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# Recent Advances on Surface Ground Deformation Measurement by means of Repeated Space-borne SAR Observations

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## Abstract

Space-borne Synthetic Aperture Radar Interferometry (INSAR) is a well known widely used remote sensing technique to get precise (sub centimetric) surface deformation measurements on large areas (thousands of km<sup>2</sup>) and high spatial density of measurement points (hundreds per km<sup>2</sup>). In this work the recent technological advances of this technique are presented. First, a short review of the INSAR basics is dedicated to readers who are not INSAR specialists. Then, an analysis of the improvement of ground motion measurement offered by multiple repeated space-borne SAR observations gathered by the new generation of high resolution SAR systems is given. An example obtained with the recent German TERRASAR-X system is shown and compared with the measurements obtained with the elder C-Band RADARSAT-1 system. Finally, a possible processing of multi-temporal analysis of SAR images that allow extracting ground motion information also from partially coherent targets is given. In this case the core idea is to relax the restrictive conditions imposed by the Permanent Scatterers technique. The results obtained in different test-sites show an increased spatial density of areal deformation

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28 trend measurements, especially in extra-urban areas at the cost of missing motions with  
29 strong velocity variation.

30

31 *Keywords:* Synthetic Aperture Radar (SAR); INSAR; Permanent Scatterers; ground  
32 deformation.

33

### 34 **1. Introduction**

35

36 Synthetic Aperture Radar (SAR) Interferometry (*Bamler et al. 1998*) is based on the  
37 phase comparison of SAR images, gathered simultaneously or at different times with  
38 slightly different looking angles from space or airborne platforms. The phase of a SAR  
39 image contains the superposition of many terms including the distance of the radar from  
40 the illuminated targets on the ground. The phase difference of 2 SAR images gathered at  
41 different times contains a phase term proportional to the target motion occurring along  
42 the sensor-target Line-of-Sight (LOS) direction during that time interval. The measured  
43 phase difference shows an ambiguity cycle of  $2\pi$  that corresponds to a 2-way travel path  
44 difference of  $\lambda$  (the used radar wavelength). Thus, in principle, SAR Interferometry  
45 (INSAR) has the potential to detect ground surface motion phenomena with the accuracy  
46 of a small fraction of the radar wavelength (usually from 3 to 24 cm) on large areas  
47 (thousands of  $\text{km}^2$ ) with high spatial resolution (up to 1m with the space borne SARs of  
48 the last generation as the German TERRASAR-X and the Italian Cosmo-SKyMed –  
49 CSK). INSAR is thus a unique remote sensing tool for mapping volcano dynamics, co-

50 seismic and post-seismic deformation along active faults, as well as slope instability and  
51 subsidence phenomena of different nature.

52 However, apart from cycle ambiguity problems, the routine use of INSAR is limited by  
53 the so called temporal and geometrical decorrelation, as well as to atmospheric artifacts.  
54 Temporal decorrelation appears where the electromagnetic signature of the targets  
55 changes with time (e.g. in presence of dense vegetation or water basins). Geometric  
56 decorrelation is generated by the target reflectivity variation as a function of the incidence  
57 angle. Finally, atmospheric heterogeneity superimposes on each SAR acquisition an  
58 atmospheric phase screen (APS) that could have the same spatial pattern (low-pass with  
59 typically 1 km decorrelation length) and amplitude of the surface deformation  
60 phenomenon under investigation (*Beauducel et al. 2000*).

61 The Permanent Scatterers (PS) Technique (*Ferretti et al. 2000, Ferretti et al. 2001,*  
62 *Kampes 2006, Hooper 2004, Berardino 2002*) developed in late nineties, is a powerful  
63 tool that overcomes the above said limitations of INSAR by simultaneously exploiting all  
64 the available SAR images gathered during repeated satellite passes (e.g. exploiting ESA,  
65 CSA, TERRASAR-X and, once available, the CSK archives).

66 After a short introduction to the PS Technique, recent examples of ground motion  
67 measurements showing the actual potential and accuracy of this remote sensing technique  
68 are presented in section 2. Also in this section the very first analysis of the improvement  
69 that can be achieved passing from the 20x5sqm resolution cell of C-Band SAR systems to  
70 the recently available 3x3sqm resolution X-band SARs is presented.

71 Finally, in the third section the results obtained by means of an INSAR data processing  
72 approach obtained by relaxing the strict conditions imposed by the PS technique are

73 shown together with an analysis of what it is gained and what is lost with respect to the  
74 PS Technique.

75

## 76 **2.0 INSAR and DINSAR (Differential SAR Interferometry)**

77

78 The European Space Agency (ESA) satellites ERS-1, ERS-2 and ENVISAT are  
79 collecting SAR data at C band (5.6 cm wavelength) since late 1991 along near polar  
80 orbits with a revisiting time of 35 days. Since 1995 the Canadian Space Agency (CSA)  
81 satellites RADARSAT-1 and RADARSAT-2 are collecting similar data with a revisiting  
82 time of 24 days. The Japanese Space Agency (JAXA) satellites J-ERS (till 1998) and  
83 ALOS have been collecting L band (23.6 cm wavelength) SAR images with a revisiting  
84 time of 44 and 46 days respectively. More recently, the German satellite TERRASAR-X  
85 and the Italian constellation of satellites Cosmo-SkyMed (CSK) started collecting SAR  
86 images at X band (3 cm wavelength) with a revisiting time of 11 and up to 4 days (with 4  
87 satellites in orbit) respectively. An impressively huge archive of repeated SAR images is  
88 thus available for imaging and INSAR applications covering the entire Earth surface.

89 All these satellite SARs observe the same area at different times from slightly different  
90 looking angles since repeated orbits do not follow exactly the same track (due to the  
91 atmospheric drag, solar wind, etc). The distance between two orbits is called  
92 interferometer baseline and its projection perpendicular to the line of sight (LOS) is  
93 called perpendicular baseline (see Figure 1).

94 *Figure 1*

95

96 The phase difference between two SAR images is called interferometric phase. The  
 97 following expression of the interferometric phase with respect to a selected ground  
 98 reference point holds (*Ferretti et al. 2007*):

99

$$100 \quad \Delta\phi = \frac{4\pi}{\lambda} \frac{B_n}{R \sin \theta} h + \frac{4\pi}{\lambda} \frac{B_n}{R \tan \theta} s + \frac{4\pi}{\lambda} d + \Delta\phi_{APS} + \Delta\phi_\gamma \quad [\text{Eq. 1}]$$

101

102 In Eq.1,  $h$  is the relative ground elevation of targets referred to a horizontal reference  
 103 plane,  $s$  is the relative slant range position of targets,  $d$  is the projection along the LOS  
 104 of the relative displacement of targets,  $B_n$  is the perpendicular baseline,  $R$  is the SAR-  
 105 target distance,  $\theta$  is the “off-nadir” angle of the LOS,  $\Delta\phi_{APS}$  is the differential  
 106 tropospheric delay phase contribution (Atmospheric Phase Screen) and  $\Delta\phi_\gamma$  is the phase  
 107 noise that depends on temporal and geometric decorrelation of targets.

108 The first two phase terms in Eq.1 can be computed and eliminated if a precise DEM is  
 109 available together with precise orbital information (baseline, sensor-target distance and  
 110 off-nadir angle). The residual phase component, the so called Differential SAR  
 111 Interferometric (DINSAR) phase, is then proportional to the terrain motion component  
 112 along the LOS plus atmospheric and decorrelation noise:

113

$$114 \quad \Delta\phi_d = \frac{4\pi}{\lambda} d + \Delta\phi_{APS} + \Delta\phi_\gamma \quad [\text{Eq. 2}]$$

115

116 The sensitivity of the DINSAR phase to terrain motion depends on the SAR wavelength  
117  $\lambda$  since a relative displacement  $d = \lambda/2$  generates a differential phase variation  
118  $\Delta\phi_d = 2\pi$ . From Eq.2 it is also clear that the actual possibility of measuring the terrain  
119 motion with a precision of a small fraction of the radar wavelength is mainly limited by  
120 the atmospheric and decorrelation noise terms.

121 Since the incidence angle of the radar signal is usually less than 30 deg (for ERS the  
122 nominal figure is 23 deg), SAR data are usually very sensitive to vertical displacements.

123 In Figure 2 the INSAR phases showing the co-seismic deformation of the Bam (Iran)  
124 earthquake that occurred on Dec. 26<sup>th</sup>, 2003 are shown. In this case the terrain motion is  
125 measured with a sub-centimetre precision all over the imaged area since the decorrelation  
126 phase noise terms are really small (due to lack of vegetation and small baseline) as well  
127 as the atmospheric components (due to the particular meteo conditions).

### 128 **Figure 2**

129 In many other situations, however, both decorrelation and atmospheric phase noise are so  
130 strong to severely affect terrain motion measurement. A typical example is illustrated in  
131 Figure 3 where the INSAR phases generated with ERS images taken in one day and one  
132 year interval respectively over the area of Ancona (Italy) are shown. Looking at the one  
133 day interferogram it can be clearly seen the phase decorrelation noise in the upper part of  
134 the image that corresponds to the Adriatic Sea and almost no decorrelation in land.  
135 However, on the one year interferogram (a time span that would allow to identify a big  
136 landslide motion) also the in land area is strongly affected by phase decorrelation thus  
137 preventing ground motion measurements.

138

139 **Figure 3**

140 It is interesting to note, however, that many targets that are not affected by decorrelation  
141 noise could be present in areas showing an apparent complete decorrelation as on the  
142 right image of Figure 3, but they cannot be identified since surrounded by noisy phases.  
143 The simple visual experiment illustrated in Figure 4 shows that up to 10% of randomly  
144 distributed perfectly phase coherent pixels cannot be identified when surrounded by  
145 totally random phase pixels.

146 **Figure 4**

147 In general, isolated phase coherent targets can be identified if more SAR scenes gathered  
148 over the area of interest are jointly analyzed. Moreover, creating many interferograms, it  
149 is usually possible to highlight problems related to spurious phase components due to  
150 DEM errors, noise and/or atmospheric signals and try to separate the different  
151 contributions. This is exactly the idea which underlies the “PS technique”.

152

### 153 **2.1 Moving from INSAR to PS**

154 As long as a significant number and density of independent radar-phase stable points (i.e.,  
155 Permanent Scatterers) exist within a radar scene and enough radar acquisitions have been  
156 collected, displacement time series and range-change rates can be calculated. Using the  
157 PS method, we can resolve surface motions at a level of  $\sim 0.5$  mm/yr at about 1km from  
158 the reference point and can resolve very small-scale features, including motions of  
159 individual targets/structures (e.g. a bridge or a dam), not previously recognized in  
160 traditional SAR interferometry (*Ferretti 2007, Adam 2009*).

161 The PS approach is based on a few basic observations. There are ground targets that  
162 maintain a coherent reflectivity to the radar in time even when observed from different  
163 looking angles (the Permanent Scatterers - PS). The interferometric phase in  
164 correspondence of these targets is not randomized by temporal and geometric  
165 decorrelation phenomena. The PSs can be identified by a statistical analysis of amplitudes  
166 and phases of a series of SAR images gathered at different times from slightly different  
167 looking angles (the larger the number of images the more reliable is the statistical  
168 analysis). Atmospheric phase artefacts show a strong spatial correlation within every  
169 single SAR acquisition, but they are uncorrelated in time. Conversely, the phase term due  
170 to the target motion is usually strongly correlated in time and can exhibit different  
171 degrees of spatial correlation depending on the phenomenon at hand (e.g. subsidence due  
172 to water pumping, fault displacements, localized sliding areas, collapsing buildings, etc.).  
173 Finally the topographic phase term shows a linear behaviour with the normal baseline (as  
174 seen from Eq.1).

175 Thus, the phase terms coming from motion, atmosphere and topography can be estimated  
176 and separated from the others in correspondence of the PS locations by looking for their  
177 different behaviour in space and time.

178 Due to the high spatial correlation of the APS, even a low density of PS (3-4 PS/km<sup>2</sup>)  
179 allows proper sampling of the atmospheric components. On each PS sub-metre elevation  
180 accuracy (due to the wide dispersion of the incidence angles available, usually 70  
181 millidegrees with respect to the reference orbit) and millimetric terrain motion detection  
182 (due to the high phase coherence of these scatterers) can be achieved, once APS's are  
183 estimated and removed. In particular, relative target LOS velocity can be estimated with

184 accuracy often better than 0.5 mm/yr, due to the long time span. The higher the accuracy  
185 of the measurements, the more reliable the differentiations between models of the  
186 deformation process under study, a key issue for landslide monitoring and risk  
187 assessment.

188 The final results of this multi-interferogram approach are the following:

- 189 • a map of the PS identified in the image and their coordinates;
- 190 • their average LOS velocity (in mm/yr);
- 191 • the estimated motion component of each PS as a function of time (in mm)
- 192 • the estimated Atmospheric Phase Delay along the LOS for every acquisition date

193

## 194 **2.2 PS Data Precision**

195 In the PS technique all the interferograms used in the processing are generated with  
196 respect to a single master scene, properly selected among all the available SAR  
197 acquisitions so that geometrical and temporal decorrelation phenomena are kept to a  
198 minimum. This strategy does not allow the exploitation of radar targets exhibiting PS  
199 behaviour only on a sub-set of images (as it will be discussed in Section 3), however, it  
200 allows:

- 201 i - the exploitation of all the available SAR images (thus maximizing the temporal  
202 sampling rate of the PS motion time series);
- 203 ii – the exploitation of large baselines (thus getting precise 3D PS positioning that is  
204 essential for estimating the atmospheric delay)
- 205 iii – the direct sampling of the actual PS motion time series.

206 Moreover, it allows a first-order precision assessment of PS results using standard  
207 procedures, e.g. the computation of the *a posteriori* standard deviations of the PS velocity  
208 and elevation values. In Table 1 the typical precision of PS results obtained processing  
209 C-band data acquired by a multi-year ESA-ERS data-set is reported. It should be pointed  
210 out that new high resolution X band sensors can achieve actually better performance in  
211 both geocoding accuracy and sensitivity to target motion, nevertheless figures are  
212 noticeable and justify why InSAR data are gaining importance in space geodetic  
213 applications (*Hilley et al. 2004, Dixon et al. 2006, Ferretti et al. 2004, Berardino 2002,*  
214 *Kampes 2006, Hooper 2004, Ferretti 2007*)

215

216 ***Table 1***

217 Although a thorough statistical analysis of PS measurements is beyond the scope of this  
218 paper, it is worth pointing out that the characterization of the precision of a PS velocity  
219 field using just one statistical figure (e.g. the maximum standard deviation value within  
220 the area of interest) can be misleading. Since the precision strongly depends on the  
221 distance between the PS under study and the reference radar benchmark used in the  
222 analysis, it is actually the *variogram* (or the autocorrelation function) of the phase  
223 components that can provide a more comprehensive statistical characterization of the  
224 results.

225 As a rule of thumb, in any DInSAR analysis, low-frequency spatial components of the  
226 deformation pattern (such as glacial rebound effects) are always more difficult to estimate  
227 than local features (such as a landslide). In fact, both atmospheric effects and orbital  
228 fringes, i.e. the main noise sources in PSInSAR analysis apart from phase unwrapping

229 errors, are characterized by high spatial correlation, since their correlation length  
230 typically exceeds 1 km. Locally, spurious phase components are compensated for by the  
231 double difference computation inherent in any DInSAR analysis, but regional signals  
232 affecting hundreds or even thousands of square kilometres can be difficult to discriminate  
233 without prior information. That is the reason why PSInSAR and GPS are complementary  
234 data that can be used in synergy to map surface deformation phenomena. Indeed, geodetic  
235 observations from a few permanent GPS stations within the area of interest (a satellite  
236 frame is typically  $100 \times 100 \text{ km}^2$  wide) can be used successfully to calibrate PS data (all  
237 PS data are referred to a PS supposed motionless) and remove systematic errors in SAR  
238 observations (e.g. orbital components).

239 If no prior information is available for the area under study, the use of many data-sets  
240 coming from different acquisition geometries (ascending, descending orbits, parallel  
241 tracks, etc.) or even multi-platform analyses can help clarifying the scenario and  
242 improving the quality of the results.

243

### 244 **2.3 The effect of resolution improvement**

245 The ESA-ERS archive, historically, was the first one to be exploited for PSInSAR  
246 analyses. The two ERS platforms followed by ENVISAT, operating at C-band and  
247 sharing a 35-day repeat cycle, created an historical archive of SAR acquisitions since  
248 1991, when the ERS-1 platform was successfully launched. Since then, an ever growing  
249 archive of SAR data with a spatial resolution of about  $20 \times 5 \text{ m}$  became available and  
250 made it possible the development of many algorithms and techniques to exploit phase  
251 information (ESA archives can be found at <http://earth.esa.int/resources/catalogues/>)

252 RADARSAT-1 archives, launched in 1995 and still operational, offer another source of  
253 InSAR data at C-band with a 24-day repeat-cycle, but the availability of many acquisition  
254 modes for the radar sensor has reduced significantly the average number of homogeneous  
255 data-stacks for interferometric applications, although in some areas (e.g. Italy) it has been  
256 carefully planned to acquire interferometric data-sets since 2003. In January 2007,  
257 RADARSAT-2 was successfully launched: this should guarantee the continuation of all  
258 the applications triggered by RADARSAT-1 data availability and allows the acquisition  
259 of high resolution ( $<3$  m) data at C-band.

260 Common to optical sensors, the general trend of the aerospace industry is towards SAR  
261 sensors featuring an ever increasing spatial resolution and shorter temporal sampling.  
262 During the last few years, four new SAR satellites operating at X-band have been  
263 launched, all featuring high spatial resolution and short repeat cycles: three belong to the  
264 dual-use Cosmo-SKymed constellation operated by the Italian Space Agency, and one is  
265 the German TerraSAR-X. It is then reasonable to ask what will be the impact of high-  
266 resolution data on PSInSAR analyses.

267 Theoretically, the X-band wavelength ( $\lambda=3$  cm) is equal to about half of the C-band (the  
268 band of the ERS, ENVISAT and RADARSAT satellites) resulting in a greater sensitivity  
269 (approximately double) to movement, that can lead to more accurate displacement  
270 measurements. Moreover, the revisiting time is much shorter (11 days for TerraSAR-X  
271 and up to 4 days for the CSK constellation, rather than 24 or 35 days) and data are  
272 characterized by higher spatial resolution ( $<3$  m), making it capable of highlighting  
273 details never-before visible in satellite C-band images.

274 Since a Permanent Scatterer usually corresponds to a scattering center dominating the  
275 radar return of a resolution cell, the probability that a pixel of a SAR image exhibits PS  
276 behavior is certainly related to the spatial resolution of the SAR data used in the analysis.  
277 In fact, the higher the resolution, the higher the probability that a certain scattering center  
278 can dominate the surrounding scatterers sharing the same resolution cell. Of course, X-  
279 band SAR interferograms over non-urban areas are more prone to temporal decorrelation  
280 phenomena than C-band or L-band data, due to the increased sensitivity of phase values  
281 to any change in scatterers distribution, but, in principle, over man-made targets or rocky  
282 areas the spatial density of PS should significantly increase with respect to lower  
283 resolution datasets. This should be expected also due to the improved orbital stability of  
284 the newer platforms, allowing lower baseline values compared to the satellite SAR  
285 sensors launched in the nineties and the shorter repeat-cycle, limiting temporal  
286 decorrelation effects, at least for interferogram generated using two successive  
287 acquisitions.

288 Apart from atmospheric effects, severe limitations to DInSAR applications can arise from  
289 possible phase unwrapping errors. Indeed, phase aliasing can occur more likely than at C-  
290 band and X-band results should be carefully checked for data consistency, at least in  
291 areas exhibiting low coherence values.

292 In order to assess the theoretical analysis summarized in the previous paragraphs, two  
293 data-stacks acquired over the same area by both RADARSAT-1 and TERRASAR-X  
294 (TSX) have been used (Table 2). The area is in the Southern part of Italy. Here 22 TSX  
295 images acquired in Strip-Map mode from April 2008 up to January 2009 (11 days  
296 revisiting time) have been processed and compared to a previous PSlInSAR result

297 obtained from 22 RADARSAT-1 S3 (Standard Beam) data gathered from December  
298 2006 to September 2008 (24 days revisiting time). In both cases, all PS exhibiting a  
299 temporal coherence exceeding 0.85 have been selected. This threshold has been set to  
300 limit the number of possible statistical outliers generated by random noise to less than  $10^5$   
301 (Colesanti et al., 2003) and corresponds, in the hypothesis of phase gaussian noise, to a  
302 standard deviation of about 0.6 rad of the phase values.

303 Two snapshots of the results are reported in Figures 5 and 6. In general, we measured an  
304 increased PS density by a factor of 12 that can open brand new applications to PS data,  
305 such as those related to the monitoring of individual buildings and structures. In  
306 particular, looking into Figure 6, it should be noted how, passing to high resolution SAR  
307 data, the highway crossing the area from North to South, can now be accurately  
308 monitored by means of PS data.

309 Since no prior information was available neither on the local topography (apart from the  
310 SRTM DEM used for the generation of the differential interferograms), nor on the  
311 surface displacement field affecting the area of interest, it was not possible to carry out a  
312 quantitative precision assessment. Moreover, it should be noted that the two datasets span  
313 two different time windows, so – at least in principle – the area could be affected by  
314 different displacement fields in the two PS results.

315 However, the two PS datasets have been compared by computing the difference of both  
316 average displacement rates and elevation values of a set of PS pairs (one from the  
317 RADARSAT dataset and one from the TSX dataset) less than 10 m apart. The standard  
318 deviation of the difference between the estimated displacement rate was 4.6 mm/yr while  
319 for elevation values we obtained a dispersion of 5.6 m. While the first figure is in

320 agreement with what should be expected based on the time spans of the datasets and the  
321 impact of atmospheric components having a dispersion of 1 rad at C-band and 1.8 rad  
322 (the ratio between the two wavelengths) at X-band, the dispersion of the elevation values  
323 is higher than expected. This is almost certainly due to the fact that the PS pairs used in  
324 the comparison could belong to different parts of a building or even to two distinct  
325 structures. Moreover any geo-coding error would impact more strongly the dispersion of  
326 the elevation values rather than the average displacement rates, since the local velocity  
327 field turned out to be smooth.

328 It is worth mentioning that we haven't experience any particular problem in unwrapping  
329 the phase values of the X-band datastack. This is probably due to the fact that the area is  
330 not affected by severe displacement phenomena and the local topography is not rough.

331 Finally in Figure 7 a vertical motion time series (LOS measurements have been projected  
332 on the vertical axis) obtained by combining RADARSAT-1 and TERRASAR-X data is  
333 shown. Here a similar vertical velocity estimate dispersion can be noted together with the  
334 higher temporal sampling offered by TERRSAR-X with respect to RADARSAT-1.

335 *Figure 5*

336 *Figure 6*

337 *Figure 7*

338 **Table 2**

339

### 340 **3.0 From point to areal motion measurements**

341 The main drawback of the PS approach is the low spatial density of Permanent Scatterers  
342 in particular extra-urban areas where targets remain coherent to the radar observation for  
343 a limited time interval (from weeks to months). Where the same ground deformation

344 affects an area covered by more resolution cells and the ground motion is strongly  
345 correlated in time, the strict conditions imposed by the PS technique (i.e. long time  
346 coherence and point-wise character of the targets) can be relaxed. Wherever the above  
347 said conditions are verified, areal ground motion information can be extracted also from  
348 partially coherent targets that are not exploited by the PS technique.

349

### 350 **3.1 Multi-master interferograms and targets life-time**

351 In the classical PS analysis the interferometric phase is generated by referring all images  
352 to a common Master acquisition. In the normal baseline – temporal baseline space this  
353 configuration can be represented with a star graph as in Figure 8, where each point  
354 indicates one of the 84 ERS images of the area of Dossena in the Italian Alps and each  
355 connection an interferogram.

356 *Figure 8*

357

358 In this framework, the actual coherent scatterer motion is sampled at the acquisition time  
359 of all the available SAR images. Of course only targets that coherently interfere with the  
360 Master acquisition can be exploited to get meaningful measurements. These targets  
361 should be then almost point-wise dominant targets within the resolution cell (in order to  
362 maintain coherence for large normal baselines) and temporally stable along the whole  
363 acquisition time interval of the SAR images (years, in most cases). Alternative SAR  
364 images combinations have been proposed in literature trying to relax the conditions under  
365 which a target acts as a Permanent Scatterer. As an example in the Small Baseline  
366 approach (SBAS) (*Berardino et al. 2002*), the entire set of available SAR images is

367 divided into subsets of images showing a very small normal baseline thus relaxing one of  
368 the target conditions requested by the Permanent Scatterers technique. As drawbacks of  
369 this approach some of the available images may not be used, the resulting graph is often  
370 disconnected thus preventing the correct motion measurement without an available a  
371 priori model and the small baseline condition does not allow a precise target 3D location  
372 in space thus preventing a good separation of elevation, motion and atmospheric phase  
373 components.

374 What is proposed here is to search for the minimum best coherence graph connecting all  
375 the images of the data-set, without imposing any pre-defined decorrelation model  
376 (temporal or spatial), simply by maximizing the interferometric coherence. In second  
377 instance, the minimum graph can also be increased by adding more connections to make  
378 the estimate more robust. Figure 9 shows the obtained graphs for the same 84 SAR  
379 images data-set used for generating the “star graph” of Figure 8. As visible in the picture,  
380 many selected connections have small normal baselines, but not all interferograms follow  
381 this rule. Moreover, the graph is connected and can change from pixel to pixel.

### 382 **Figure 9**

383 During the generation of the time-baseline connection graph, the coherence of all the  
384  $\frac{(N-1)N}{2}$  interferograms that can be generated with  $N$  SAR images should be analyzed.

385 From the analysis of these coherence maps it is possible to generate a map of the average  
386 coherent life-time of the imaged scatterers. The map is obtained by averaging the  
387 interferometric temporal baselines weighted by the corresponding interferometric  
388 coherence. By using data of the ESA-ERS archive that include also the so called  
389 “tandem” interferometric pairs gathered with just one day time interval, the measurable

390 scatterers life-time ranges between one day and some years (e.g. 10 years for the data set  
391 used in this example). In Figure 10 such a scatterer's life-time map is shown referred to  
392 the area of Dossena. The logarithmic colour scale of Figure 10 ranges from blue (1 day)  
393 to red (more than 1000 days). The red (long life time) scatterers correspond to urban and  
394 exposed rocks areas (i.e. they are good PS candidates) whereas blue scatterers remain  
395 stable just for one day and cannot be exploited for ground motion estimation (non-  
396 coherent scatterers are not colored at all). In between there are very many scatterers with  
397 a medium lifetime shorter than that of PSs, but long enough (a few months) to allow  
398 ground motion measurement. Moreover, the "birth" and "death" dates of such medium  
399 life-time scatterers belonging to a small area affected by the same surface motion are  
400 different and by combining their individual life interval, the measurable time interval of  
401 the areal ground motion can be extended up to several years.

402 ***Figure 10***

403 The core idea of the new technique is to jointly estimate elevation and deformation trend  
404 of a given point from the complex interferometric spatial coherence. In this way, the  
405 absolute value of the spatial coherence acts as a weight in the estimation process and only  
406 coherent interferograms play a role in the retrieval of the target parameters (uncoherent  
407 ones are weighed out). Note that the set of the actually used coherent interferograms can  
408 be different from point to point. Moreover, the phase used in the estimate is filtered by  
409 the coherence estimation process. This is an advantage for distributed targets but can lead  
410 to errors in case of high density point-wise targets areas whose elevation and motion are  
411 averaged.

412 As an example, the average ground areal velocity of the area of Dossena measured by  
413 exploiting the above said multi-master interferograms and partially coherent targets  
414 strategy is shown in Figure 11. As a comparison the single target average ground velocity  
415 of the same area measured by means of the standard PS Technique is shown in figure 12.  
416 By comparing Figures 11 and 12, it is quite evident that the number of measurement  
417 points increases by more than one order of magnitude passing from PSs to partially  
418 coherent targets. A detailed comparison of the estimated ground velocities at the PSs  
419 locations has shown that they are often in good agreement (standard deviation around .5  
420 mm/year), but for some cases where two or more neighbouring PSs with different  
421 velocities have been averaged during the coherence estimation step of the partially  
422 coherent targets processing.

423 *Figure 11*

424 *Figure 12*

425

#### 426 **4.0 Conclusions**

427 The recent technological advances of multi-temporal SAR images signal processing  
428 together with the availability of new high resolution SAR sensors with a short revisiting  
429 time can be exploited to get precise surface ground motion on a high density of  
430 measurement points covering large areas. In particular it has been shown that by  
431 increasing the spatial resolution by a factor of more than 10 (passing from the C-band  
432 RADARSAT-1 data to the X-band TERRASAR ones), the density of measurement points  
433 achieved by the Permanent Scatterers Technique increases by a factor of more than 5.  
434 Moreover, in case of the Cosmo SKY-Med mission, the shorter revisiting time of this

435 new sensors constellation would allow monitoring more rapid ground deformation  
436 phenomena than in the past.

437 It has also been shown that the theoretically less precise areal measurements on a higher  
438 set of partially coherent targets can complement the more precise point wise scatterers  
439 time series achievable with the PS Technique.

440 The integration of these techniques with other independent measurements (e.g. GPS)  
441 represents a powerful tool that can be exploited by geologists and geophysicists for  
442 investigating many ground deformation phenomena (*Burgmann 2006*).

443 Finally it should be pointed out that maps of the differential travel time delay are  
444 generated as a side product of these techniques. These maps could be usefully exploited  
445 to get information on the troposphere water vapor content with unprecedented spatial  
446 resolution.

447

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505

506 **Figure Captions**

507 **Figure 1** - INSAR acquisition geometry.

508 **Figure 2** - Example of co-seismic interferogram of the Bam (Iran) earthquake, Dec. 26<sup>th</sup>,  
509 2003 formed with 2 ENVISAT images (about 30x40km) taken before and after the  
510 earthquake respectively. Each colour cycle corresponds to a relative ground displacement  
511  $d = \lambda/2$  (i.e. about 2.8cm).

512 **Figure 3** - Example of interferograms of the town of Ancona (on the Adriatic Italian  
513 coast) formed with ERS images taken in one day (left) and one year time interval (right)  
514 respectively.

515 **Figure 4** - Left: random spatial distribution of phase coherent samples (10% of the total)  
516 showing a possible terrain subsidence with a gaussian shape. Right: the image on the left  
517 has been filled with random phase samples. Coherent pixels are still there, but they  
518 cannot be identified visually or by means of any sort of spatial filtering.

519 **Figure 5** - Spatial distribution of the Permanent Scatterers identified in an urban area  
520 located in the Southern part of Italy (an aerial orthophoto is used as background). The  
521 color scale is related to PS elevation, ranging from red (sea level) to blue (50 m). Upper  
522 image: PS obtained by processing 62 RADARSAT-1 S3 (Standard Beam) images  
523 covering the period 2003-2007. Lower image: PS obtained by processing 22 TSX images  
524 acquired in Strip-Map mode from April 2008 up to January 2009.

525 **Figure 6** – Average Spatial distribution of the Permanent Scatterers identified in a semi-  
526 urban area located in the Southern part of Italy (an aerial orthophoto is used as

527 background). The color scale is related to PS elevation, ranging from red (sea level) to  
528 blue (50 m). Upper image: PS obtained by processing 62 RADARSAT-1 S3 (Standard  
529 Beam) images covering the period 2003-2007. Lower image: PS obtained by processing  
530 22 TSX images acquired in Strip-Map mode from April 2008 up to January 2009.

531 **Figure 7** – Vertical velocity time series of a PS obtained by combining RADARSAT and  
532 TSX data.

533 **Figure 8** - Normal baseline – temporal baseline space of 84 ERS SAR images of the area  
534 of Dossena in the Italian Alps. Each point indicates an image whose acquisition time with  
535 respect to the Master is shown in abscissa (days) and perpendicular baseline with respect  
536 to the Master is shown in ordinate (m). The Master image has coordinates (0,0) and each  
537 of the 83 connections indicates that an interferogram is formed between the Master and  
538 the remaining 83 Slave images.

539 **Figure 9** - Normal baseline – temporal baseline space of the same 84 ERS SAR images  
540 data-set used in Figure 8. Left: 83 lines connect all the images in such a way that 83  
541 interferograms with the highest possible coherence are generated. The colour of the  
542 connection lines indicates the estimated coherence of each interferometric pair. The  
543 minimum best coherence graph can change from pixel to pixel. Right: Some among the  
544 3403 possible connections (i.e. higher coherence interferograms) have been added to the  
545 minimum best coherence graph.

546 **Figure 10** - Scatterers life-time map of an area of the Italian Alps. The logarithmic colour  
547 scale ranges from blue (1 day) and is saturated to red (more than 1000 days).

548 **Figure 11** - average ground areal velocity of the area of Dossena measured by exploiting  
549 the multi-master interferograms and partially coherent targets strategy.

550 **Figure 12** - single target average ground velocity of the area of Dossena measured by  
551 means of the standard PS Technique

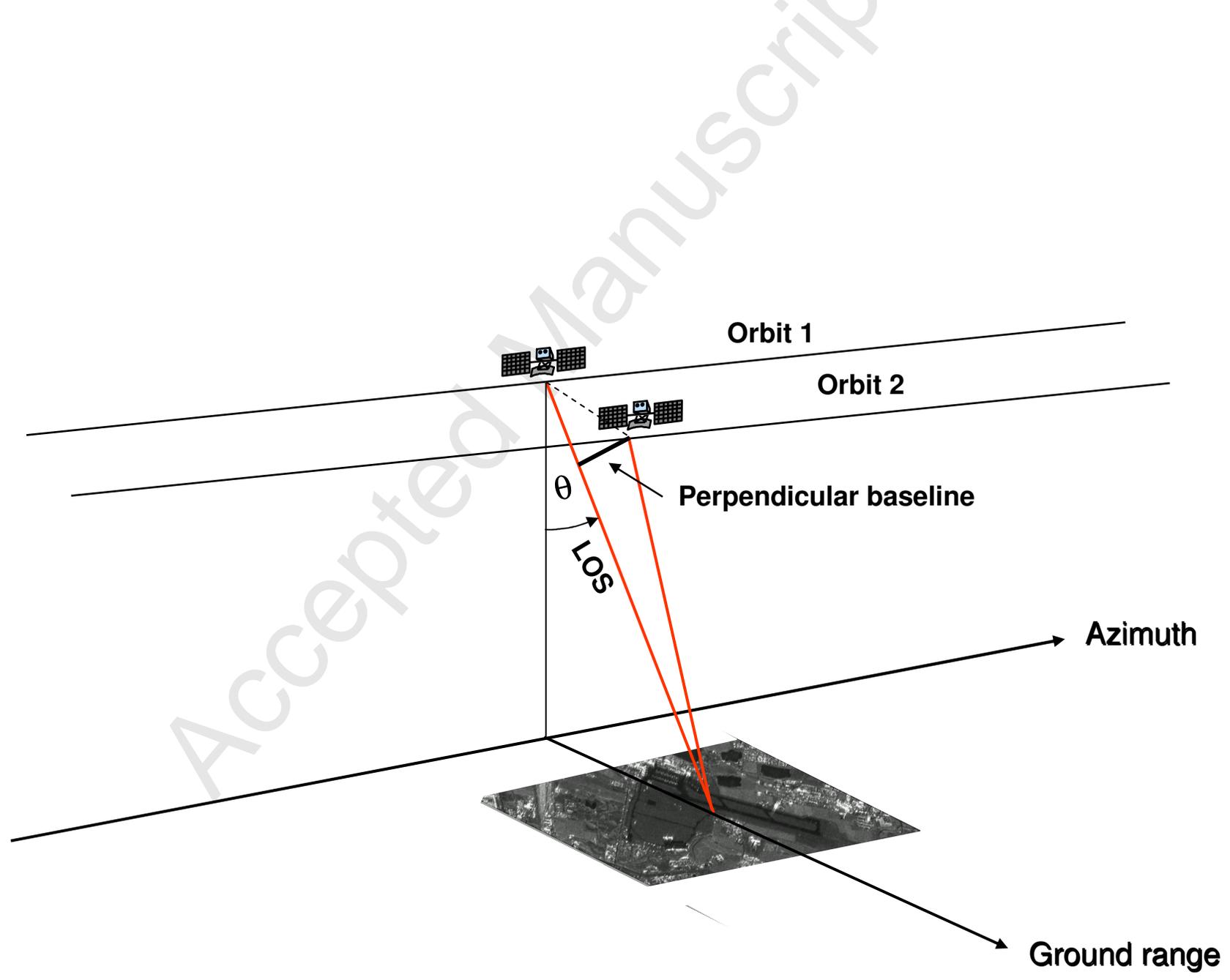
552 **Tables**

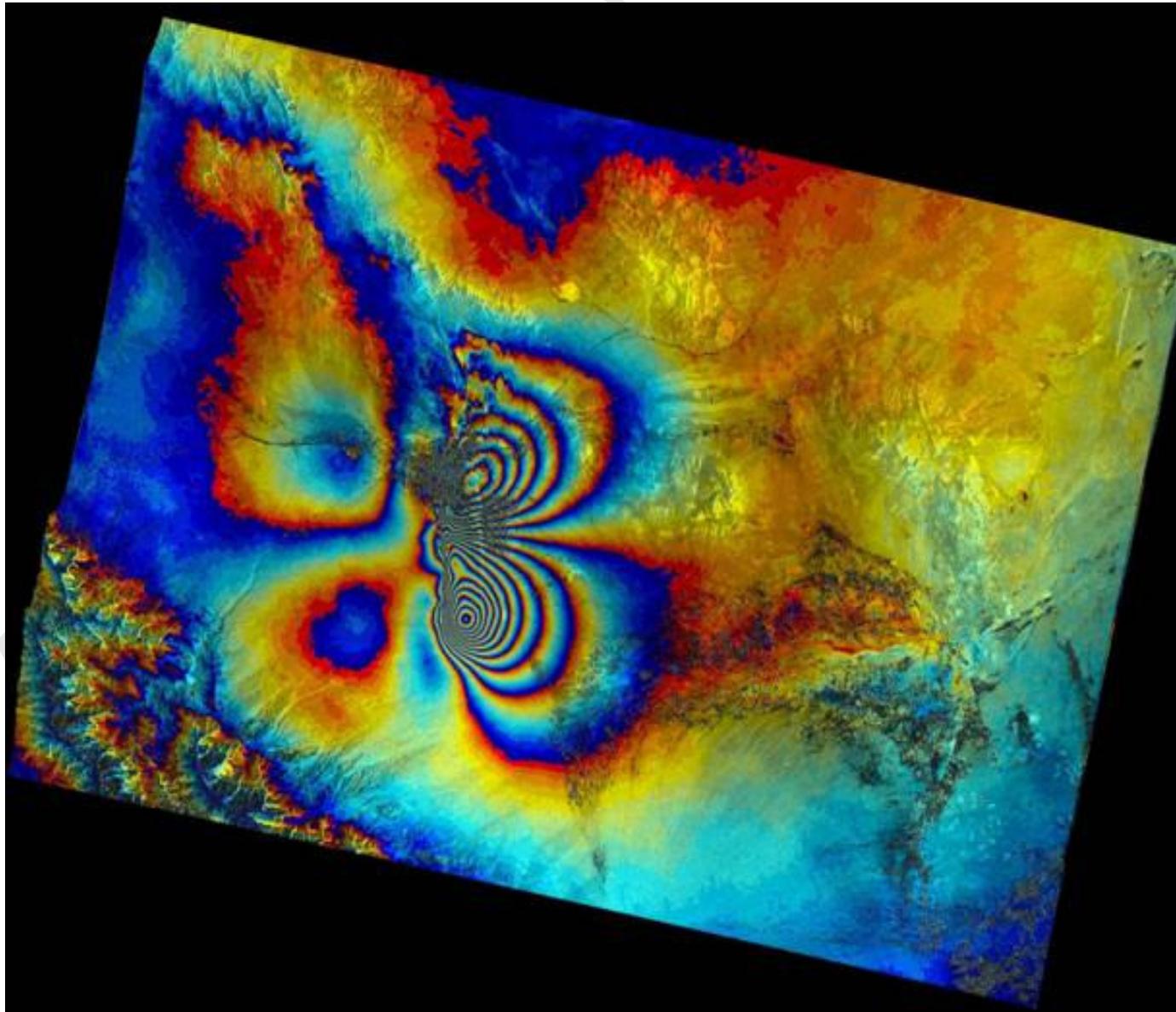
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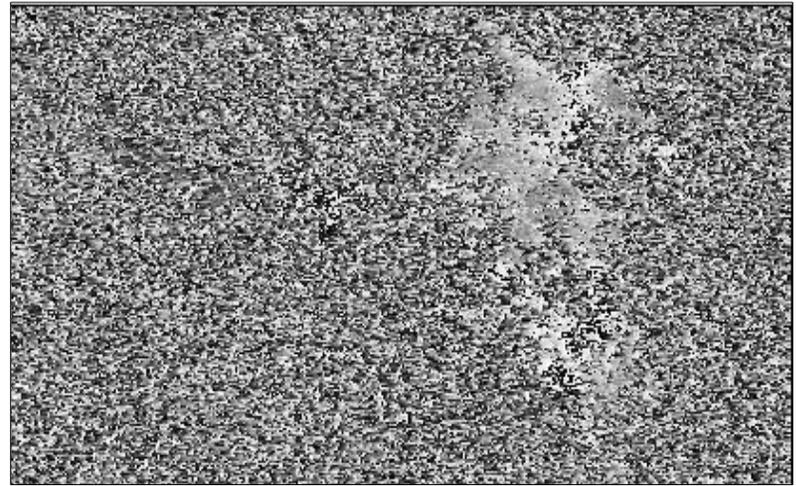
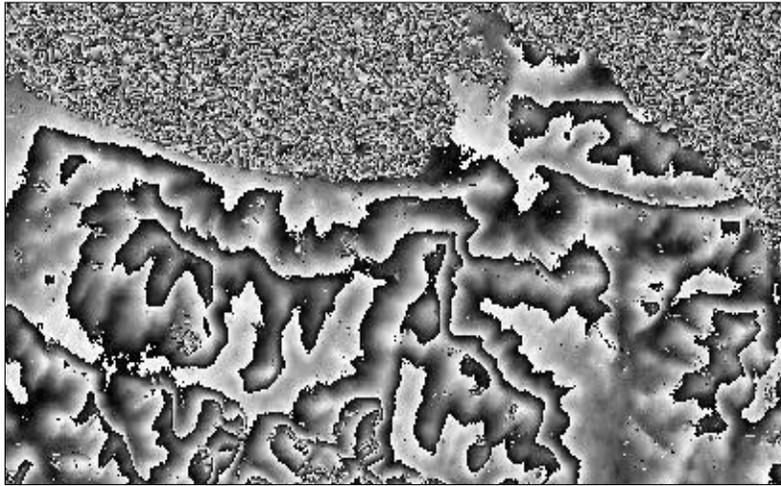
554 Table 1: Typical precision figures for PS results obtained by processing an ESA-ERS  
555 dataset (C-band radar data) having at least 40 scenes (35-day temporal sampling) at a  
556 distance less than 1 km from the reference PS.

557

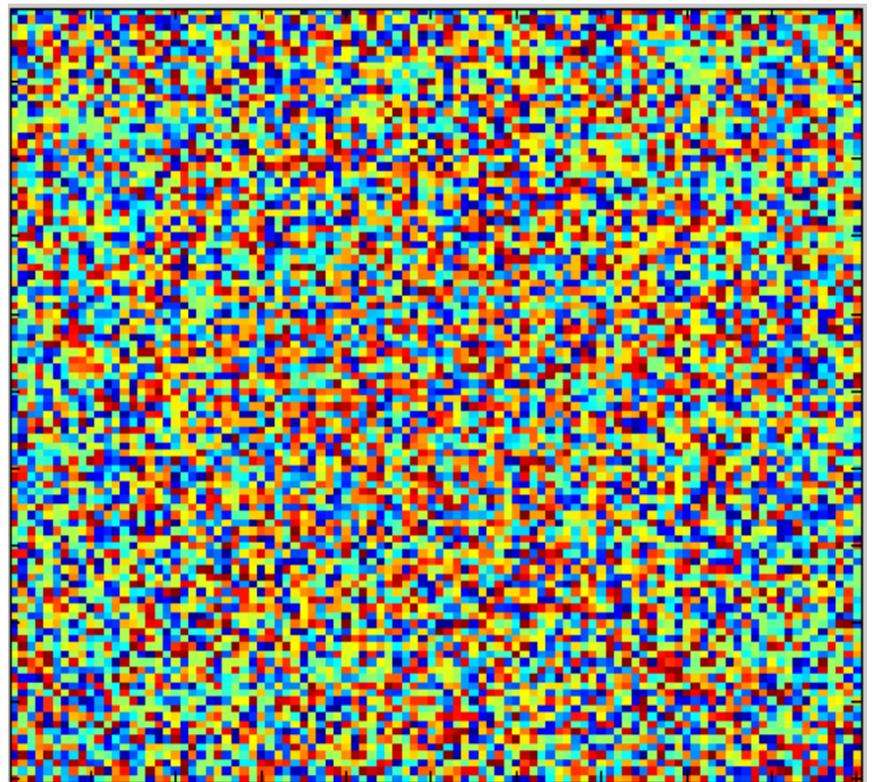
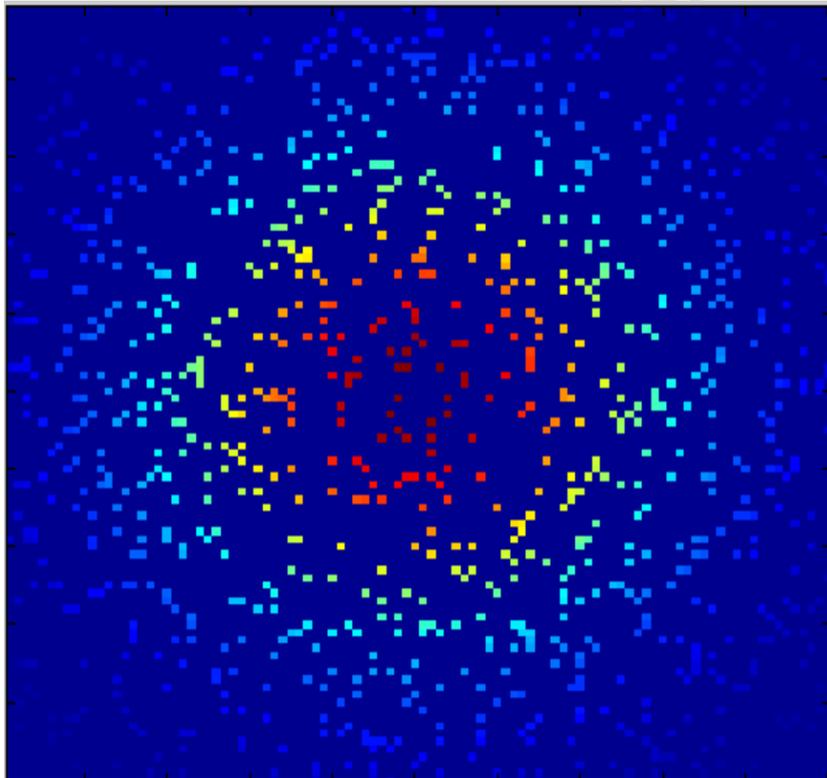
558 Table 2: Nominal parameters values of RADARSAT-1 and TERRASAR-X data used in  
559 the comparison analyzed in the text.

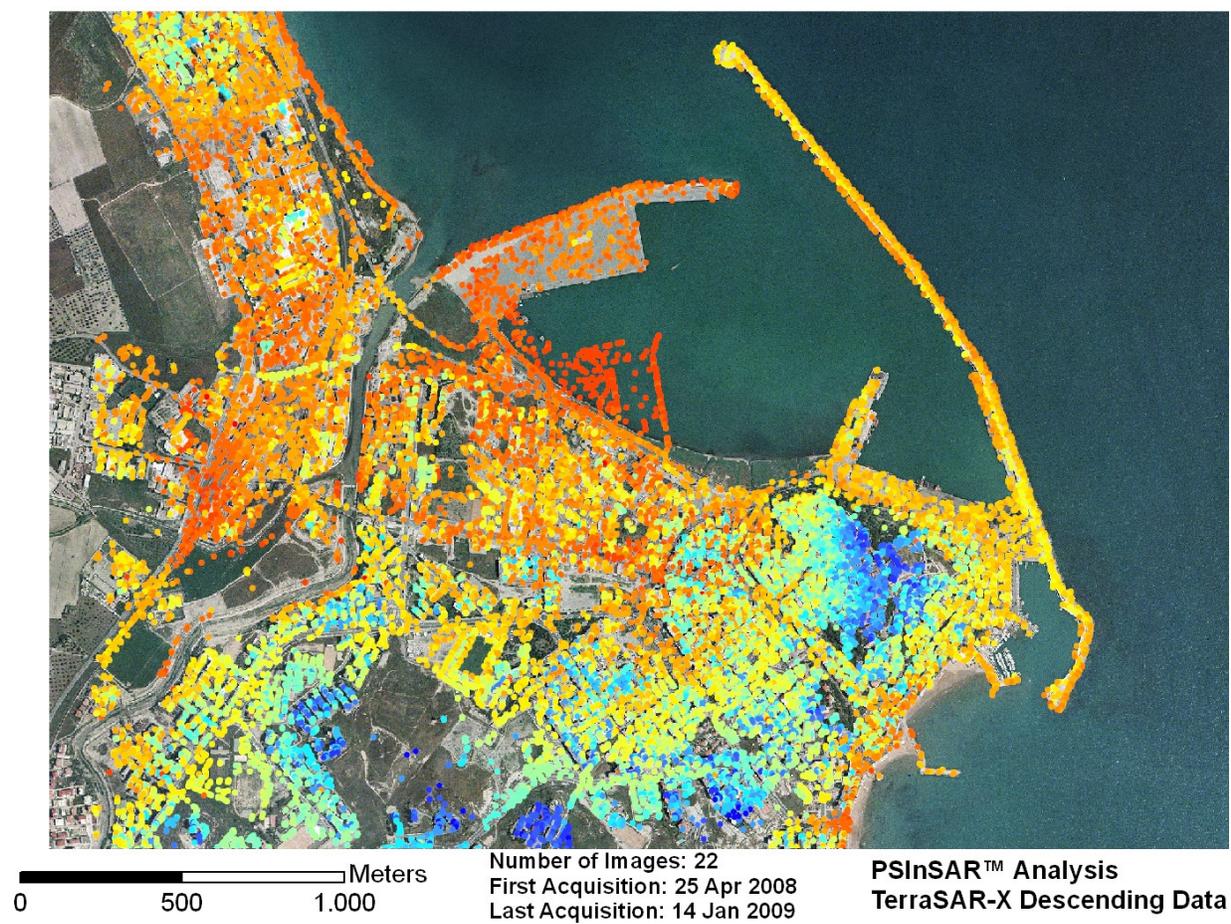
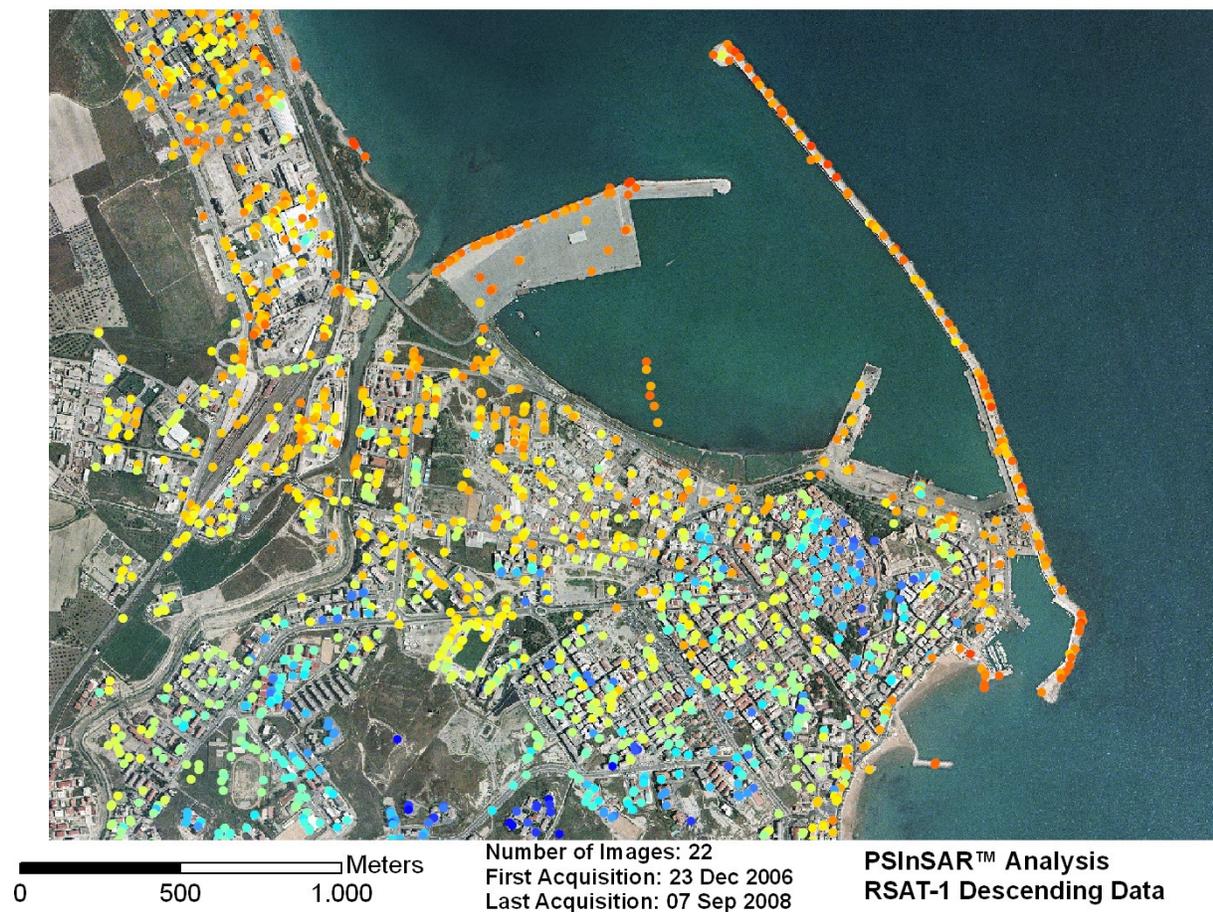


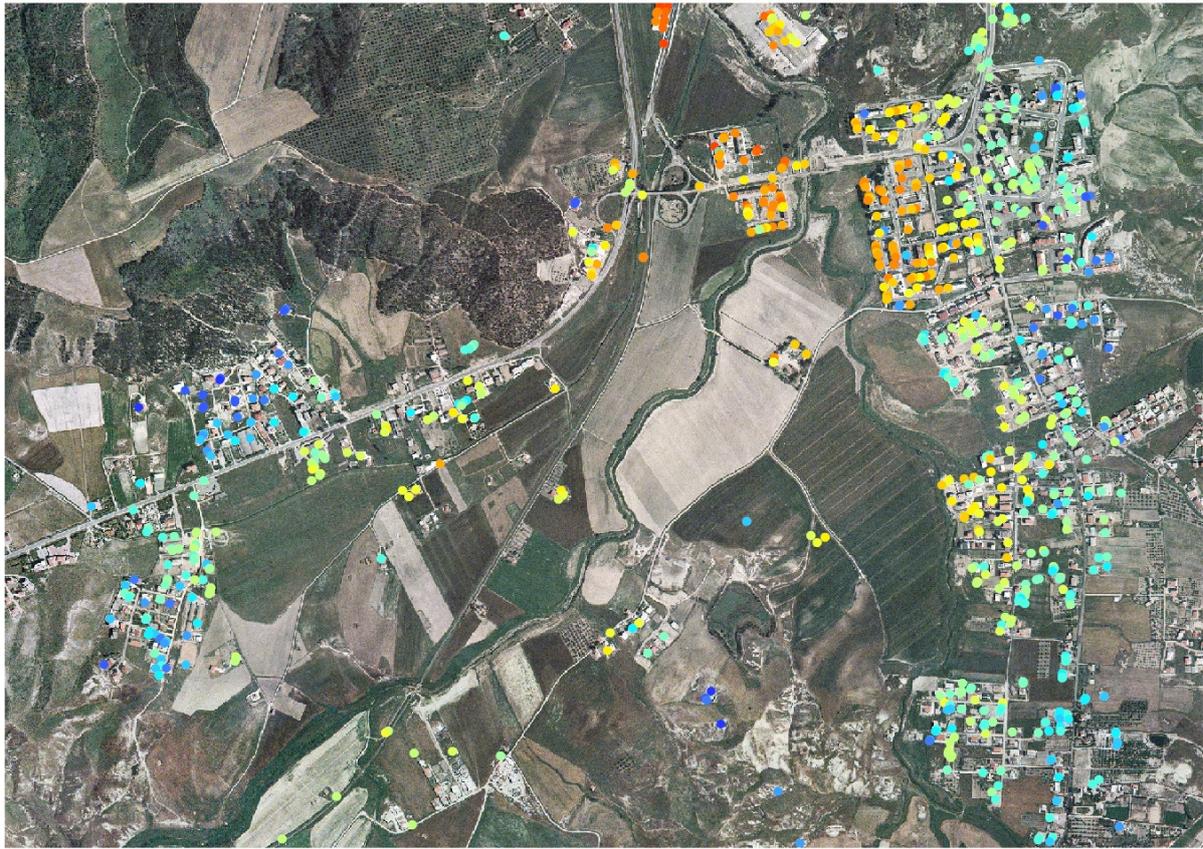




Manuscript



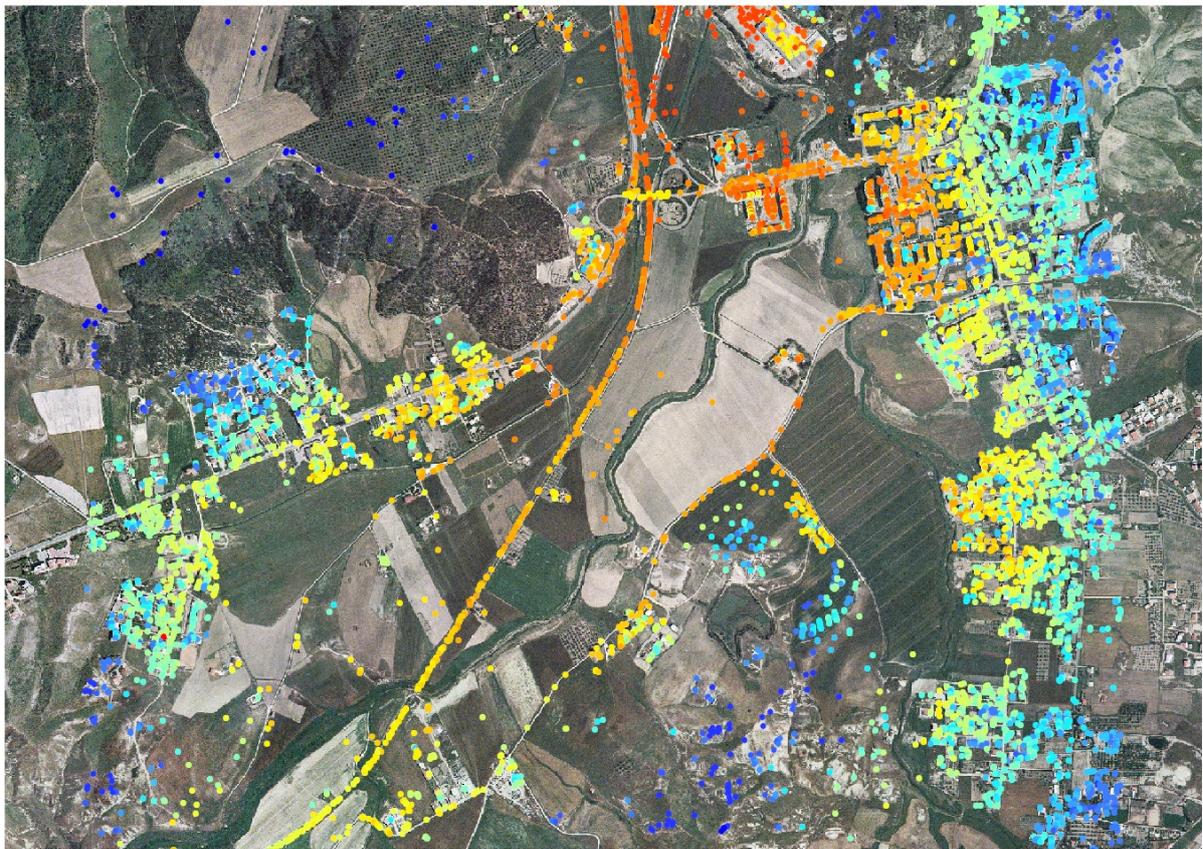




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First Acquisition: 23 Dec 2006  
Last Acquisition: 07 Sep 2008

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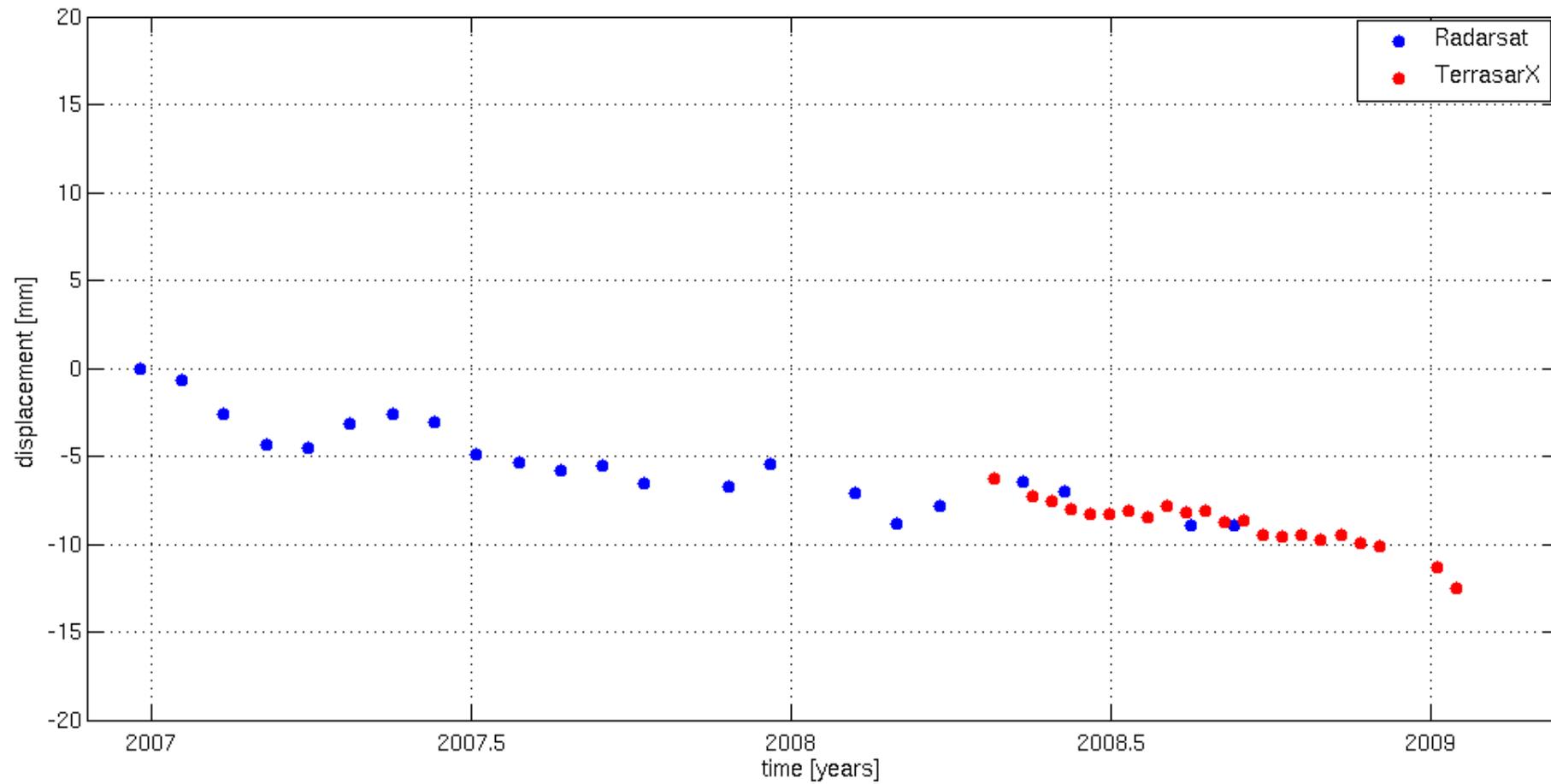


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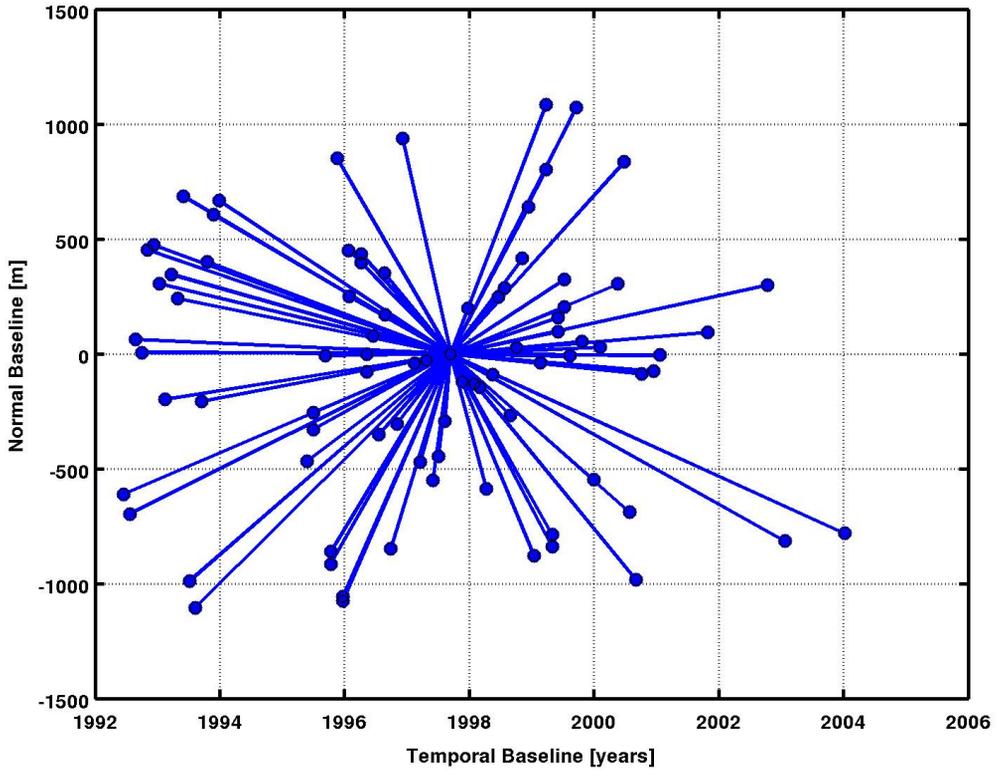
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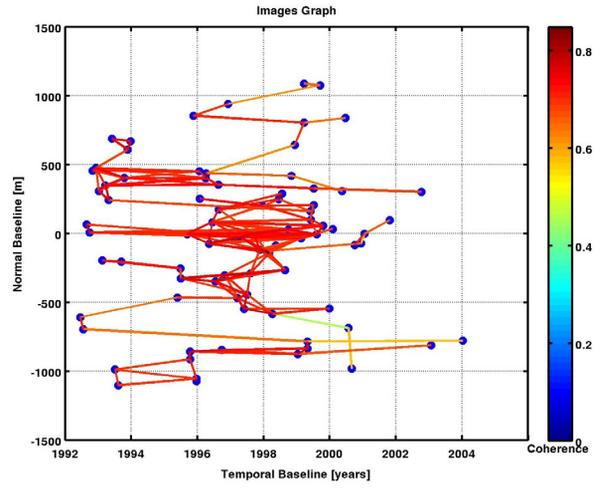
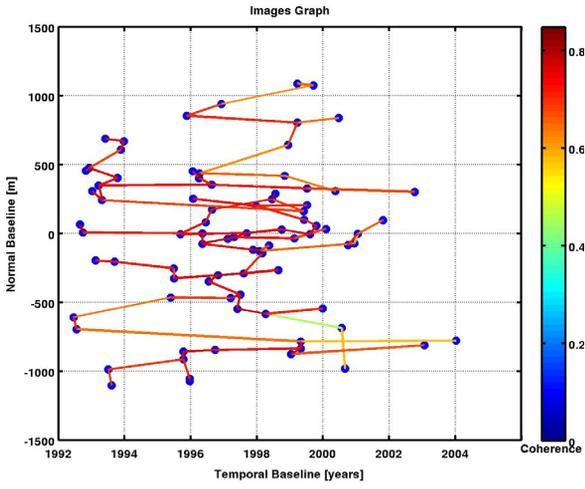
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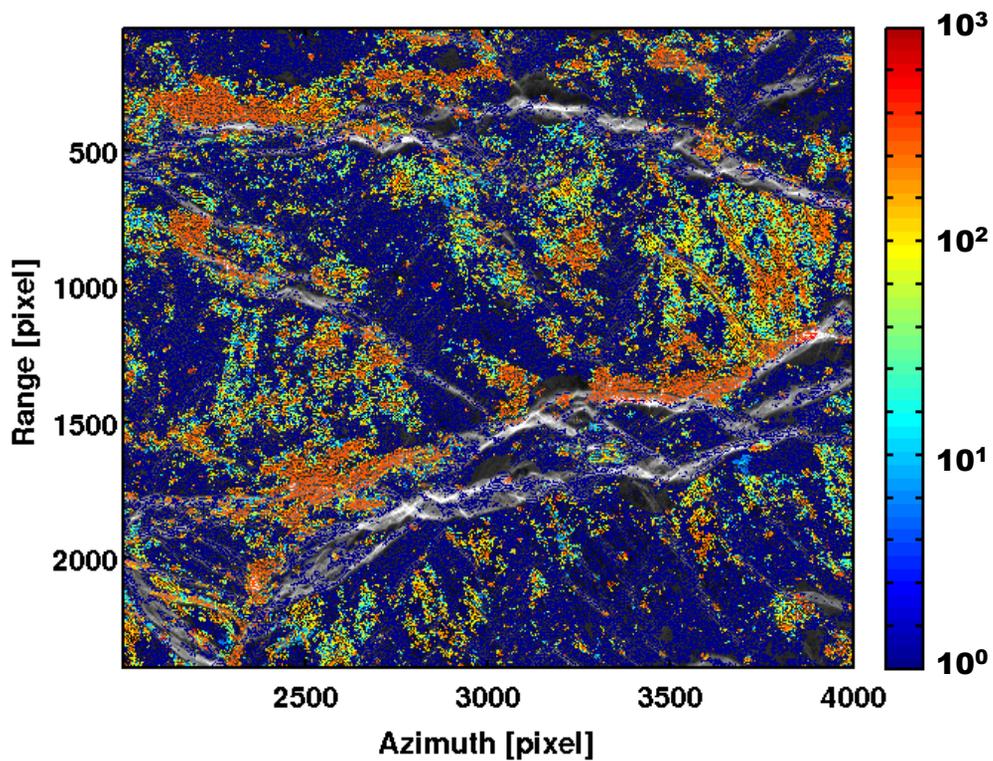
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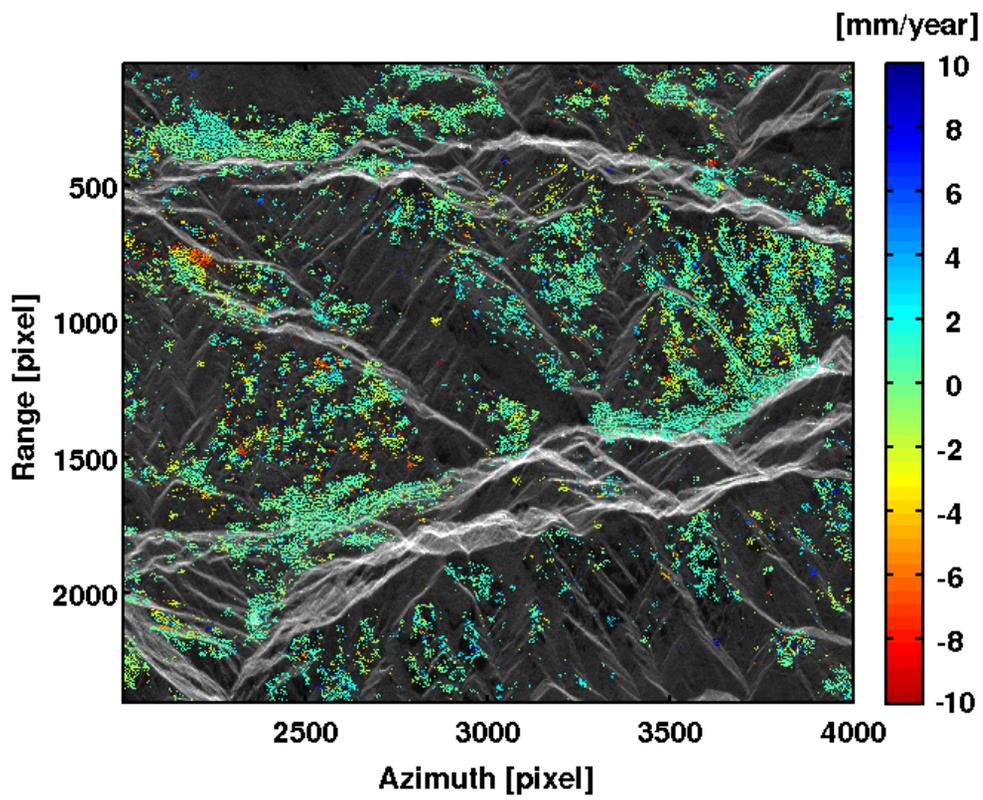
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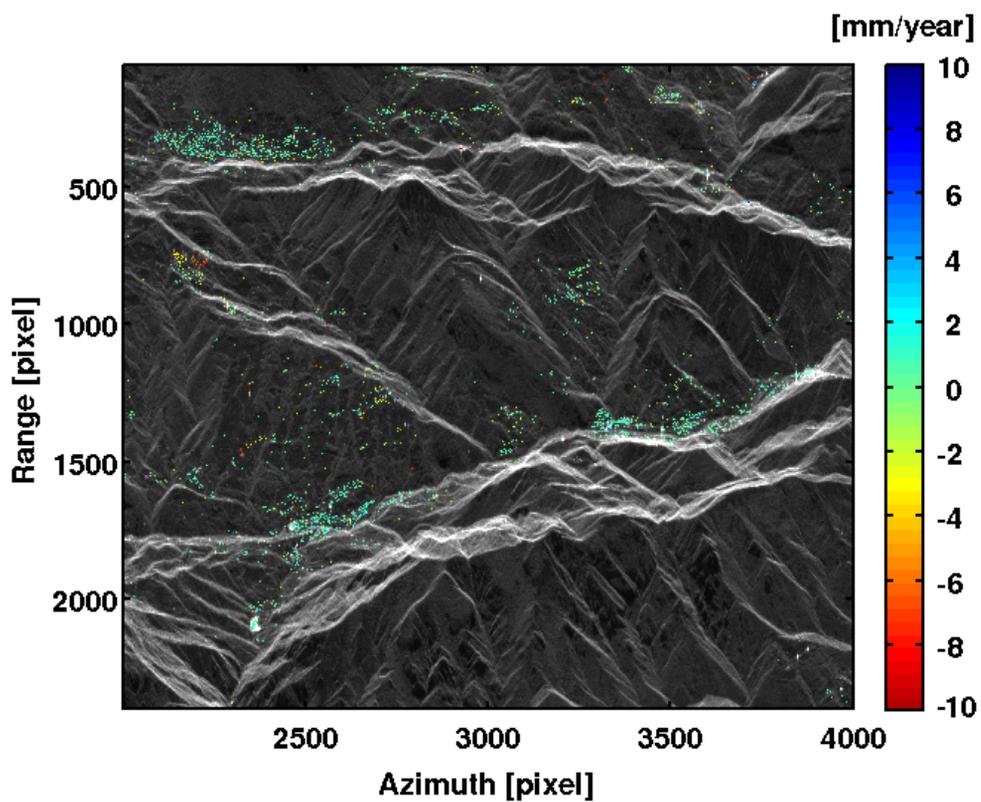
Accepted



Accepted



Accepted



Accepted

	Precision ( $1 \sigma$ )
Easting	<5 m
Northing	<2 m
Height	<1 m
Displacement Rate	<0.5 mm/yr
Single Displacement Measurement	<5 mm

Accepted Manuscript

	<b>RADARSAT-1</b>	<b>TERRASAR-X</b>
Acquisition Mode	Standard Beam - S3	Strip-map -SM
Orbit	Descending	Descending
Incidence angle	37 deg	29 deg
Bandwidth	11.6 MHz	150 MHz
Wavelength	5.6 cm	3.1 cm
Pixel posting (azimuth)	5.1 m	2.1 m
Pixel posting (range)	11.6 m	0.9 m
Polarization	HH	HH

Accepted Manuscript