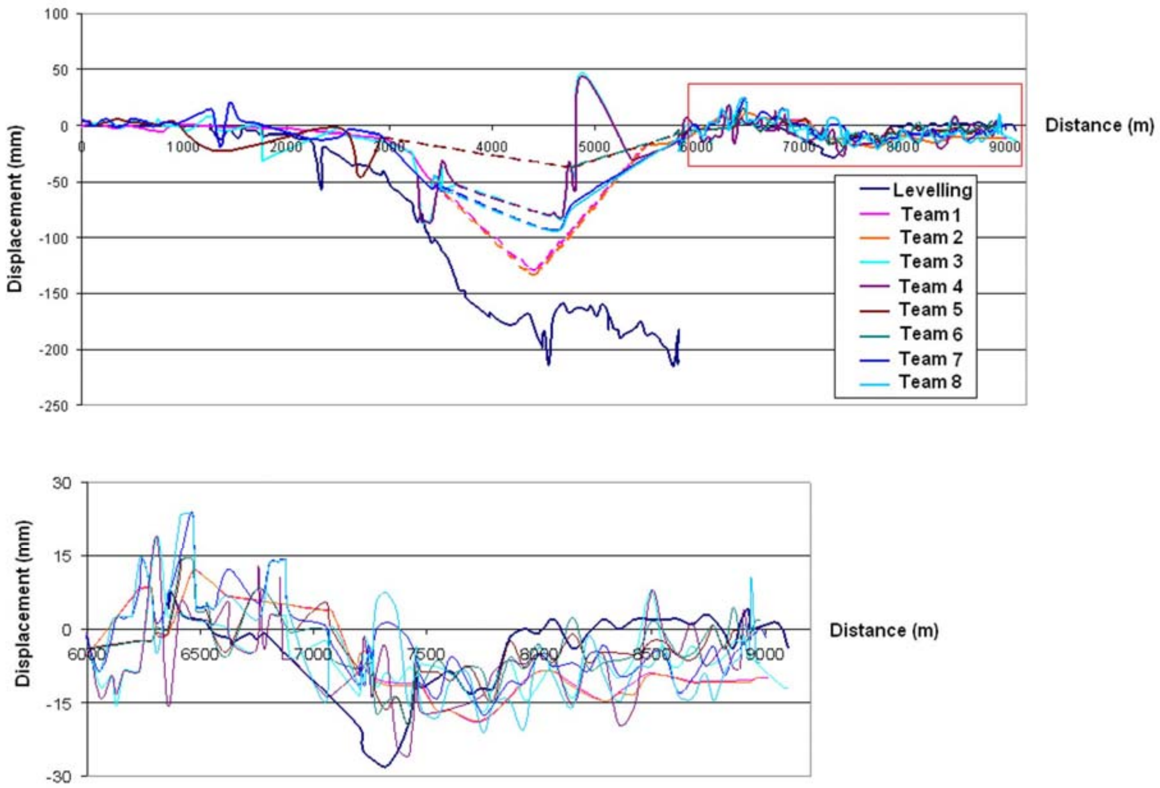
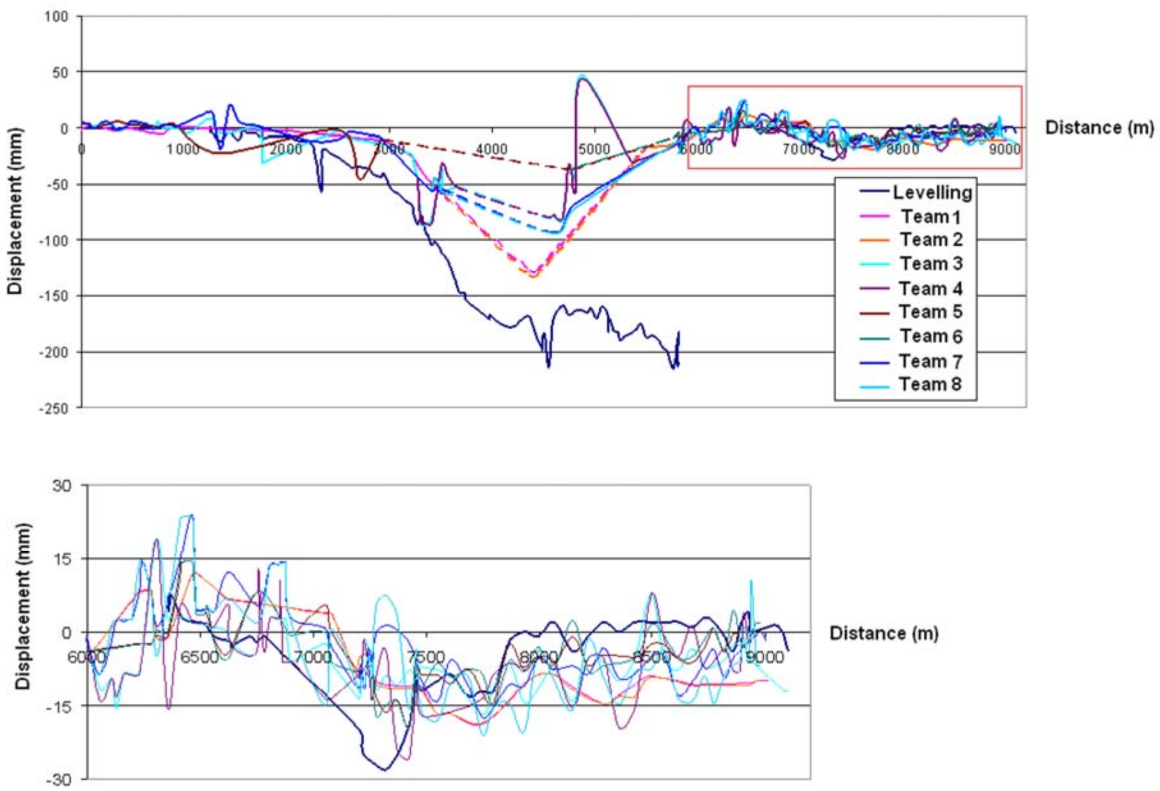
200 - 300
300 - 550


Displacement (mm)
Distance (m)
Levelling
Team 1
Team 2
Team 3
Team 4
Team 5
Team 6
Team 7
Team 8
100
50
0
-50
-100
-150
-200
-250
1000
2000
3000
4000
5000
6000
7000
8000
9000
30
15
-15
-30
6000
6500
7000
7500
8000
8500
9000


Displacement (mm)
Distance (m)
Levelling
Team 1
Team 2
Team 3
Team 4
Team 5
Team 6
Team 7
Team 8
100
50
0
-50
-100
-150
-200
-250
1000
2000
3000
4000
5000
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7000
8000
9000
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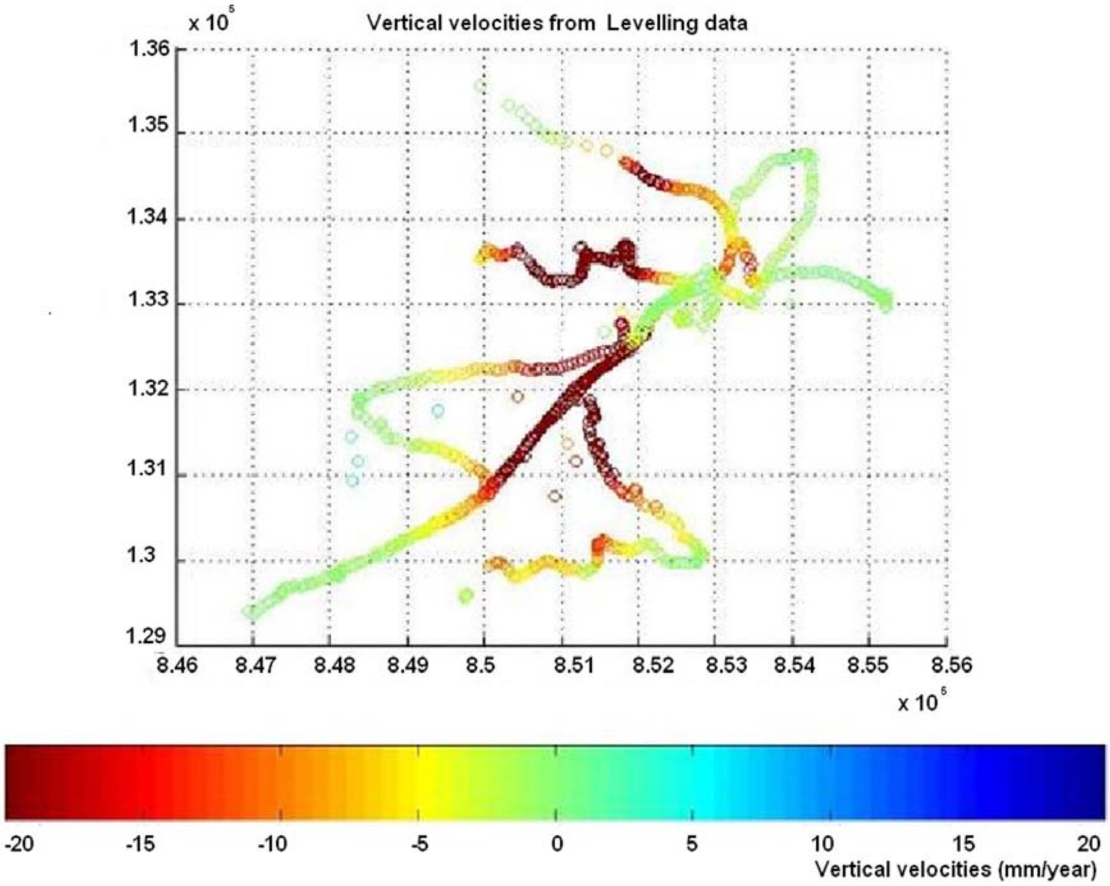
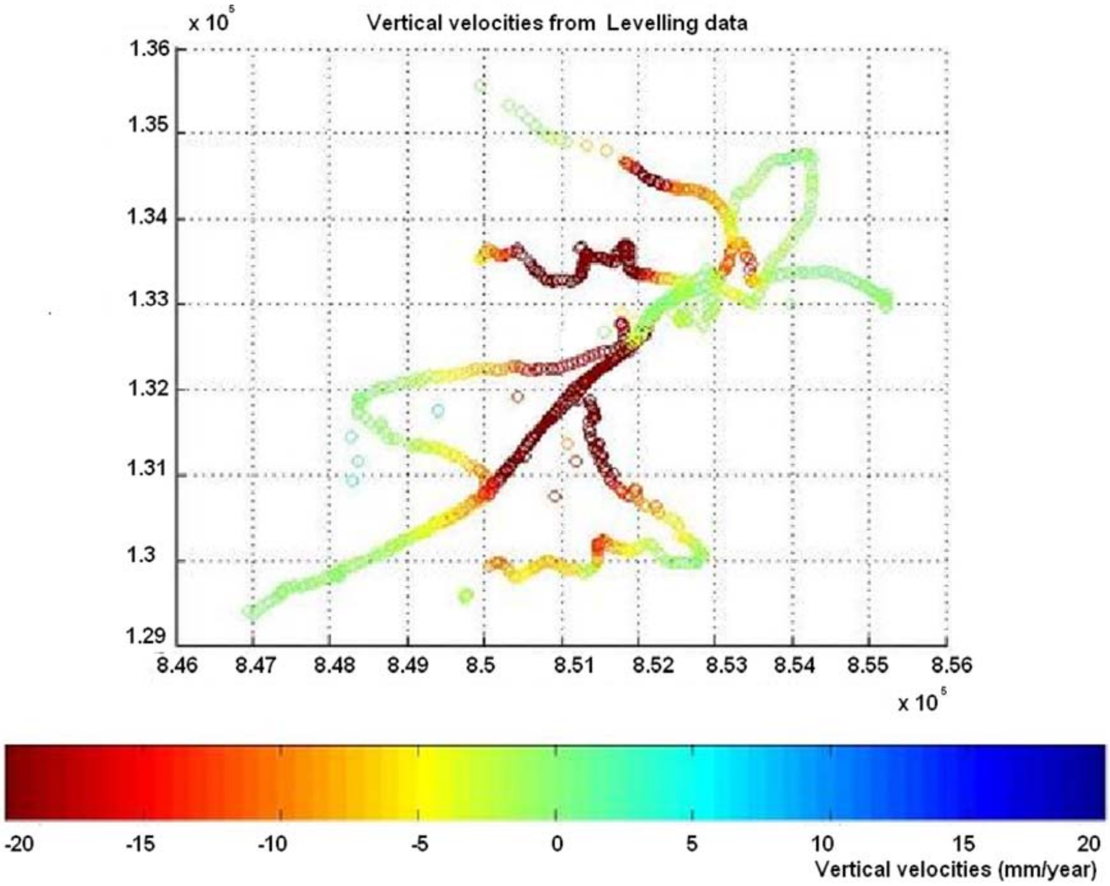
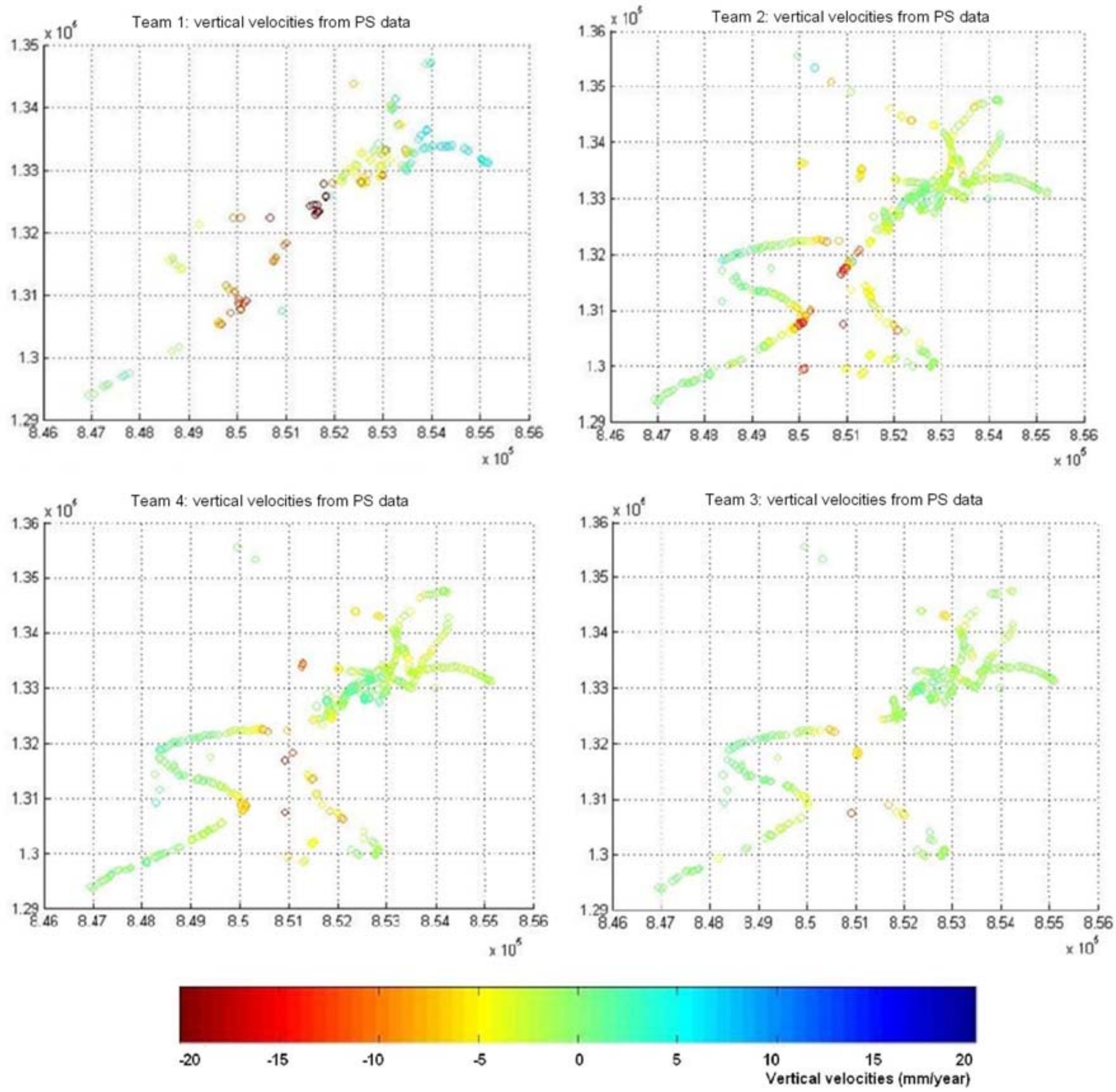
6000
6500
7000
7500
8000
8500
9000

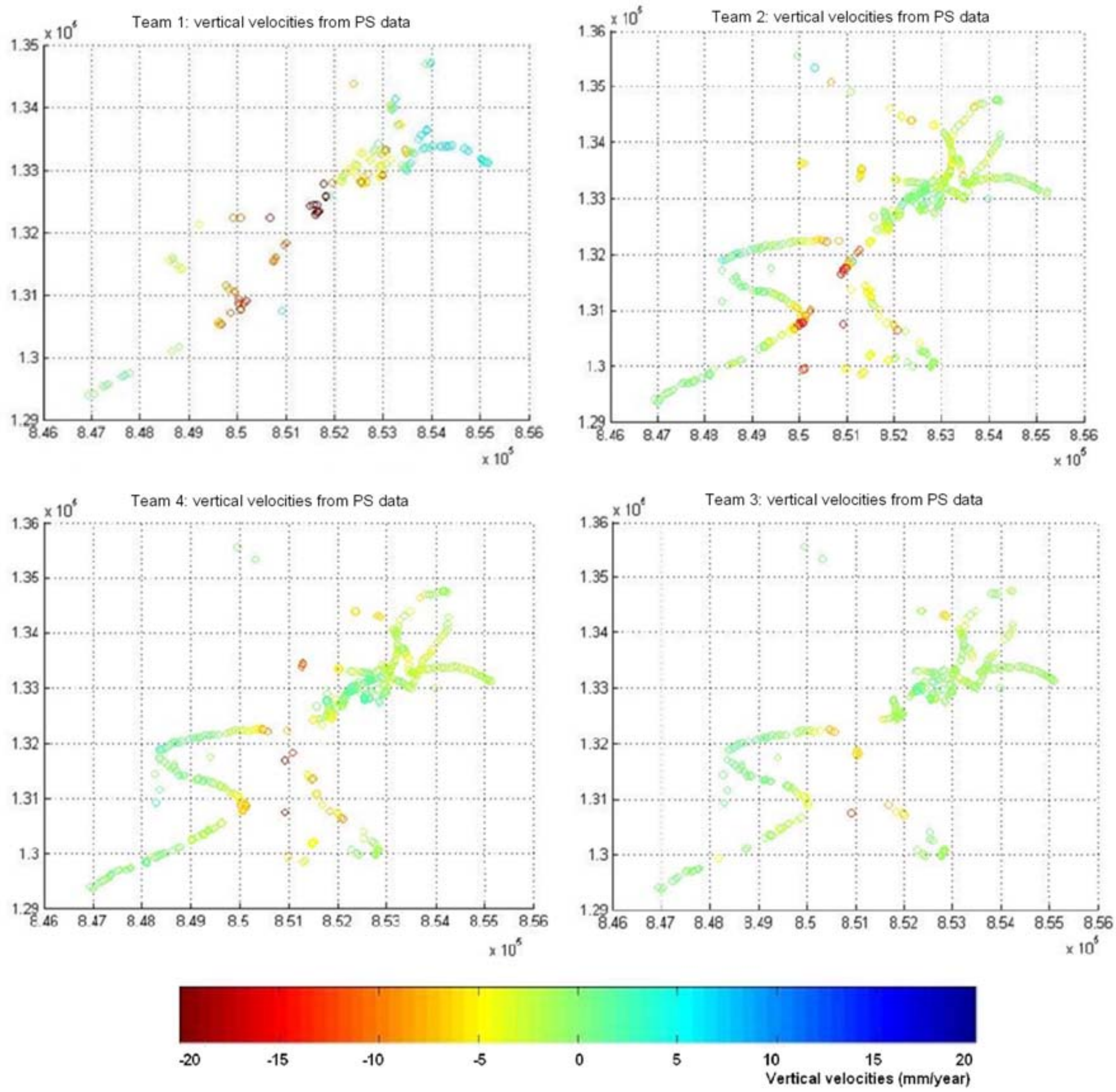

Vertical velocities from Levelling data
x 10^5
1.36
1.35
1.34
1.33
1.32
1.31
1.3
1.29
8.46
8.47
8.48
8.49
8.5
8.51
8.52
8.53
8.54
8.55
8.56
x 10^5
-20
-15
-10
-5
0
5
10
15
20
Vertical velocities (mm/year)

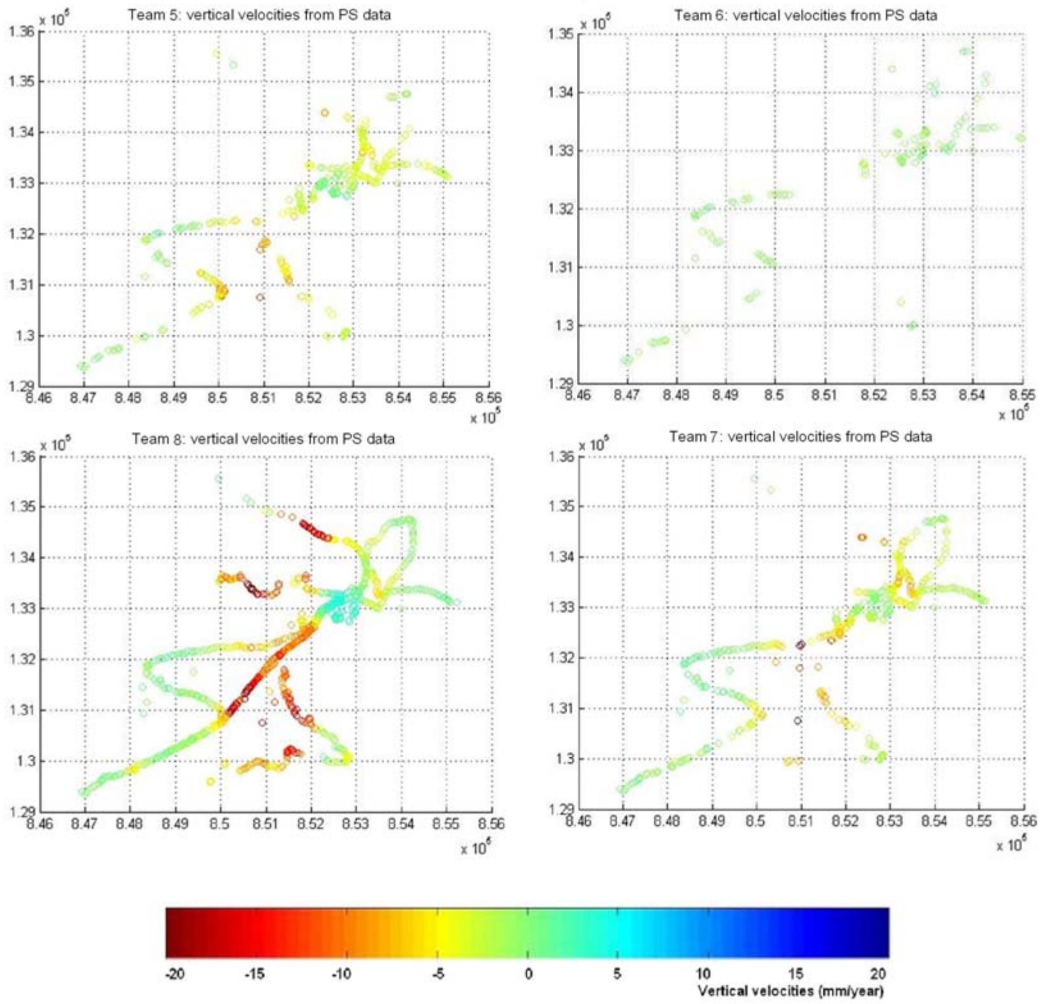


Vertical velocities from Levelling data
x 10^5
1.36
1.35
1.34
1.33
1.32
1.31
1.3
1.29
8.46
8.47
8.48
8.49
8.5
8.51
8.52
8.53
8.54
8.55
8.56
x 10^5
-20
-15
-10
-5
0
5
10
15
20
Vertical velocities (mm/year)

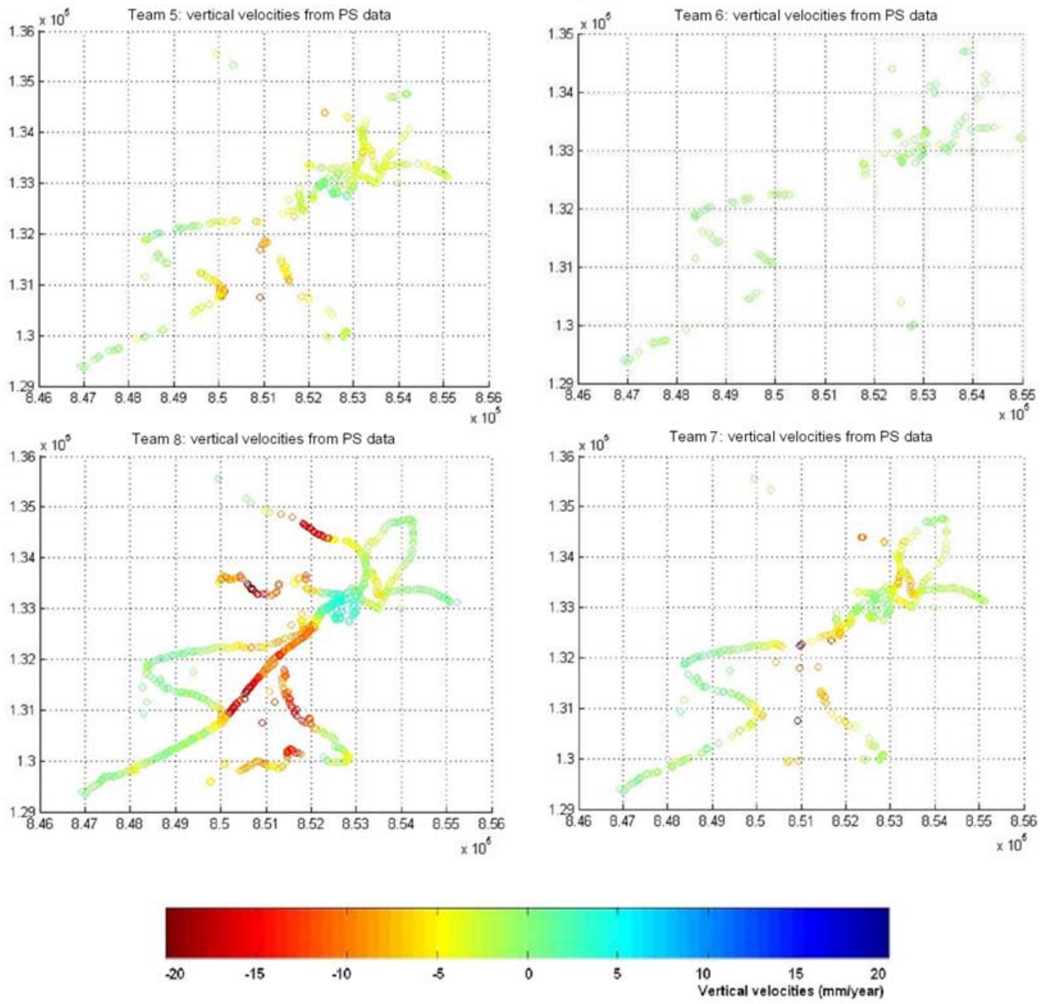
609


Team 1: vertical velocities from PS data
Team 2: vertical velocities from PS data
Team 4: vertical velocities from PS data
Team 3: vertical velocities from PS data
Vertical velocities (mm/year)


Team 1: vertical velocities from PS data
Team 2: vertical velocities from PS data
Team 4: vertical velocities from PS data
Team 3: vertical velocities from PS data
-20
-15
-10
-5
0
5
10
15
20
Vertical velocities (mm/year)



Team 5: vertical velocities from PS data
Team 6: vertical velocities from PS data
Team 8: vertical velocities from PS data
Team 7: vertical velocities from PS data
x 10^5
-20 -15 -10 -5 0 5 10 15 20
Vertical velocities (mm/year)


Team 5: vertical velocities from PS data
Team 6: vertical velocities from PS data
Team 8: vertical velocities from PS data
Team 7: vertical velocities from PS data
x 10^5
1.29
1.3
1.31
1.32
1.33
1.34
1.35
1.36
8.46
8.47
8.48
8.49
8.5
8.51
8.52
8.53
8.54
8.55
8.56
-20
-15
-10
-5
0
5
10
15
20
Vertical velocities (mm/year)