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Validation and intercomparison of Persistent Scatterers interferometry: PSIC4 project results

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1 **Validation and Intercomparison of Persistent Scatterers Interferometry:**

2 **PSIC4 project results.**

3
4
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28

29 **1. Abstract:**

30

31

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

50

51

52 **2. Introduction**

53

54 Repeat spaceborne Interferometry is a well known technique to assess the displacement of the ground
55 surface. It measures the displacement in the sensor's Line-Of-Sight direction from the phase of the

56 signal measured by Synthetic Aperture Radar (SAR) onboard a satellite (Goldstein et al., 1988,
57 Massonnet and Rabaute, 1993).

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

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

80 Eight PSI teams, from business or academic organizations, participated in the project: Altamira
81 Information (Crosetto et al., 2008), DLR (German Space Agency, Adam et al., 2003), Gamma-RS
82 (Werner et al., 2003), IREA-CNR (Institute for Electromagnetic Sensing of the Environment National
83 Research Council of Italy, Bernardino et al., 2002), TRE (TeleRilevamento Europa, Ferretti et al.,

84 2007), TUDelft (Delft University of Technology, Kampes, 2005), UPC (Catalonia Polytechnics
85 University, Mora et al, 2003), and Vexcel (Van der Kooij et al., 2005). 107 ERS and 10 Envisat ASAR
86 images were delivered to each of the teams by ESA for them to produce their own PSI deformation
87 products. Their results were then analysed by an independent validation consortium (BRGM, BGS,
88 TNO, IG) as an anonymous procedure so the validation consortium received the data without any
89 identification, except for a random number assigned to each one of the teams.

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

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

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

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

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

103

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

107

108 This paper describes the work performed during PSIC4 activities. In this project, six of the eight PSI
109 teams used different implementations of the Persistent Scatterers technique, while the other two teams
110 used alternative concepts (basically two coherent-based approaches). In this paper, the eight PSI teams

111 were asked to process the SAR data according to their own PSI methodology without any *a priori*
112 information about the type and location of deformation in the chosen test area. In addition to this
113 paper, an extensive description of the project is available in the PSIC4 final report (Raucoules et al.,
114 2007).

115

116 **3. Test site**

117

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

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

125

126 **[insert figure 1]**

127

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

129

130

131

132

133

134 The coal field (lignite) here has been mined since the Middle Ages Exploitation stopped in February
135 2003. Different mining techniques were used in the area. For the period of interest (1991-2004), the
136 observed ground subsidence is associated with the coal mining exploitation using long wall mining
137 technique at nearly 1000 m below the surface (figure 2). This technique has particular consequences in
138 terms of size (the width of a panel is 250m) and evolution (almost immediate) of the deformation

139 compared to older mining techniques. The older methods include chamber and pillar extraction with
140 localised subsidence occurring over a longer time-scale.

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

145

146

147

148

149

150 [insert figure 2]

151

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

154

155

156

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159

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

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

165

166

167 [insert figure 3]

168

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

171

172

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

175

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

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

178

179 **4. Pre-processing**

180

181 4.1 Previous corrections of the data

182

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

186 The only way to carry out the data comparison was to adjust those shifts to make the data comparable.

187 We observed geocoding shifts by overlaying the PSI data on an ortho-rectified (in the local Lambert
188 III Sud cartographic projection) aerial photograph. The geocoding discrepancies ranged between 5m

189 and 80m depending on the team. After correction, the residual geocoding shifts estimated on other

190 control points were between 3m and 23m. It is important to note that these residual errors include the

191 error made in the identification of the radar features on the ground. A linearly varying shift would

192 probably have provided a better final geolocation. However, we assumed that the constant shift we

193 applied to the data was sufficient for the purpose of this study.

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

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

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

216

217

218 [insert Figure 4]

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

222

223

224 4.1 Interpolation of the data

225

226 The major issue for the comparison between levelling data and the PSI results comes from the fact that
227 the spatial and temporal sampling of the PS-field and Time Series and the levelling lines do not
228 coincide. The levelling frequency is about twice a year whereas the PSI data correspond to the sensor
229 acquisition rate which is on average every 40 days (taking into account a gap in the acquisitions during
230 1994). The number of levelling points are fewer than the number of PSI points. The objective of
231 interpolation is to define which value derived from the SAR data can be compared with a given value
232 derived from the levelling.

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

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

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

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

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

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

254

255

256 **5. Intercomparison**

257

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

262

263 1) Average deformation rates.

264

265 To estimate the discrepancies between the teams' results in terms of velocity maps, we resampled the
266 data included in a common area to a 50m by 50m grid containing the velocities of each of the teams.

267 Using the ISATISTM software, we carried out a comparison by pairs of teams: for each pair of
268 produced PSI sets, we assessed the mean of the differences, the correlation value and the standard
269 deviation of the differences on the cell occupied by the two compared teams.

270 The main indicator is the standard deviation that reflects the discrepancies between teams. It ranges
271 from 0.6 mm/yr to 1.86 mm/yr.

272 The mean of the differences can show possible biases, although these values have been partially
273 affected by the stable area correction and are therefore less relevant as a performance indicator. These
274 values range from -0.84 mm/yr to +0.44 mm/yr. The following table shows the full set of velocity
275 intercomparison values.

276

277

278

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	

279

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

284

285

286 2) Density and spatial distribution of the PS

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

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

292 [insert figure 5]

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

295 [insert figure 6]

296

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

299

300 **6. Validation results**

301

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

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

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

311

312

313 [insert figure 7]

314

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

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

323

324

325

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

331

332

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

333

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

335

336

337

338

339 [insert figure 8]

340 Figure 8: RMSE per velocity class and per processing chain

341

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

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

347

348

349 [insert figure 9]

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

351

352

353

354

355 [insert figure 10]

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

357

358

359 [insert figure 11]

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

361

362 Table 3 gives a quantitative assessment of the discrepancies. In the conditions of the experiment
363 (characteristics of deformation and land-use) the standard deviation of the velocity differences is about
364 6 mm/yr.

365

366

367

368

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

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

371

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

378

379

380 **7. Discussion**

381

382

383 • The PSIC4 exercise was conceived as an inter-comparison and validation of PSI data computed by
384 eight different teams. The aim of this exercise was to evaluate the performance of eight different PSI
385 methodologies by comparing the results with ground based observations and by inter-comparing the
386 results from the eight processing chains. The results of this study provide an assessment of the

387 absolute (validation) and relative (inter-comparison) performance of the PSI techniques. The PSIC4
388 exercise is a blind test, carried out on a mining site characterised by different magnitudes and
389 evolutions of deformation and variable land cover. It is worth emphasising that the PSIC4 project
390 represents a unique experiment for the number of PSI teams involved and for the quality of the
391 available ground truth, which involve more than 1000 levelling benchmarks measured once or twice
392 per year.

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

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

401

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

404

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

414

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

418

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

421

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

423

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

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

443 the subsidence takes place over a relatively short time-span. The strong correlation between RMSE
444 and magnitude of displacement for two consecutive SAR-acquisition dates, suggests that the results
445 have certainly been affected by phase unwrapping ambiguities, leading to a systematic
446 underestimation of the subsidence rates.

447

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

453

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

463

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

468

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

472

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

475

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

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

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

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

495 3) The PSIC4 project was conceived in a specific framework, where the teams worked under “blind
496 conditions”, with no a priori information on deformation type, driving mechanism, deformation
497 magnitude, etc. Furthermore, they had no information about the exact deformation signal of interest,
498 i.e. the goal of the PSI analysis. By contrast, the validation was focused on a specific deformation
499 phenomenon, *i.e.* the deformation associated with the mining area of Gardanne. This point is important
500 because it played a key role in the PSI processing. In fact, instead of tailoring the processing to a
501 specific objective of the analysis, the teams used a standard approach and processing which is feasible
502 with reasonable resources. It is worth emphasising that the area covered by most of the teams is
503 considerably larger than the 100 km² area used for the validation. None of the PSI teams has
504 performed an advanced or refined PSI analysis, because neither the area of interest nor the goal of the
505 refinement was defined. This again explains most of the PSIC4 results, e.g. the lack of PS in the
506 mining area “of interest”.

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

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

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

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

526

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528

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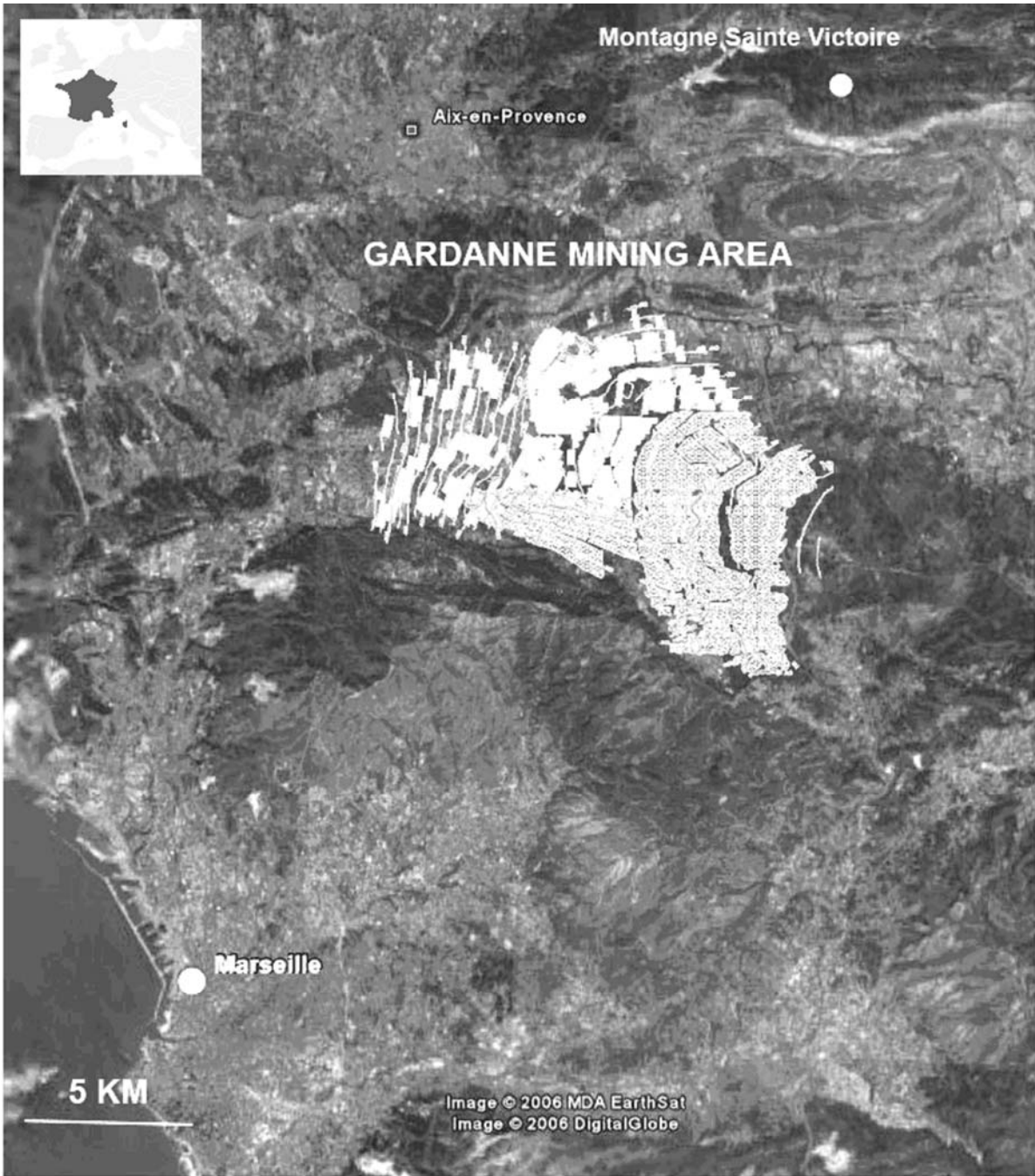
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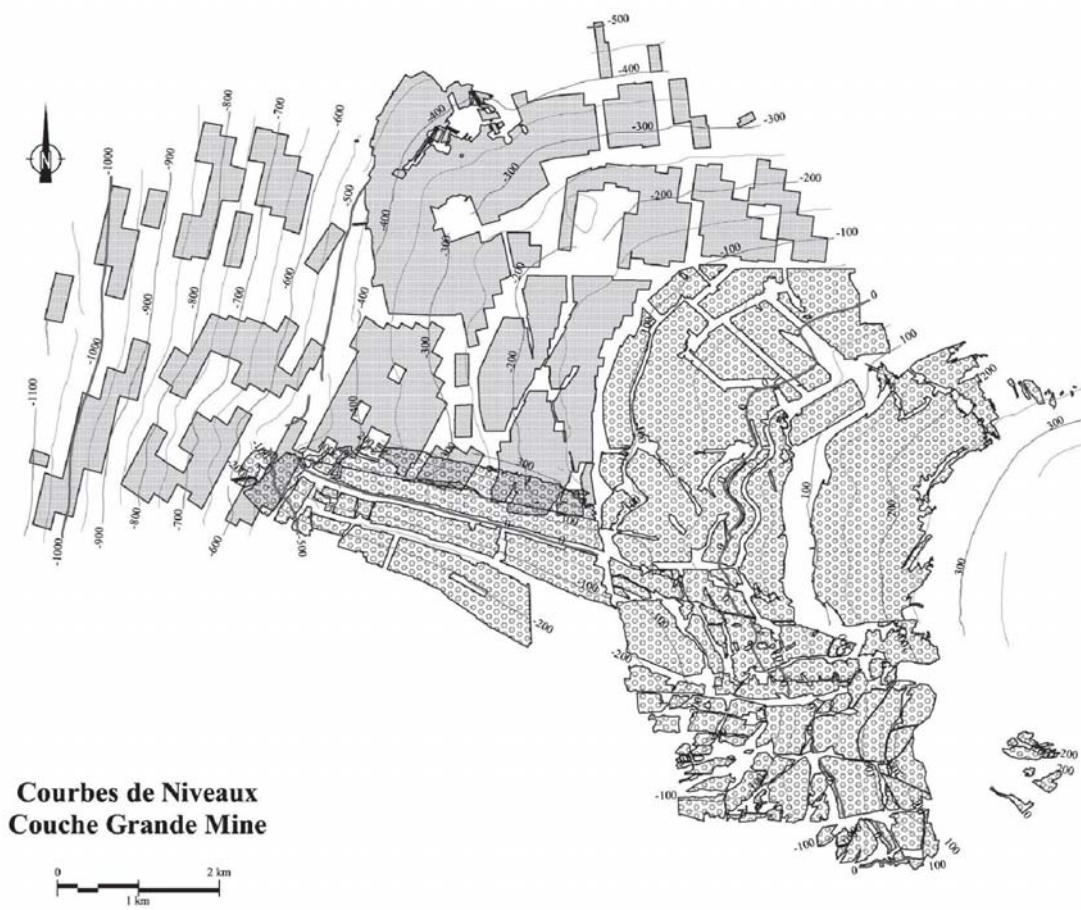
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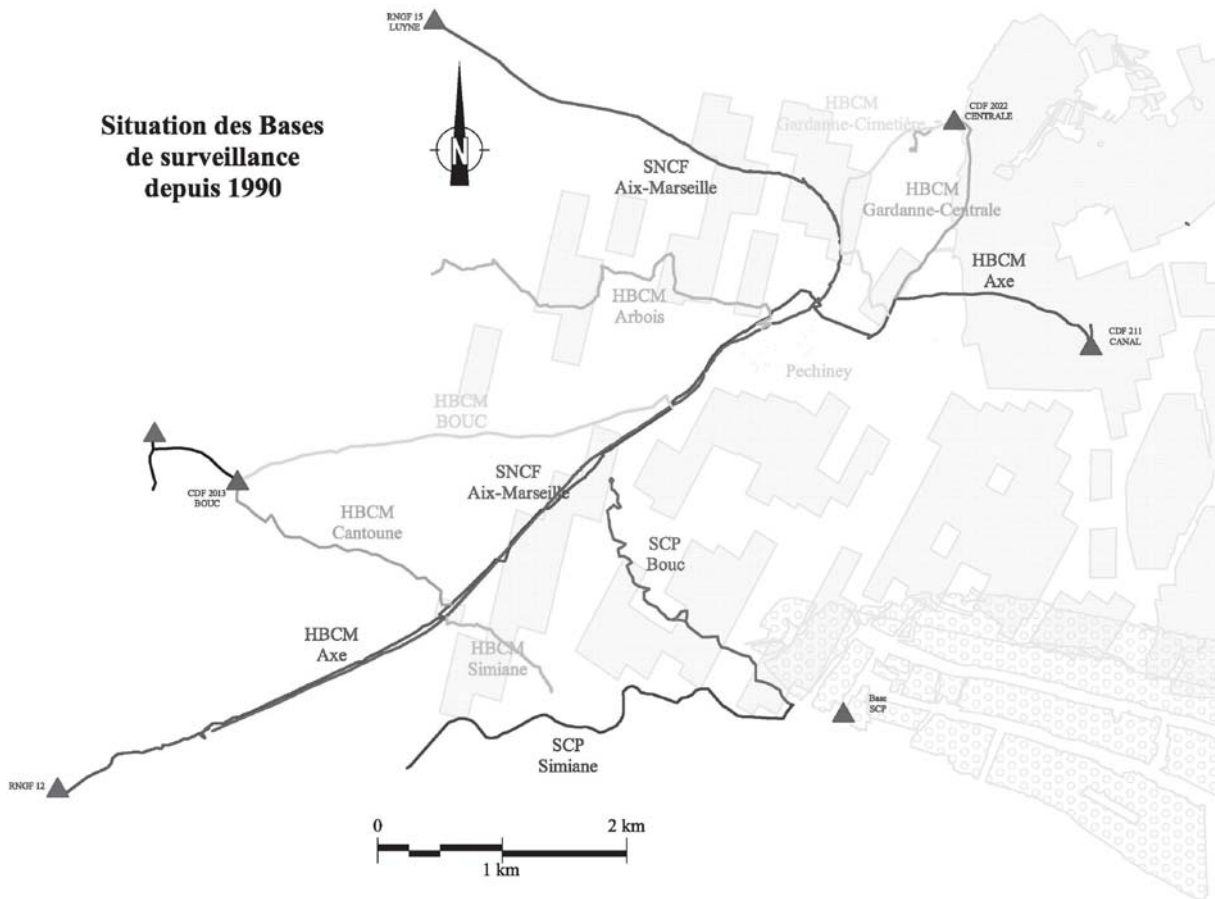
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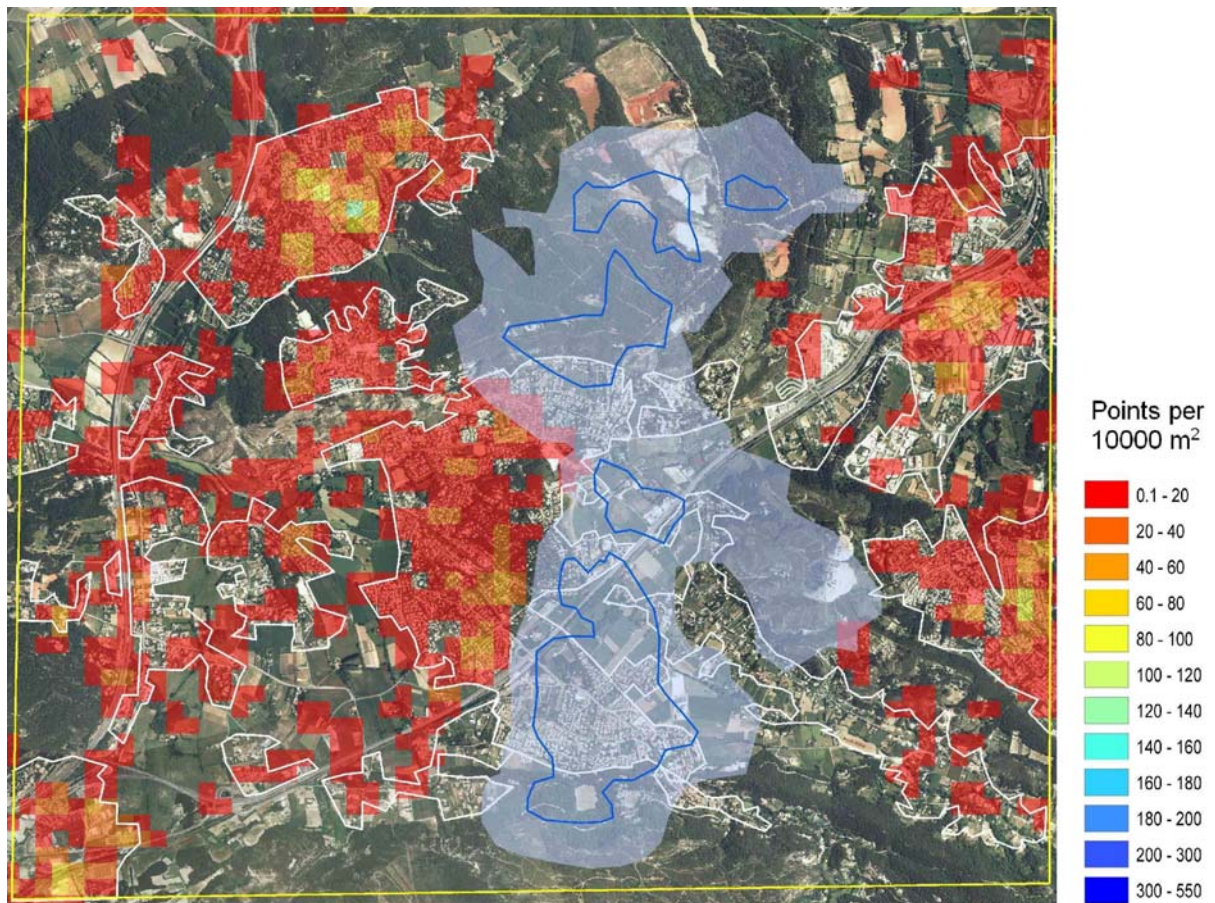
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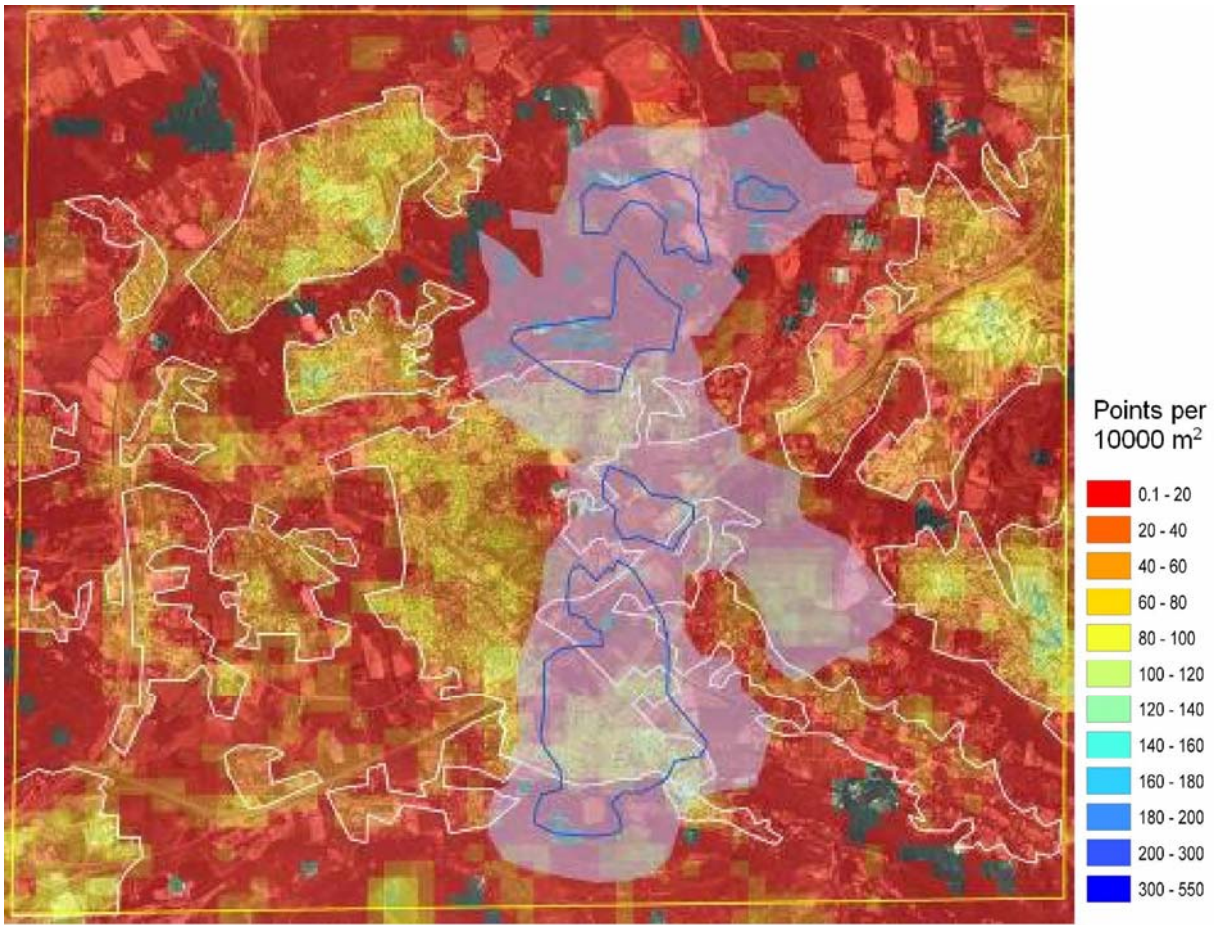
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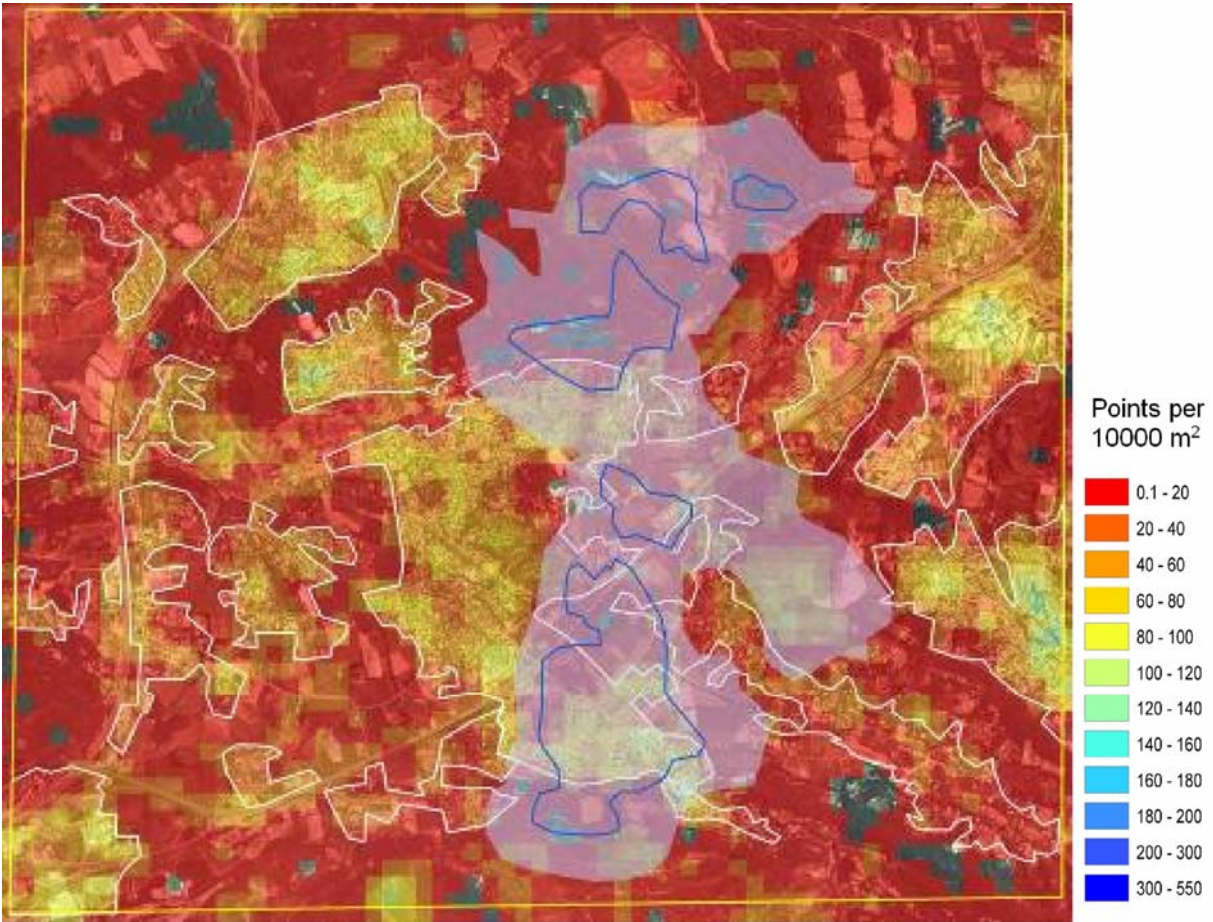
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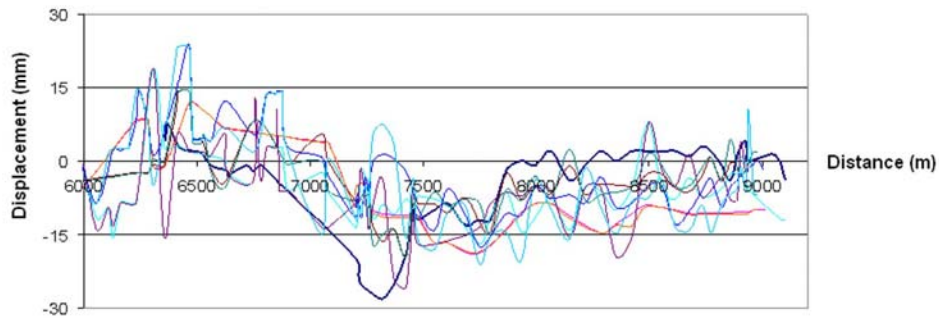
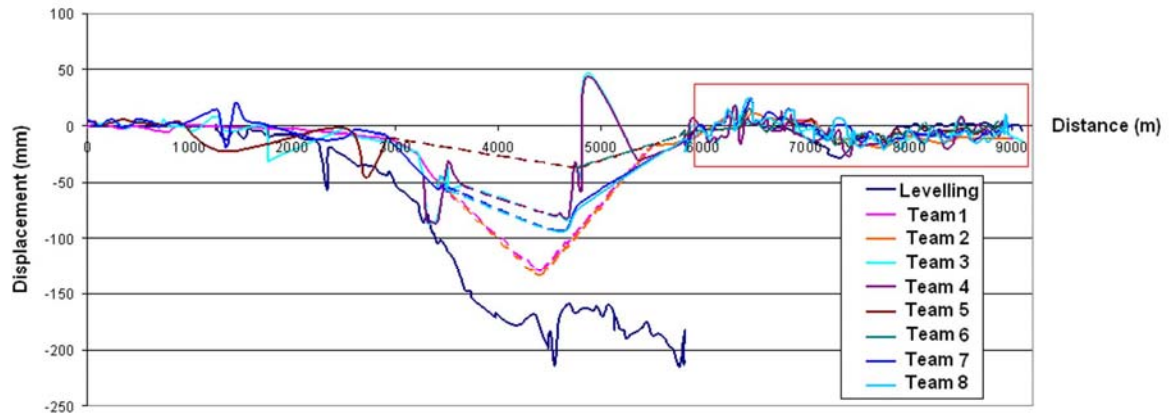


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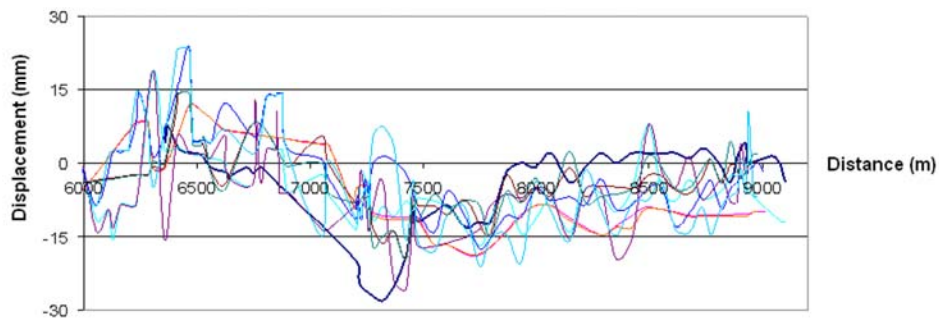
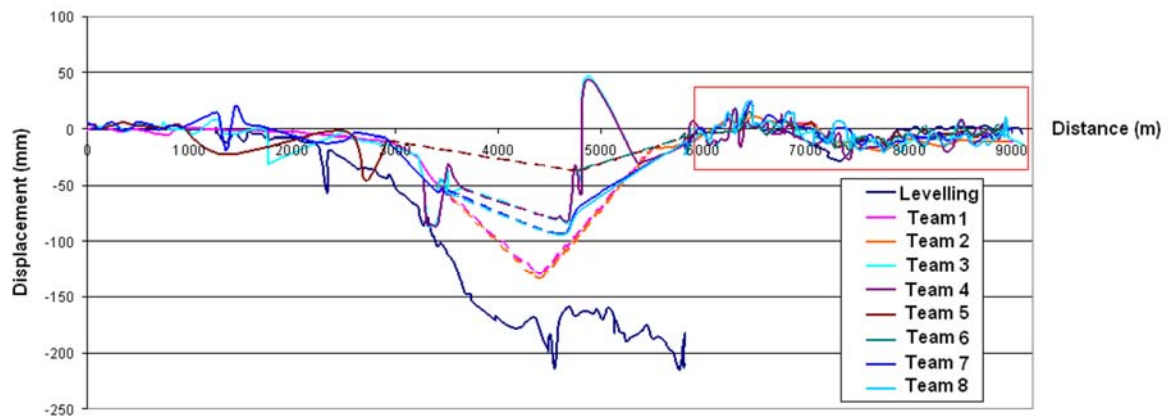


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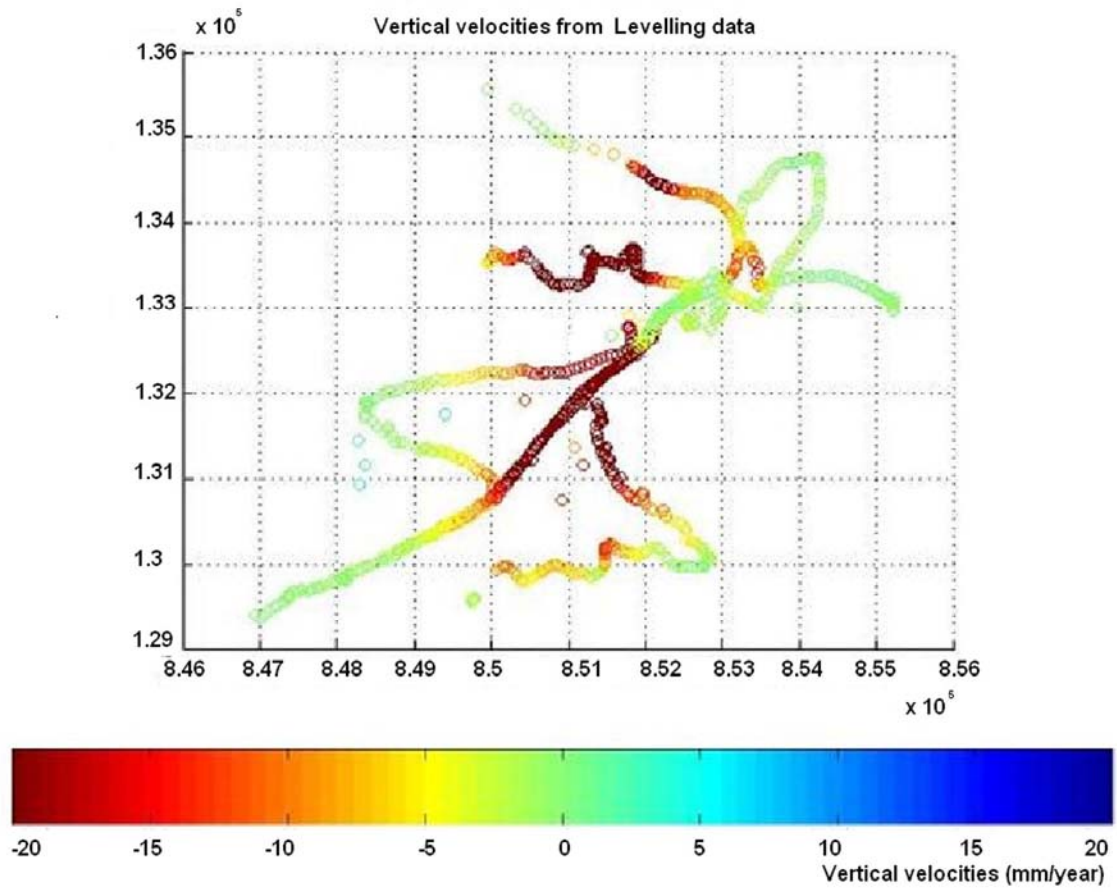
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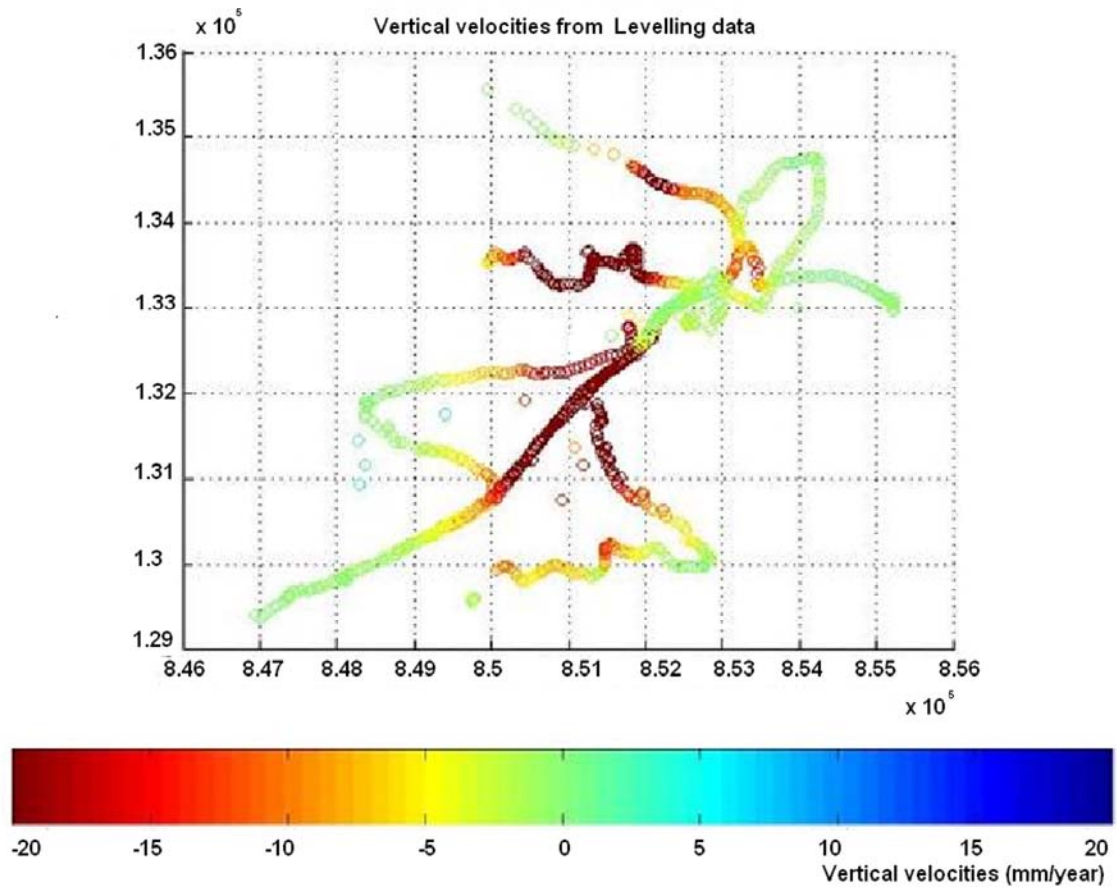
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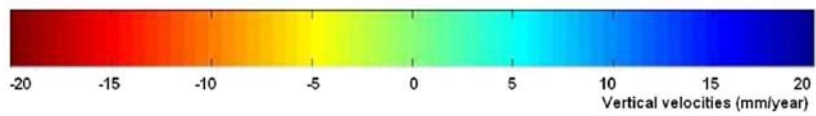
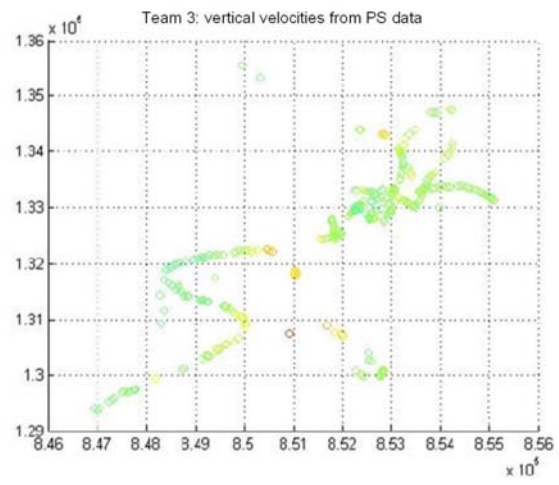
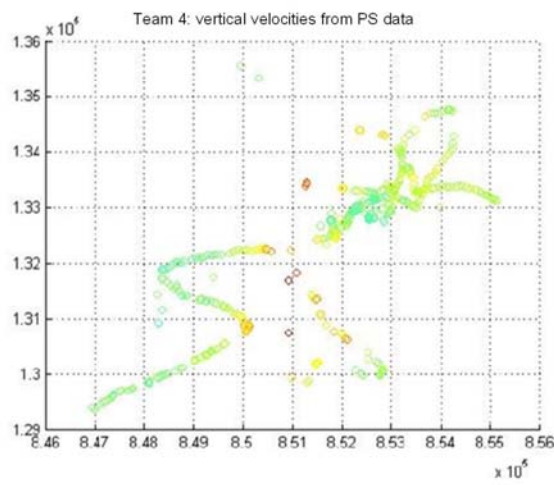
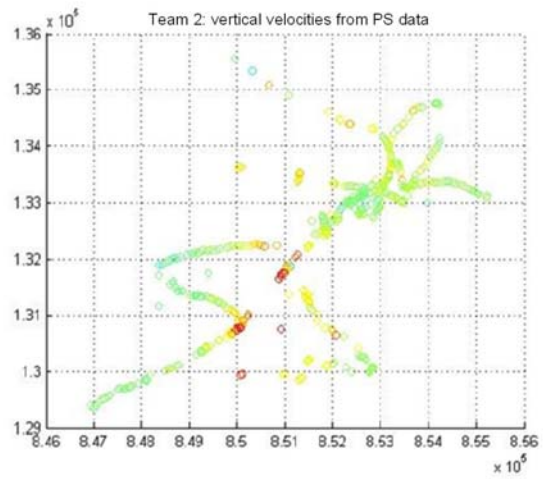
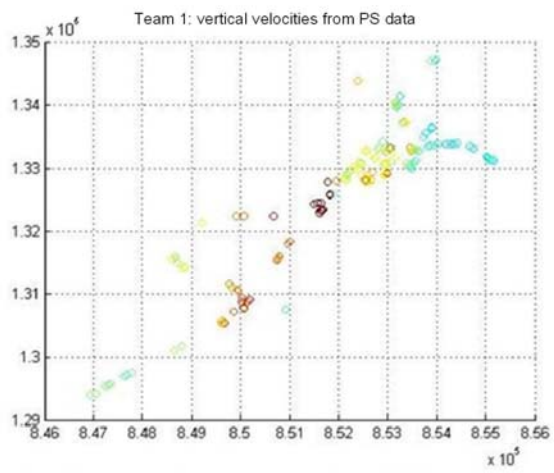
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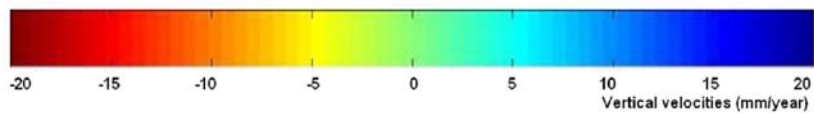
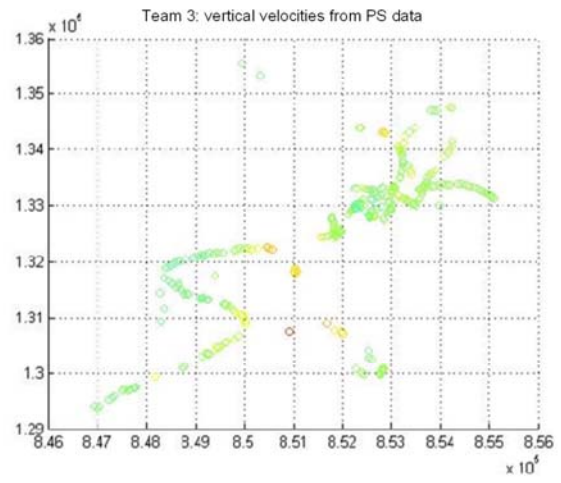
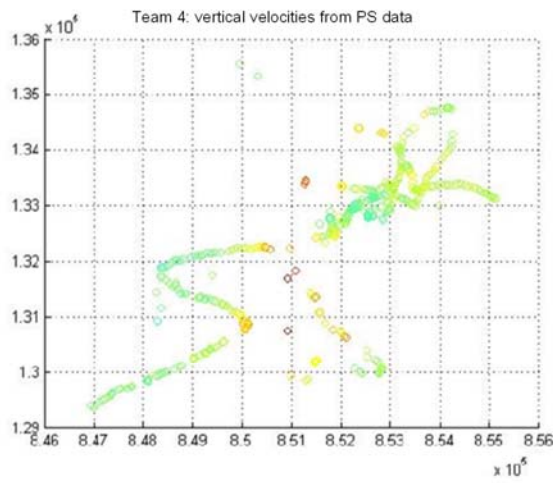
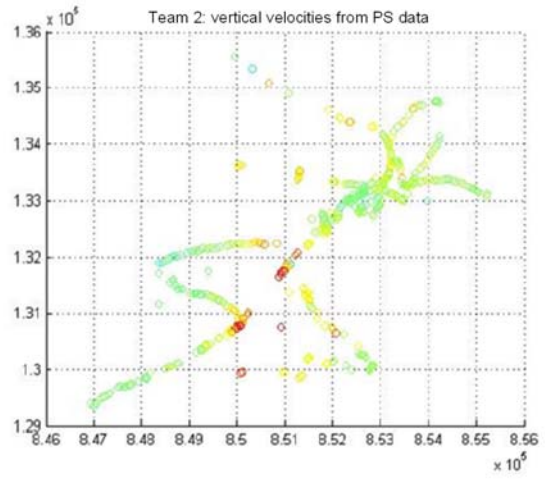
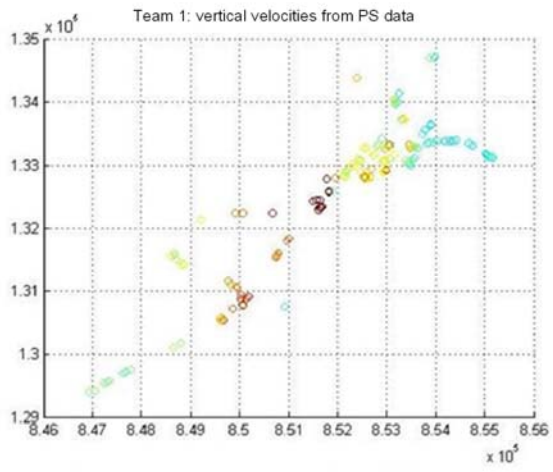


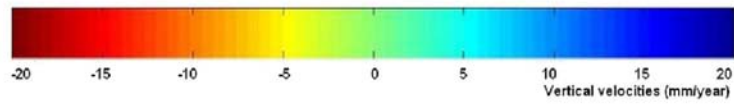
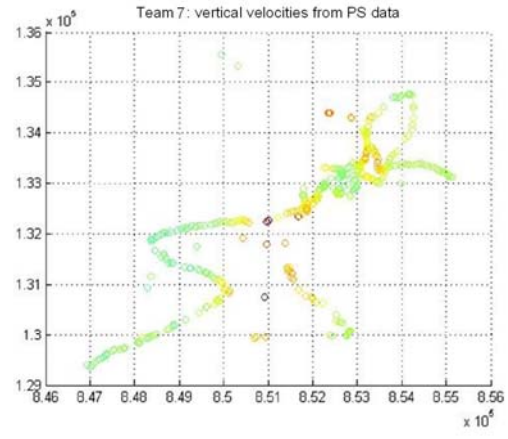
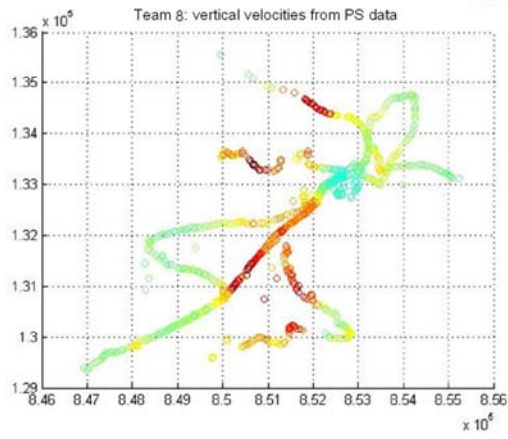
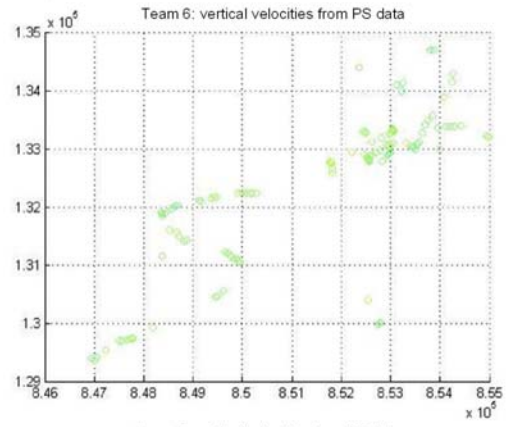
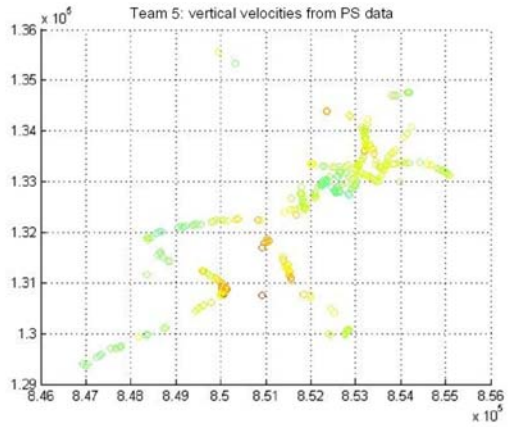
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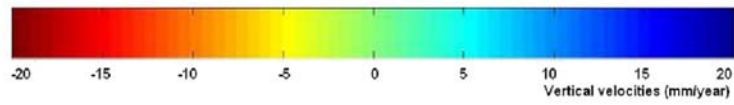
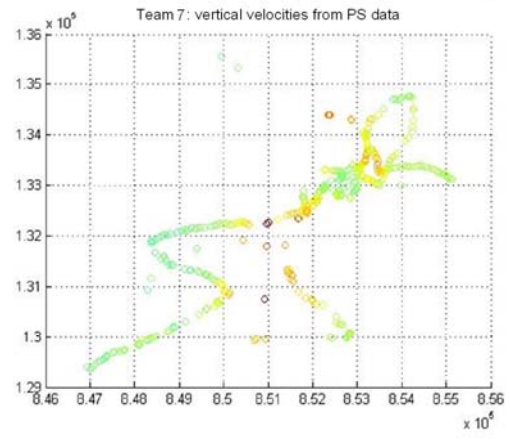
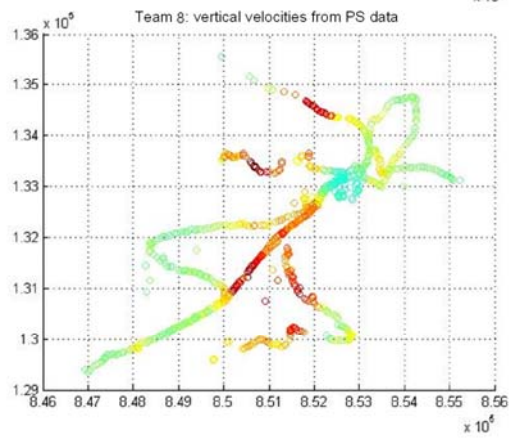
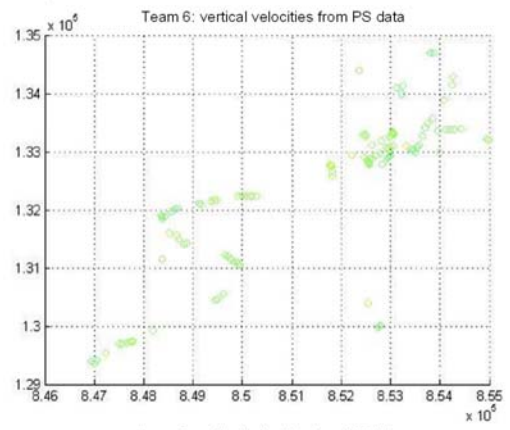
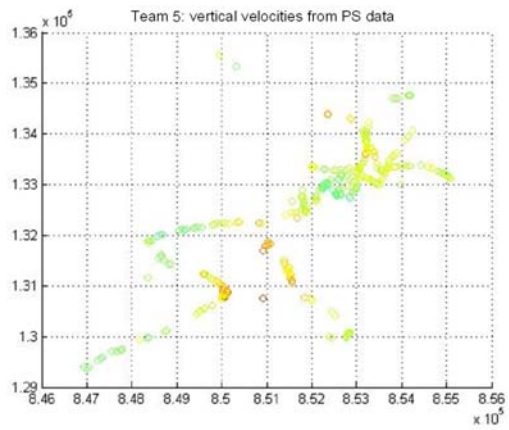
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