



THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

## Fusion of remotely sensed displacement measurements: current status and challenges

### Citation for published version:

Yan, Y, Dehecq, A, Trouve, E, Mauris, G, Gourmelen, N & Vernier, F 2016, 'Fusion of remotely sensed displacement measurements: current status and challenges', *IEEE Geoscience and Remote Sensing Magazine*, vol. 4, no. 1, pp. 6 - 25. <https://doi.org/10.1109/MGRS.2016.2516278>

### Digital Object Identifier (DOI):

[10.1109/MGRS.2016.2516278](https://doi.org/10.1109/MGRS.2016.2516278)

### Link:

[Link to publication record in Edinburgh Research Explorer](#)

### Document Version:

Peer reviewed version

### Published In:

IEEE Geoscience and Remote Sensing Magazine

### General rights

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

### Take down policy

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact [openaccess@ed.ac.uk](mailto:openaccess@ed.ac.uk) providing details, and we will remove access to the work immediately and investigate your claim.



# Fusion of remotely sensed displacement measurements: current status and challenges

Y. Yan<sup>1</sup>, A. Dehecq<sup>1,2</sup>, E. Trouvé<sup>1</sup>, G. Mauris<sup>1</sup>, N. Gourmelen<sup>2</sup>, F. Vernier<sup>1</sup>

1: LISTIC, Polytech Annecy-Chambéry, Université Savoie Mont Blanc, Annecy, France

Email: yajing.yan@univ-smb.fr

2: School of Geosciences, University of Edinburgh, UK

November 18, 2015

## ABSTRACT

Nowadays, data fusion constitutes the key subject in numerous applications of remotely sensed displacement measurements, with the increasing availability of remote sensing data and the requirement of improvement of the measurement accuracy. This paper addresses the current status and challenges in the fusion of remotely sensed displacement measurements. An overview is given to discuss the remote sensing sources and techniques extensively used for displacement measurement and the recent development and achievement of displacement measurements fusion. Fusion between displacement measurements and integration of a geophysical model are discussed. The fusion strategies and uncertainty propagation approaches are illustrated in two main applications: 1) surface displacement measurements fusion to retrieve surface displacement with **reduced uncertainty** in case of redundancy, with larger spatial extension or of higher level in case of complementarity 2) surface displacement measurements fusion to estimate the geometrical parameters of a physical deformation model in case of redundancy and complementarity. Finally, the current status and challenges of remotely sensed displacement measurements fusion are highlighted. Moreover, some potential ways are proposed to deal with heterogeneous data types and to assimilate remote sensing data into physical models in order to realise near real time displacement monitoring.

## 1 Introduction

The surface of the Earth is deforming permanently due to mass transfer, either internal or external, either natural or man-made activities. The displacement at the Earth's surface vary a lot in terms of spatial

23 extension, amplitude and temporal evolution. The investigation of the displacement at the Earth's surface  
24 represents an essential part of geodesy and its quantification constitutes a major topic in the community  
25 of geoscience, since it is of particular importance for natural hazards monitoring. For example, the dis-  
26 placement measurements and the deformation model inferred from these measurements provide crucial  
27 information in order to avoid the installation of emergency shelter and reconstruction over affected areas  
28 that will result in further damage in a later earthquake [1, 2]. Further, these sources of information enrich  
29 the disaster early warning system in order to prevent the future natural hazards. Displacement measure-  
30 ments also present great potential for underground exploitation, bridges and dams sinking monitoring and  
31 they are of particular interest in civil engineering [3, 4, 5, 6].

32 At the end of the 20th century, the development of spatial geodetic techniques (optical & SAR imagery,  
33 GPS) has allowed for drastic improvement of the spatial coverage, the resolution and the accuracy of  
34 displacement measurements. **Spaceborne optical and radar sensors observe the Earth's surface**  
35 **continuously, across both space and time, but with limited flexibility in terms of revisit**  
36 **time and acquisition geometry. Airborne optical and radar sensors provide displacement**  
37 **measurements with limited spatial/temporal coverage, but improved flexibility in terms of**  
38 **revisit time and acquisition geometry. Moreover, ground based optical and radar sensors,**  
39 **with good flexibility in terms of revisit time and acquisition geometry, often give precise**  
40 **information for small scale phenomena.** Thanks to these techniques, spectacular results have been  
41 obtained in numerous applications with displacement of various characteristics in terms of magnitude,  
42 duration, spatial distribution, etc.: the study of subsidence in urban areas [3, 7, 8, 9, 10, 11], of the  
43 co-seismic, inter-seismic and post-seismic motions [12, 13, 14, 15, 16], of glacier flows [17, 18, 19], of volcanic  
44 deformation [20, 21, 22, 23], etc. Nowadays, the displacement maps obtained by remote sensing techniques  
45 reach an accuracy within millimetres per year for deformation velocity and cover almost the whole **land**  
46 **of the Earth**, including the non-instrumented remote areas and areas that do not have the necessary  
47 financial means and human resources for ground instrumentation. They have also proven very useful for  
48 regional studies. Moreover, due to the archiving system, a posteriori studies can be performed on areas  
49 where an interesting phenomenon has been detected. We thus have access to the initial phase. Therefore,  
50 remote sensing displacement measurements have obtained significant development in the past few years.  
51 They are considered as the predominant source for the detection and the quantification of the terrestrial  
52 deformation, from which geophysical models have been retrieved to further understand the deformation  
53 source in depth and the physical process that induces the displacement observed from the Earth's surface.

54 To this end, a good knowledge of the reliability of the remotely sensed measurements, as well as

55 of the geophysical models accordingly obtained, is crucial for all the researches and applications that  
56 use these sources of information. However, remote sensing displacement measurements are subject to  
57 incompleteness and uncertainty. Uncertainty is also present in the geophysical model due to limited  
58 knowledge about the phenomenon under observation and approximations made in the modelling, as well as  
59 uncertainties associated with the displacement measurements used to constrain the model. A perspective  
60 of significant **reduction in the uncertainty** of the displacement measurement appears thus with the  
61 increasing availability of different types of remote sensing measurements and the blooming development  
62 of displacement information extraction techniques. Thereby, the role of data fusion, making use of the  
63 redundant and complementary displacement information brought by different sources, becomes more and  
64 more important. Methodological development of the fusion of different types of displacement measurements  
65 and of the integration of a physical model based on supercomputer facilities seems necessary to improve  
66 the spatial extension and the accuracy of displacement measurements. In this context, this paper addresses  
67 the current status and challenges of the fusion of remotely sensed displacement measurements.

68 This paper is organised as follows: In Section 2, remote sensing sources including optical, SAR images, in  
69 situ GPS measurements and levelling sources, as well as displacement extraction techniques such as offset-  
70 tracking, differential interferometry (DInSAR) are introduced. Moreover, the uncertainty quantification  
71 of measurements issued from these techniques is also discussed. In Section 3, the fusion of displacement  
72 measurements and the integration of geophysical models are presented. The fusion issues are presented  
73 through 2 main applications: from raw measurements to fused measurements and from measurements to  
74 model parameters. Finally, in Section 4, the current status and challenges are highlighted and perspectives  
75 to deal with heterogeneous data types and to assimilate remote sensing data into physical models are  
76 proposed.

## 77 **2 Displacement measurement data**

78 Nowadays, SAR and optical images constitute the predominant remote sensing source for displacement  
79 measurement, due to their high capacity in providing displacement measurement over large area and of  
80 great accuracy. GPS and levelling measurements, thanks to their high **precision**, are also widely used as  
81 complementary sources to **remote sensing data**.

## 82 2.1 Displacement extraction techniques

83 Two different families of technique have been developed to extract displacement information from SAR  
84 or optical images: offset-tracking of amplitude SAR or optical images and DInSAR. Techniques in the  
85 family of offset-tracking, based on the cross-correlation between the master image and the slave image,  
86 provide two dimensional (2D) measurements (namely correlation measurements hereafter), with one hor-  
87 izontal component in the direction of the sensor motion and the other component in the perpendicular  
88 direction in the horizontal plane for optical images and in the Line Of Sight (LOS) for SAR images. The  
89 accuracy of these techniques is limited by the resolution of the images used, the stereoscopic effect and the  
90 decorrelation. Numerous studies have confirmed that the displacement error is generally included between  
91 tenth of pixel and one pixel [24, 25]. The best accuracy obtained is recorded as 1/30 pixel for SAR images  
92 [26] and 1/200 of pixel for optical images [27] with careful data processing. **The application of offset**  
93 **tracking techniques is thus mainly determined by the resolution of the images used and the**  
94 **magnitude of the displacement to measure. Therefore, they are commonly applied for large**  
95 **displacement, e.g.** glacier flow monitoring [28, 29, 30, 31] and strong earthquake measurement in the  
96 field near the fault rupture [24, 12, 32, 33, 34, 35].

97 DInSAR, on the other hand, makes use of the phase information included in a pair of SAR images  
98 and allows for the measurement of the displacement occurred between the two acquisitions in the LOS  
99 direction. Compared to offset-tracking, this technique requires **strong coherence between two SAR**  
100 **images, for which the geometrical and temporal baselines between the two acquisitions should**  
101 **be as small as possible. Moreover,** more complex processing steps such as the orbital, topographical  
102 and atmospheric correction and phase unwrapping **are necessary**. In particular, phase unwrapping de-  
103 termining the success of the application of DInSAR, is difficult and delicate since the choice of the phase  
104 unwrapping method depends on the nature of the interferograms to be processed. The problems mainly  
105 encountered are the discontinuity of the coherent areas and the strong gradient of the displacement that  
106 can cause potential aliasing problem. Today, no method seems fully operational. DInSAR has been widely  
107 used to measure small displacements such as surface subsidence in urban area [7, 36, 37, 8], inter-seismic  
108 deformation [14, 38, 16] or glacier flow [39, 40, 41, 18], with an average accuracy of centimetres. With the  
109 increasing availability of SAR images, techniques such as Permanent Scatterer (PS) [42, 43, 44, 45] and  
110 Small BAseLine Subset (SBAS) [46, 47, 48, 49, 50] dealing with time series have been developed in order to  
111 **reduce the uncertainty** of the displacement measurement and to get around of the principal limitations  
112 of the conventional DInSAR technique. With these techniques **and the availability of the X-band high**  
113 **resolution images (TerraSAR-X, COSMO-SkyMed), precision** on the order of millimetres per year

114 has been obtained for displacement rate. Recently, combination of these two techniques is performed in  
115 order to further **reduce the uncertainty** of the displacement measurements and promising results have  
116 been obtained [51, 52, 9]. **Furthermore, multiple aperture InSAR (MAI) technique, based on**  
117 **split-beam InSAR processing, has been developed in order to extract along-track displace-**  
118 **ment from DInSAR data [53, 54]. The along-track displacement obtained is consistent with**  
119 **that obtained from offset-tracking. Note also that, in multitemporal InSAR processing, the**  
120 **deformation velocity estimation can be strongly biased by the thermal dilation of the imaged**  
121 **objects. Improvement of existing approaches and development of new approaches [55, 56, 57]**  
122 **have been proposed to deal with this issue. With these approaches, it is possible to achieve**  
123 **an extremely accurate monitoring of thermal dilation, up to a sensitivity on the order of**  
124 **1 mm in the deformation measurement [56].**

125 Besides SAR and optical images, continuous GPS, as a complementary remote sensing source, is also  
126 widely used in displacement measurement. Different from SAR/optical imagery, GPS provides the 3D  
127 displacement (with 3 components: East, North, Up in the terrestrial reference) on a much sparse and  
128 irregular spatial grid with temporal sampling every 5 minutes or even less. The uncertainty associated  
129 with the GPS displacement measurement is sufficiently small, on the order of 5 - 10 mm and 10 - 20 mm  
130 in horizontal and in vertical respectively [58]. Thanks to the dense temporal sampling, GPS allows us to  
131 obtain time series for displacement varying over time, at the scale of days and years. GPS measurements  
132 have been used in detection of tectonic activities like earthquake [59, 15]), volcano [60], glacier flow [61],  
133 plate movement [62], etc. Moreover, levelling, the measurement of elevation difference between 2 points at  
134 the Earth's surface, can also be considered as a precise method for vertical displacement measurement. It  
135 has been used for displacement measurement for more than half a century [63, 64, 65, 15]). **A precision on**  
136 **the order of mm/yr has been reported for vertical displacement rate [66]. However, besides the punctuality**  
137 **of the measurement, the major disadvantages of levelling also include the high cost and the large amount**  
138 **of time needed for collecting the data over long distances or over a large network.**

## 139 **2.2 Uncertainty quantification**

140 The sources of uncertainty in optical/SAR imagery are very complex: they come from different pertur-  
141 bations that take place along the electromagnetic wave propagation (e.g. atmosphere) and at the back-  
142 scattering surface (e.g. properties change during two acquisitions), as well as the noise generated in the  
143 electronic processing. Moreover, imperfect displacement extraction technique (accuracy of the algorithm)  
144 and pre/post-processing treatment (coregistration, geometrical correction, etc) also induce uncertainties

145 in the displacement measurement. The sources of possible uncertainty in GPS measurements come from  
 146 the atmospheric effects, the measurement noise or distortion of the signal caused by electrical interference  
 147 or errors inherent in the GPS receiver, clock drift, etc. These diverse sources results in uncertainties with  
 148 very complex characteristics. In addition, the ground truth is not available in most cases of terrestrial  
 149 deformation. For all these reasons, the quantification of the uncertainty **and the accuracy** associated  
 150 with the displacement measurement still remains a delicate problem.

151 For feature-tracking measurements from optical/SAR images, two methods exist in the literature to  
 152 estimate the displacement uncertainty. The first method adopts parameters associated with the correlation  
 153 algorithm, for example, the correlation peak, the full width at half maximum, the curvature of the correla-  
 154 tion surface, to represent the displacement uncertainty [67]. This kind of parameters indicate the relative  
 155 reliability of the displacement measurement, they are thus not a measure of the uncertainty in strict sense.  
 156 The second method consists of estimating a statistical variance in known stable areas [29, 68]. With this  
 157 method, the spatial distribution of uncertainty is not available, since only one value is estimated for one  
 158 pair of image. With large data sets, however, it is possible to statistically estimate the uncertainty at each  
 159 point [19]. In case of earthquakes, pre-seismic image pairs are often used. This kind of uncertainty charac-  
 160 terises essentially the random variation of the displacement, it cannot represent systematic and spatially  
 161 correlated uncertainties. For DInSAR measurements, the main sources of uncertainty are considered from  
 162 phase unwrapping. In [69, 7], phase unwrapping errors are analysed through the misclosure of the interfer-  
 163 ograms networks, given that the redundancy exists between the interferograms used. In [70], the variance  
 164 of the phase is estimated from the coherence. This variance can only represent the random part of the  
 165 uncertainty due to the presence of random noise in the interferogram. In [71, 72, 16], **the spatially corre-**  
 166 **lated error is characterised in areas where neither deformation signal is expected nor visible**  
 167 **on the interferogram assuming stationary and isotropic noise. For this, the semi-variogram**  
 168 **and the semi-covariogram are computed as follows:**

$$\hat{\gamma}(h_c) = \frac{1}{2N} \sum_{i=1, \|r_i - s_i\| \simeq h_c}^N [d(r_i) - d(s_i)]^2 \quad (1)$$

$$\hat{C}(h_c) = \frac{1}{2N} \sum_{i=1, \|r_i - s_i\| \simeq h_c}^N d(r_i) \cdot d(s_i) \quad (2)$$

169 where  $\hat{\gamma}$ ,  $\hat{C}$  are the discrete sample semi-variogram value and the discrete sample semi-covariogram value  
 170 for distance  $h_c$ .  $N$  is the number of data points pairs at locations  $r_i$  and  $s_i$  such that  $\|r_i - s_i\| \simeq h_c$ .  $d$  is

171 **the displacement value measured in interferograms.**

172 With respect to the previous approaches, the advantage of this approach lies on the consideration of the  
173 spatially correlated error which constitutes an important part of the uncertainty that should be taken into  
174 account, since this part of uncertainty almost always exists in the interferogram due to the atmospheric  
175 and topographic effects.

176 GPS measurements are often repeated observations and they are assumed to be samples of stochastically  
177 independent normally distributed random variables. The variability of the samples, the standard deviation,  
178 is often used as uncertainty associated with the displacement measurement. More elaborated analyses are  
179 described in [73]. The vertical displacement measured by levelling are also supposed to be samples of  
180 stochastically independent normally distributed random variables. The variance of the displacement can  
181 be deduced from the combination of the variance of the reference point (point without displacement, the  
182 absolute displacement is determined with respect to this point) and that of the elevation differences [74].  
183 The standard deviation is used as the uncertainty associated with the displacement. A more elaborated  
184 method to estimate the complete covariance matrix for levelling measurements is proposed in [75].

### 185 **3 Fusion of displacement measurements**

186 Fusion constitutes a formal framework in which are expressed the means and techniques that allows for  
187 the combination of information from diverse sources. The general principle consists of associating various  
188 information on the same problem in order to improve the knowledge. The imperfection of individual infor-  
189 mation such as the uncertainty, the incompleteness, the ambiguity, etc, constitutes the primary motivation  
190 of the fusion. Depending on the phenomenon under consideration, different fusion strategies are necessary  
191 to reduce the imperfection of individual information, benefiting the redundancy and the complementarity  
192 of one source of information with respect to the others. In displacement measurement, **the main imper-**  
193 **fection to be improved by the fusion includes: 1) incompleteness due to limitations of data**  
194 **acquisition and/or data processing 2) uncertainty due to noise from data acquisition until**  
195 **the final displacement results.**

#### 196 **3.1 Fusion between displacement measurements**

197 Remote sensing measurements mainly provide displacement information at the Earth's surface. Currently,  
198 the fusion of these surface displacement measurements can be summarised into 2 groups according to the



199 objectives. The first group corresponds to the processing "from raw measurements to fused measurements".  
200 In case of redundancy, the surface displacement measurements are combined to retrieve a surface displace-  
201 ment with **reduced uncertainty**. In case of complementarity, they are combined to retrieve a surface  
202 displacement with larger spatial extension or of higher level (for example, the 3D displacement field). The  
203 second group corresponds to the processing "from measurements to model parameters". Surface displace-  
204 ment measurements are combined to estimate the geometrical parameters of a physical deformation model  
205 in case of redundancy and complementarity.

### 206 **3.1.1 From raw measurements to fused measurements**

207 In case of redundancy, the common and intuitive approach consists in averaging all available measurements  
208 in order to obtain an estimation as **precise** as possible [76, 77, 78, 79]. However, this approach is subject to  
209 the difficulty in determining the contribution of each measurement and to the limitation of computational  
210 capacity while dealing with large volume data sets. Figure 1 gives an example of interferograms stacking  
211 for displacement measurement on the Hayward fault in the San Francisco Bay Area from 1992 to 2000  
212 [78]. For this, 37 interferograms with spatial baseline less than 200 m and temporal baseline longer than  
213 1 year are selected. This set of 37 interferograms are stacked by dividing the cumulative range change  
214 by the cumulative time span, which preferentially weighs the range change rate of those interferograms  
215 with longer temporal baseline. Afterwards, interferograms where more than 5% of the coherent phase  
216 exceeds 3 standard deviations from the stacked results are removed. Finally, a subset of 13 independent  
217 interferograms are selected for the stacking and the standard deviation is used as uncertainty measure  
218 associated with the stacked range change rate. Thanks to this stack, the atmospheric artefacts in individual  
219 interferograms are reduced significantly.

220 [Figure 1 about here.]

221 In case of spatial complementarity, a mosaic is usually performed in order to obtain a displacement  
222 measurement over large area. This is very useful to generate displacement maps at global scale [18, 68, 19].  
223 Figure 2 shows the annual velocity field obtained from feature-tracking of Landsat images to measure  
224 glaciers flow over the Karakoram. Panel (a) shows the result for a single pair (the pair with the highest  
225 spatial coverage among all available pairs): many gaps appear in saturated areas or areas covered by clouds  
226 (corresponding to measurements with a signal-to-noise ratio below 4), limiting the percentage of estimates  
227 over glaciers to 70%. Velocities in stable areas, expected to be null, are in the range of 10 m/year due  
228 to orthorectification errors. On the other hand, panel (b) shows the velocity obtained from fusion of 29

229 annual pairs available for the period 1999-2001 and taking the median value at each location. The spatial  
230 coverage is increased to 94% thanks to the complementarity from one pair to another. Velocities in stable  
231 areas are reduced to 2.0 m/year thanks to the redundancy, and because orthorectification errors are not  
232 coherent [19].

233 [Figure 2 about here.]

234 In case of temporal complementarity, measurements time series can be used to follow the temporal  
235 evolution of the event with appropriate method, such as PS and SBAS approaches [46, 42, 43, 50, 80,  
236 44]. These approaches have been modified and improved since their first applications. Variants of SBAS  
237 approach such as PO-SBAS [26] and PSBAS [81] have been developed in order to **make use of pixel**  
238 **offset measurements** and to deal with large data sets. Variant of PS approach such as SqueeSAR [82]  
239 has been developed in order to improve the performance of the PS technique proposed previously. **Along**  
240 **with PS interferometry, SAR tomography based approaches allow for an improvement in the**  
241 **detection of permanent scatterers in urban areas [83, 84, 85, 86, 87].** Figure 3 gives an example  
242 of surface displacement time series obtained with SBAS [50] and PO-SBAS [26] for Fernandina and Sierra  
243 Negra. The temporal evolution of the surface displacement for these two calderas is characterised thanks  
244 to the temporal complementarity. The eruptions for both calderas have been well identified by the abrupt  
245 change of the displacement magnitude from the time series. Regarding the quantification of the uncertainty  
246 associated with the displacement time series, it constitutes a truly complex task. For PS approaches,  
247 because of the iterative process (including the temporal phase unwrapping and the spatial integration)  
248 adopted by most PS approaches, the propagation of the input uncertainty and the quantification of the  
249 final uncertainty seem extremely difficult. The phase standard deviation is usually used as an indicator  
250 of the quality of the displacement velocity obtained. However, this parameter is strongly related to the  
251 nonlinear motion according to [51], thus not an appropriate indicator of the displacement uncertainty. For  
252 SBAS approaches, the main difficulty also lies on the quantification of the phase unwrapping error. In  
253 [7], the RMS misclosure is calculated to assess the phase unwrapping quality, but no clear uncertainty  
254 associated with the final displacement time series is provided.

255 [Figure 3 about here.]

256 In case of geometrical complementarity (from diverse acquisition geometries: different incident an-  
257 gles, different orbital directions (descending and ascending), different displacement directions (range and  
258 azimuth)), the 3D displacement at the Earth's surface is usually retrieved by a linear inversion in least

259 square sense in order to interpret the surface displacement field in an homogeneous and intuitive way  
 260 [40, 88, 89, 12, 90]. For example, in the displacement measurement of the Kashmir earthquake in 2005,  
 261 surface displacement measurements from correlation of SAR amplitude images and DInSAR, including  
 262 ascending and descending passes and different incident angles, are available. Both redundancy and spatial  
 263 and geometrical complementarity thus exist. In particular, correlation and DInSAR measurements issued  
 264 from the same pair of SAR images are available and these two types of measurements provide essentially  
 265 complementary displacement information. On one hand, correlation measurements are reliable in areas  
 266 where the displacement is large (usually close to the deformation source), while DInSAR measurements are  
 267 mainly available in areas where the displacement is small (usually far from the deformation source). On  
 268 the other hand, besides the displacement measurement in LOS direction, correlation measurements provide  
 269 displacement measurement in azimuth direction, which is complementary to the DInSAR measurements.  
 270 Regarding the redundancy of displacement measurement in LOS direction provided by both measurements  
 271 in areas of moderate displacement, correlation measurements can be used to check the existence of phase  
 272 unwrapping error and to retrieve the absolute displacement value in DInSAR measurements since relative  
 273 displacement value is obtained from the phase. Further, since the **precision** of DInSAR measurement is  
 274 much higher than that of correlation measurements, the contribution of DInSAR measurement is naturally  
 275 more significant than that of correlation measurements.

276 For the Kashmir earthquake (2005) example, 23 surface displacement data sets are available in total.  
 277 Two fusion strategies, namely joint inversion and pre-fusion are investigated together with two uncertainty  
 278 propagation approaches: one based on the probability theory and the other based on the possibility theory  
 279 [91, 92]. In joint inversion, all available measurements are used simultaneously in the inversion. Pre-fusion  
 280 consists of a fusion step before inversion. This fusion step can be performed for example using the mean  
 281 value, the median value of a set of measurements or by selecting the best one according to certain criteria,  
 282 for example, the reliability of measurements or the signal-to-noise ratio. Afterwards, the refined data  
 283 sets are input in the inversion. In the probabilistic approach, displacement errors are assumed random  
 284 and independent (optimist hypothesis that cannot be justified in most cases). They are represented and  
 285 propagated by Gaussian distributions. With this hypothesis, the more measurements are fused, the smaller  
 286 the output uncertainty is. The solution (displacement value  $U$  and displacement uncertainty  $\Sigma_U$ ) given by  
 287 the least squares inversion is shown in equation 3.

$$\begin{aligned}
U &= (P^t \Sigma_R^{-1} P)^{-1} P^t \Sigma_R^{-1} R \\
\Sigma_U &= (P^t \Sigma_R^{-1} P)^{-1}
\end{aligned} \tag{3}$$

288 where  $U$  denotes the 3D displacement vector with 3 components.  $P$  is the projection vector from the 3D dis-  
289 placement to displacements measured by correlation and DInSAR. **It is determined by the acquisition**  
290 **geometry:**  $P_{LOS} = (-\cos\varphi\sin\theta, \sin\varphi\sin\theta, -\cos\theta)$ ,  $P_{azimuth} = (\sin\varphi, \cos\varphi, 0)$  **with  $\varphi$  azimuth of the**  
291 **satellite trajectory and  $\theta$  the incident angle.**  $R$  corresponds to the vector of displacement measured  
292 by correlation and/or DInSAR.  $\Sigma_R$  and  $\Sigma_U$  represent the error covariances of  $R$  and  $U$  respectively.

293 In the possibilistic approach, no hypothesis is made on the displacement errors and they are represented  
294 and propagated by possibility distributions. The output uncertainty takes into account the worst bound  
295 among all the fused measurements (pessimist approach). As a result, even with more measurements, the  
296 output uncertainty is not decreased. The solution (possibility distribution  $\hat{U}$  including the displacement  
297 value and the displacement uncertainty at the same time) given by the least squares inversion is shown in  
298 given by:

$$\hat{U} = (P^t \Sigma_R^{-1} P)^{-1} P^t \Sigma_R^{-1} \otimes \hat{R} \tag{4}$$

299  $\hat{U}$  denotes the possibility distribution of the 3D displacement vector.  $\hat{R}$  corresponds to the possibility  
300 distribution of the vector of displacement measured by correlation and/or DInSAR.  $^t$  denotes the transpose  
301 and  $\otimes$  refers to the matrix operator of fuzzy multiplication where the sum and the conventional scalar  
302 product are replaced by the corresponding fuzzy operations (**min and max operators in most cases**)  
303 [**93, 91**].

304 An example of the Up component of the 3D displacement and the associated uncertainties is given in  
305 Figure 4. With the probabilistic approach, compared to pre-fusion, the uncertainty is reduced in areas  
306 where more measurements are available in joint inversion, while with possibilistic approach, the uncertainty  
307 is increased in the same areas, because of a different approach of uncertainty propagation. According to  
308 further demonstrations and analyses in [94], authors concluded that with both fusion strategies, the un-  
309 certainties associated with the 3D displacement field are reduced by fusion. On one hand, when random  
310 uncertainties are present in the measurements, the strategy of joint inversion can most reduce the un-  
311 certainty and the probabilistic approach is appropriate to represent and propagate the uncertainty. On

312 the other hand, when systematic uncertainties are present in the measurements, the strategy of pre-fusion  
313 gives better results and the possibilistic approach seems appropriate to represent and propagate the un-  
314 certainty. In addition, the strategy of pre-fusion is computationally more efficient than the strategy of  
315 joint inversion. In most real cases, random and systematic uncertainties are often present simultaneously  
316 in the displacement measurements. The uncertainty associated with the 3D displacement obtained with  
317 the probabilistic approach provides a lower bound, whereas that obtained with the possibilistic approach  
318 provides an upper bound. The real value should be situated in between. When random uncertainty is  
319 the main source of uncertainty in correlation/DInSAR measurements, the 3D displacement uncertainty is  
320 closer to the probabilistic result (equation 3). On the contrary, when systematic uncertainty dominates  
321 the uncertainty in correlation/DInSAR measurements, the 3D displacement uncertainty is closer to the  
322 possibilistic result (equation 4).

323 [Figure 4 about here.]

### 324 **3.1.2 From measurements to model parameters**

325 One of the most important objectives of geophysics is to estimate, from surface displacement measurements,  
326 the geometry and the force of the deformation source in depth, e.g. a fault rupture and the associated slip  
327 in case of an earthquake or of a magmatic intrusion and an opening in volcanic context. Fusion of SAR,  
328 optical displacement measurements, GPS and other sources of information to constrain a physical model,  
329 such as the Okada model [95] and the Mogi model [96], by linear/nonlinear inversion thus constitutes a  
330 major topic in displacement measurement. In this case, spatial and geometrical complementarity is very  
331 important to infer model parameters correctly, because trade-off between model parameters exists and  
332 some parameters are only sensitive to surface displacements in a certain area or in a certain direction.  
333 Partial displacement information thus results in erroneous model parameters estimation. Because of the  
334 complexity of the model inversion, the fusion processing, especially the uncertainty propagation is much  
335 more complicated than in the previous case. The common fusion strategy is the joint inversion using  
336 all of the available surface displacement measurements. For sake of computational efficiency, surface  
337 displacement measurements are often subsampled in quadree so that the measurement point distribution  
338 varies as a function of the displacement gradient [97, 98, 99, 78].

### 339 3.1.2.a Fusion of same type displacement measurements

340 In case of displacement measurements of the same type, SAR or optical measurements alone, the fusion  
341 strategy of pre-fusion, for example selecting highest quality measurements among all of the available  
342 measurements, can provide better results, given that good agreement cannot be obtained between all  
343 the measurements and the selected high quality measurements include almost all the useful information.  
344 In the case of the Kashmir earthquake (2005), a fault rupture model is inferred from the selection of high  
345 quality SAR measurements and this model cannot be obtained with the strategy of joint inversion. Artefact  
346 **(erroneous slip with large magnitude situated at 40-50 km and 80-90 km along strike distance)**  
347 **exists in depth (deeper than 20 km along dip distance)** using all of the available measurements as  
348 shown in Figure 5. Because of the noise present in the measurements, it is easier to adjust a model to a  
349 small number of measurements of high quality, but covering sufficient displacement information.

350 [Figure 5 about here.]

351 Regarding the uncertainty propagation, the approach commonly used consists of performing a large  
352 number (hundreds to thousands) of noise realisations in the surface displacement measurements and running  
353 repeatedly the model inversion in order to obtain the distribution and the correlation of model parame-  
354 ters [100]. An example is shown in Figure 6. The uncertainty associated with each model parameter is  
355 characterised by the histogram and the correlation between parameters is represented by the scatterplot.  
356 In this way, the uncertainties of the input measurements are propagated to the model parameters through  
357 the model functionality. However, note that uncertainty already exists in the input measurements before  
358 the noise realisation. Therefore, double levels of uncertainty exist in the measurements after the noise re-  
359 alisation. Uncertainties associated with the model parameters accordingly obtained thus do not represent  
360 the real uncertainties. They rather reveal the sensitivity of the model to noise. In practice, this approach  
361 is not always applied because of the computational cost. Instead, the quality of the retrieved model is  
362 evaluated directly by the residual compared to the measurements used in the model retrieval in some works  
363 [89, 100, 12, 34].

364 [Figure 6 about here.]

### 365 3.1.2.b Fusion of different types displacement measurements

366 In case of heterogeneous measurements with diverse characteristics and **uncertainties**, the fusion pro-  
367 cessing can be very complex. **There have been numerous investigations that combine GPS and**  
368 **InSAR data to optimally measure coseismic deformation [98, 97, 99, 72, 101, 102, 103, 104],**  
369 **interseismic deformation [105, 38], post-seismic deformation [106, 107, 108] and volcanic de-**  
370 **formation [109].** The major difficulty lies on the determination of the relative contribution of each  
371 measurement. In general, the weight of each measurement depends on the associated uncertainty. For  
372 one data set, we can determine the contribution of each measurement according to their associated uncer-  
373 tainty. However, it is very difficult to provide a link between the measurements of one data set and the  
374 measurements of another data set of different type. In other words, we usually have information about  
375 the error covariance between measurements inside one data set (namely the first level weighting hereafter),  
376 but we do not have information about the error covariance between different data sets (namely the second  
377 level weighting hereafter), the full covariance matrix of error is thus unknown. The relative contributions  
378 of different data sets are often decided in an arbitrary way. **For example**, in [98, 99, 72], only the first  
379 level weighting was taken into consideration, on the basis of the uncertainty associated with displacement  
380 at each pixel. In [97, 78, 38], the two levels of weighting are performed. The relative contribution of  
381 each data set was determined by minimising the residual of all the types of measurements. For this, first  
382 sets of relative weight obtained from separate inversions with different types of data are necessary. An  
383 example for the latter (the two levels of weighting) is given in Figure 7. The slip models for the slow slip  
384 events in 2006 in the Guerrero seismic gap inferred from GPS and DInSAR measurements separately and  
385 jointly are shown. According to [38], the model obtained from one data type alone cannot explain well the  
386 displacement behaviour observed from the other data type and the joint minimisation of the residual of  
387 both GPS and DInSAR measurements allows for better constrain of the slip model, since the displacement  
388 behaviours observed from both data types are taken into account.

389 [Figure 7 about here.]

390 However, in this way, the uncertainty associated with each data set is not really taken into account. For  
391 a data set whose uncertainty is larger, it is normal that the corresponding residual is larger. Moreover, if  
392 the phenomenon under consideration is more sensitive to the horizontal displacement than to the vertical  
393 displacement, naturally the model to be adjusted takes more contributions of the measurements in the East  
394 and North directions of GPS data sets into account. This can cause a larger residual for the measurement  
395 in the LOS direction of DInSAR data sets. Therefore, the approach based on the joint minimisation of

396 residual is not appropriate in some cases. A potential way to avoid the disadvantages mentioned previously  
397 consists in constructing the full covariance matrix of error from a large number of noise realisations, inspired  
398 from the principle of the Ensemble Kalman Filter [110]. Regarding the uncertainty propagation in this case,  
399 the approaches of the noise realisation and the residual comparison mentioned previously (section 3.1.2.a)  
400 are used [98, 97, 72].

## 401 **3.2 Integration of geophysical model**

402 Besides the displacement measurements, the deformation model also provides useful displacement infor-  
403 mation, especially when displacement measurements are not available over some areas or during some  
404 periods. Fusion between the measurements and the predictions of the model in different manners has also  
405 been reported in previous works [78, 7, 111, 34].

### 406 **3.2.1 Model prediction for displacement measurement extraction**

407 The model prediction can be used to aid the displacement measurement extraction. The a priori infor-  
408 mation provided by the model can be considered as a guide for the displacement measurement extraction.  
409 For example, in SAR imagery, the deformation model can be used to facilitate the phase unwrapping,  
410 even though the displacement predicted by the model is not perfectly accurate. With the displacement  
411 predicted by the model removed from the interferogram, the number of fringes can be reduced, which  
412 makes the phase unwrapping easier, especially when the displacement gradient is large. In [78], a defor-  
413 mation model constrained by GPS data is used to remove the displacement from each interferogram. In  
414 [7], a deformation model is obtained from stacking the 5 best interferograms, then the phase unwrapping  
415 is guided by this deformation model. **In [112], the smoothed range offset is used as a proxy for**  
416 **interferogram phase.** In the previous works, it is much easier to unwrap the residual (original inter-  
417 ferogram - deformation model) instead of unwrapping the original interferogram. In this way, the phase  
418 unwrapping error is reduced significantly. In [111, 34], authors estimated the displacement field with the  
419 help of a mechanical deformation model and used multi-scale local frequencies of the phase (phase gradient)  
420 for phase unwrapping. Thanks to this method, the DInSAR has been applied successfully for the first time  
421 in displacement measurement of the Kashmir earthquake (2005). An example of this approach is shown  
422 in Figure 8. The deformation model in LOS direction corresponds to the surface displacement predicted  
423 by an homogeneous elastic linear deformation model obtained from the coseismic slip distribution in [12].  
424 From this model, the optimal scale (number of multi-looking), at which the phase unwrapping can be



425 performed in keeping the best resolution and avoiding the aliasing problem at the same time, is estimated.  
426 Thereafter, on one hand, phase unwrapping is carried out using the multi-scale local frequencies of the  
427 phase with a global least squares method. On the other hand, the wrapped interferogram is filtered by the  
428 multi-scale local frequencies of the phase in order to highlight the fringe patterns. Finally, the residual,  
429 calculated by comparing the re-wrapped unwrapped phase to the filtered phase, is quantified to validate  
430 the results. Only the interferograms whose residual is inferior to  $2\pi$  are considered as correctly unwrapped.

431 [Figure 8 about here.]

### 432 **3.2.2 Joint use of model prediction and displacement measurement**

433 The measurements and the model prediction can be used jointly to obtain some displacement information  
434 with improved quality or some displacement information that cannot be obtained with the measurements  
435 or the model alone. In [34], authors proposed a 2-segment fault rupture model that fitted better the  
436 observations than other 1-segment models obtained in previous work. This 2-segment model is inferred  
437 based on the surface displacement measurements and a 1-segment model obtained in the previous work  
438 [12]. With either the measurements or the 1-segment model alone, it is impossible that this 2-segments  
439 model can be retrieved. In [15], the coseismic and post-seismic slip distributions on the Paganica fault  
440 and the Campotosto fault of the 2009 L'Aquila earthquake are obtained based on the Paganica fault  
441 rupture plane geometry estimated in [113] and the Campotosto fault geometry derived from geological  
442 mapping studies (Figure 9). Small translation and rotation are performed to the modelled fault plane  
443 geometry in order to make it consistent with the observed surface rupture. The coseismic and post-seismic  
444 slip distributions are estimated based on these fault geometries and using DInSAR, GPS and levelling  
445 measurements. Indeed, for a given event, the fault geometry and slip distribution models in the previously  
446 published works often provide useful information for similar works later. **Moreover, [114, 115] used**  
447 **jointly wrapped interferograms and geophysical deformation models to estimate the fault**  
448 **rupture parameters, avoiding the phase unwrapping which constitutes a major problem in**  
449 **interferometric processing.** In addition, the measurements and the physical model can be combined  
450 together in a dynamic context to follow the temporal evolution, even to predict the future behaviour of  
451 the phenomenon under observation, which corresponds to the data assimilation that is commonly used in  
452 atmosphere and ocean science and has gained more and more attention in geoscience. In [116], the DInSAR  
453 surface displacement measurements are combined with a geomechanical model to characterise the evolution  
454 of the underground gas storage and to reduce the uncertainty associated with the model parameters.

[Figure 9 about here.]

455

### 456 3.3 Discussion

457 In displacement measurement, data fusion is often realised by linear and/or nonlinear inversion. In general,  
458 a consistency check is necessary before data fusion. It constitutes an important step that allows for  
459 an identification of the possible conflict between different measurements, then of the possible aberration  
460 present in some measurements. The latter should be removed in the data fusion process in order not to  
461 degrade the quality of the fusion results. Moreover, an analysis of the redundancy and the complementarity  
462 between different measurements is of particular importance to provide useful information for the choice  
463 of the fusion strategy. Furthermore, the characterisation of the displacement uncertainty is also essential  
464 for the choice of the appropriate fusion strategy. However, the uncertainty quantification investigation  
465 seems insufficient currently. In many studies, the detailed description of the displacement uncertainty is  
466 not available.

467 In case of redundancy, if random uncertainty is present in the individual displacement measurement,  
468 all the measurements can be used jointly in linear inversion in order to maximise the reduction of the un-  
469 certainty associated with the fusion results, given enough computational capacity. For nonlinear inversion,  
470 the performance of this strategy depends on the data quality (noise level). This strategy can fail when it is  
471 difficult to adjust a model among a large number of noisy data. If systematic uncertainty is present in the  
472 individual displacement measurement, the pre-fusion can be a good choice for both linear and nonlinear in-  
473 versions. An appropriate fusion step before the inversion allows reducing most the systematic uncertainty.  
474 In case of complementarity, since each individual measurement brings non-replaceable information, all the  
475 measurements should be used. In both cases of redundancy and complementarity, data fusion can provide  
476 optimal results only if the specification of the displacement uncertainty is appropriate.

477 In practice, both redundancy and complementarity exist in most studies. Moreover, the uncertainty  
478 associated with each measurement is not always reliable, even unavailable in some cases, which makes  
479 the judgement of the agreement between different measurements difficult. Currently, the main topic on  
480 displacement measurement fusion consists of using as many measurements as possible, joint inversion is  
481 thus the most used fusion strategy with expectation that we can obtain new information using more  
482 measurements. With good data quality (random uncertainty of small amplitude), this strategy can give  
483 satisfactory results, while with moderate or poor data quality (random uncertainty of large magnitude  
484 of systematic uncertainty), this strategy can fail because, it is difficult, on one hand, to adjust a model

485 among many noisy data, on the other hand, to determine the appropriate relative contribution of each  
486 measurement, even though numerous studies have been focused on the search of the optimal weighting  
487 of heterogeneous measurements. In this case, pre-fusion can be considered as a good choice. In case of  
488 complex geophysical model inversion where the computational time is the main concern, a step of pre-  
489 fusion between redundant measurements before the inversion is also preferred in order not to burden the  
490 inversion system.

## 491 4 Conclusions and perspectives

492 The arrival of remote sensing has caused a true revolution in displacement measurement by significantly  
493 improving the spatial coverage and the measurement accuracy. Spectacular results have been obtained  
494 in numerous fields: the study of urban subsidence, of coseismic, inter-seismic and post-seismic motion, of  
495 glacier flow, of volcanic deformation, etc. With the continuous launching of Earth observation satellites  
496 and the increasing availability of the amount of remote sensing data, data fusion becomes necessary and  
497 plays a more and more important role in displacement measurements. However, using all of the available  
498 measurements cannot always provide satisfactory results, but always presents difficulties such as unknown  
499 weighting coefficients and high computational cost. Intelligent fusion strategies and methods, involving  
500 how to benefit from the large volume of data in an efficient way to reduce the displacement uncertainty  
501 and to improve our knowledge on the physical process of the phenomenon under observation, constitutes a  
502 living topic in many works. Meanwhile, more and more attention is paid to the displacement uncertainty  
503 characterisation and quantification. The consideration lies not only on independent random uncertainty  
504 but also on correlated or systematic uncertainty. The uncertainty management approach has also been  
505 extended from a probabilistic approach to a possibilistic approach. On the other hand, the techniques  
506 in displacement measurement by remote sensing are still being improved in order to integrate as much  
507 as possible the benefit of the high spatial resolution and the increasing frequency of data acquisition for  
508 terrestrial displacement measurements. Moreover, efforts have been made to combine different techniques,  
509 for instance, the combination of PS and SBAS methods, of correlation and DInSAR, seeking to make the  
510 best use of the information contained in the data by exploiting the complementarity of different techniques.

511 Besides the achievement in displacement measurements fusion, challenges are also present. Even though  
512 rapid development has been obtained in the recent years, the fusion of heterogeneous measurements, from  
513 SAR, optical images, GPS and other sources of information, still remains a delicate problem. No fusion  
514 method nor strategy is completely operational to deal with diverse characteristics and **uncertainty** levels

515 of the heterogeneous measurements in an inversion system. No efficient solution has been proposed to the  
516 determination of the contribution of each individual measurement, as well as their covariance. From the  
517 computational point of view, even with the availability of supercomputing facilities, we can still be quickly  
518 limited by the memory and storage capacity, as well as the computation time, given the high spatial reso-  
519 lution and the strong repetitiveness of acquisitions. For **accuracy** and uncertainty consideration, **on one**  
520 **hand, the quantification and the improvement of the accuracy are always very challenging,**  
521 **given that in most cases the ground truth is not available. On the other hand,** it is always  
522 difficult to characterise the uncertainty in displacement measurements, then to choose an appropriate  
523 uncertainty management approach. In satellite imagery, uncertainty comes from different perturbations  
524 generated along the wave propagation path, at the back-scattering surface, as well as from noise generated  
525 in the electronic processing. In addition, imperfect corrections (atmospheric and/or geometric corrections)  
526 performed in the displacement extraction chain also introduce systematic uncertainties. These diverse  
527 sources result in uncertainties of complex characteristics. Moreover, in case of model inversion, it is very  
528 difficult to propagate the uncertainty. The retrieved deformation models are often provided without un-  
529 certainty information. The evaluation of these models obtained with more or less different measurements  
530 is thus a challenging task. For example, in the case of the Kashmir earthquake (2005), [12, 32, 117, 34]  
531 obtained different fault rupture models by using different surface displacement measurements. Without  
532 ground truth, it is impossible to assess these models in an objective way.

533 Given the current status and the future development of displacement measurement fusion, **sophis-**  
534 **ticated statistic tools, such as the Kalman Filter, the Bayesian theory and so on, can be**  
535 **expected to further improve the results. Meanwhile,** it will be important to modify the processing  
536 algorithms and to adapt our way of working. Inspired from the ocean reanalysis, different measurements  
537 with different spatial coverage, different spatial resolution, different time spans, bringing different infor-  
538 mation, including correlation of SAR, optical images, DInSAR, GPS and other in situ measurements, can  
539 be homogenised through a realistic physical model in order to produce spatially and temporally regular  
540 displacement maps (namely displacement reanalysis) to record the properties of the displacement over  
541 time. Later, instead of keeping and processing different types of measurements of large volume, these dis-  
542 placement reanalyses present numerous advantages. Currently, the displacement measurement by remote  
543 sensing is still mainly applied to past events that have taken place before the data processing. With the  
544 launching by ESA of the Sentinel series, remote sensing data can be acquired nearly everywhere on the  
545 Earth at least every 6 days. By adding the data issued from other satellites, TerraSAR-X and TanDEM-X,  
546 Landsat 8, the four satellites **COSMO-SkyMed**, ALOS-2, etc, real time monitoring by time series will

547 become possible. The combination in real time of displacement measurements from remote sensing im-  
548 agery and physical models is possible. It will thus be possible to predict the evolution of an event such as  
549 a magma reload of a reservoir located beneath an active volcano or a rupture of a serac. Data assimilation  
550 extensively investigated in atmosphere and ocean science will open new perspective for the observation and  
551 the prevention of natural hazards.

## 552 References

- 553 [1] J. Anhorn and B. Khazai, “Open space suitability analysis for emergency shelter after an earthquake,”  
554 *Natural Hazards and Earth System Science*, vol. 15, pp. 789–803, 2015.
- 555 [2] W. T. Yang, M. Wang, N. Kerle, C. J. V. Westen, L. Y. Liu, and P. J. Shi, “Analysis of changes  
556 in post-seismic landslide distribution and its effect on building reconstruction,” *Natural Hazards and*  
557 *Earth System Science*, vol. 15, pp. 817–825, 2015.
- 558 [3] B. Fruneau, J. Achache, and C. Delacourt, “Observation and modelling of the Saint-Etienne-de-Tinée  
559 landslide using SAR interferometry,” *Tectonophysics*, vol. 265, pp. 181–190, 1996.
- 560 [4] T. Wang, D. Perissin, F. Rocca, and M. Liao, “Three Gorges Dam stability monitoring with time-  
561 series InSAR image analysis,” *Science China Earth Sciences*, vol. 54, no. 5, pp. 720–732, 2011.
- 562 [5] G. Vasile, A. Anghel, D. Boldo, R. Boudon, G. D’Urso, and R. Muja, “Potential of multi-pass  
563 high-resolution SAR interferometry for dam monitoring,” *MTA Review*, vol. 22, no. 4, pp. 235–246,  
564 2012.
- 565 [6] J. Sousa and L. Bastos, “Multi-temporal sar interferometry reveals acceleration of bridge sinking  
566 before collapse,” *Natural Hazards and Earth System Science*, vol. 13, pp. 659–667, 2013.
- 567 [7] P. Lopez-Quiroz, M. P. Doin, F. Tupin, P. Briole, and J. M. Nicolas, “Time series analysis of Mexico  
568 City subsidence constrained by radar interferometry,” *Journal of Applied Geophysics*, vol. 69, no. 1,  
569 pp. 1–15, 2009.
- 570 [8] Q. Luo, D. Perissin, H. Lin, Y. Zhang, and W. Wang, “Subsidence Monitoring of Tianjin Suburbs by  
571 TerraSAR-X Persistent Scatterers Interferometry,” *IEEE Transactions on Geoscience and Remote*  
572 *Sensing*, vol. 7, no. 5, pp. 1642–1650, 2014.

- 573 [9] K. Goel and N. Adam, “A Distributed Scatterer Interferometry Approach for Precision Monitoring of  
574 Known Surface Deformation Phenomena,” *IEEE Transactions on Geoscience and Remote Sensing*,  
575 vol. 52, no. 9, pp. 5454–5468, 2014.
- 576 [10] R. Iglesias, A. Aguasca, X. F. J. Mallorqui, D. Monells, C. C. Lopez-Martinez, and L. Pipia, “Ground-  
577 Based Polarimetric SAR Interferometry for the Monitoring of Terrain Displacement Phenomena–Part  
578 I: Theoretical Description,” *IEEE Journal of Selected Topics in Applied Earth Observations and*  
579 *Remote Sensing*, vol. 8, no. 3, pp. 980 – 993, 2015.
- 580 [11] R. Iglesias, A. Aguasca, X. F. J. Mallorqui, D. Monells, C. C. Lopez-Martinez, and L. Pipia, “Ground-  
581 Based Polarimetric SAR Interferometry for the Monitoring of Terrain Displacement Phenomena–Part  
582 II: Applications,” *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sens-*  
583 *ing*, vol. 8, no. 3, pp. 994 – 1007, 2015.
- 584 [12] E. Pathier, E. J. Fielding, T. J. Wright, R. Walker, B. E. Parsons, and S. Hensley, “Displacement  
585 field and slip distribution of the 2005 Kashmir earthquake from SAR imagery,” *Geophysical Research*  
586 *Letters*, vol. 33, no. L20310, pp. 1–5, 2006.
- 587 [13] N. D’Agostino, D. Cheloni, G. Fornaro, R. Giuliani, and D. Reale, “Space-time distribution of after-  
588 slip following the 2009 L’Aquila earthquake,” *Journal of Geophysical Research*, vol. 117, no. B02402,  
589 pp. 1–23, 2012.
- 590 [14] R. Jolivet, C. Lasserre, M. Doin, G. Peltzer, J. Avouac, R. Dailu, and J. Sun, “Spatio-temporal  
591 evolution of aseismic slip along the haiyuan fault, china : Implications for fault frictional properties,”  
592 *Earth and Planetary Science Letters*, vol. 377-378, pp. 22–33, 2013.
- 593 [15] D. Cheloni, R. Giuliani, E.D’Anostasio, S. Atzori, R. Walters, L. Bonci, N. D’Agostino, M. Mattone,  
594 S. Calcaterra, P. Gambino, F. Deninno, R. Maseroli, and G. Stefanelli, “Coseismic and post-seismic  
595 slip of the 2009 L’Aquila (central Italy) Mw 6.3 earthquake and implications for seismic potential  
596 along the Campotosto fault from joint inversion of high-precision levelling, Insar and GPS data,”  
597 *Tectonophysics*, vol. 622, pp. 168–185, 2014.
- 598 [16] D. Bekaert, A. Hooper, and T. Wright, “Reassessing the 2006 Guerrero slow-slip event, Mexico:  
599 Implications for large earthquakes in the Guerrero Gap,” *Journal of Geophysical Research*, vol. 120,  
600 no. 2, pp. 1357–1375, 2015.

- 601 [17] E. Berthier, H. Vadon, D. Baratous, Y. Arnaud, C. Vincent, K. L. Feigl, F. Rémy, and B. Legrésy,  
602 “Surface motion of mountain glaciers derived from satellite optical imagery,” *Remote Sensing of*  
603 *Environment*, vol. 95, pp. 14–28, 2006.
- 604 [18] E. Rignot, J. Mouginot, and B. Scheuchl, “Ice flow of the Antarctic ice sheet,” *Science*, vol. 333,  
605 pp. 1427–1430, 2011.
- 606 [19] A. Dehecq, N. Gourmelen, and E. Trouvé, “Deriving large-scale glacier velocities from a complete  
607 satellite archive : Application to the Pamir-Karakoram-Himalaya,” *Remote Sensing of Environment*,  
608 vol. 162, pp. 55–66, 2015.
- 609 [20] F. Sigmundsson, S. Hreinsdottir, A. Hooper, T. Arnadottir, R. Pedersen, M. J. Roberts, N. Os-  
610 karsson, A. Auriac, J. Decriem, P. Einarsson, H. Geirsson, M. Hensch, B. Ofeigsson, E. Sturkell,  
611 H. Sveinbjornsson, and K. L. Feigl, “Intrusion triggering of the 2010 Eyjafjallajökull explosive erup-  
612 tion,” *Nature*, vol. 468, pp. 426–430, 2010.
- 613 [21] A. Hooper, F. Prata, and F. Sigmundsson, “Remote sensing of Volcanic Hazards and Their Precur-  
614 sors,” *Proceedings of the IEEE*, vol. 100, pp. 2908–2930, 2012.
- 615 [22] A. Auriac, K. Spaans, F. Sigmundsson, A. Hooper, P. Schmidt, and B. Lund, “Iceland rising: Solid  
616 Earth response to ice retreat inferred from satellite radar interferometry and visocelastic modeling,”  
617 *Journal of Geophysical Research*, vol. 118, no. 4, pp. 1331–1344, 2013.
- 618 [23] V. Pinel, M. Poland, and A. Hooper, “Volcanology: Lessons learned from Synthetic Aperture Radar  
619 imagery,” *Journal of Volcanology and Geothermal Research*, vol. 289, pp. 81–113, 2014.
- 620 [24] R. Michel, J. Avouac, and J. Taboury, “Measuring ground displacements from sar amplitude images:  
621 application to the landers earthquake,” *Geophysical Research Letters*, vol. 26, no. 7, pp. 875–878,  
622 1999.
- 623 [25] M. Tobita, M. Murakami, H. Nakagawa, and H. Yurai, “3-D surface deformation of the 2000 Usu  
624 eruption measured by matching of SAR images,” *Geophysical Research Letters*, vol. 28, no. 22,  
625 pp. 4291–4294, 2001.
- 626 [26] F. Casu, A. Manconi, A. Pepe, and R. Lanari, “Deformation Time-Series Generation in Areas Char-  
627 acterized by Large Displacement Dynamics: The SAR Amplitude Pixel-Offset SBAS Technique,”  
628 *IEEE Transactions on Geoscience and Remote Sensing*, vol. 49, no. 99, pp. 1–12, 2011.

- 629 [27] S. Leprince, S. Barbot, F. Ayoub, and J. Avouac, “Automatic and Precise Orthorectification, Coreg-  
630 istration, and Subpixel Correlation of Satellite Images, Application to Ground Deformation Mea-  
631 surements,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. 45, no. 6, pp. 1529–1558,  
632 2007.
- 633 [28] T. Scambos, M. Dutkiewicz, J. Wilson, and R. Bindshadler, “Application of image cross-correlation  
634 to the measurement of glacier velocity using satellite image data,” *Remote Sensing of Environment*,  
635 vol. 42, pp. 177–186, 1992.
- 636 [29] E. Berthier, H. Vadon, D. Baratoux, Y. Arnaud, C. Vincent, K. Feigl, F. Remi, and B. Legresy,  
637 “Surface motion of mountain glaciers derived from satellite optical imagery,” *Remote Sensing of*  
638 *Environment*, vol. 95, pp. 14–28, 2005.
- 639 [30] A. Luckman, D. Quincey, and S. Bevan, “The potential of satellite radar interferometry and feature  
640 tracking for monitoring flow rates of himalayan glaciers,” *Remote Sensing of Environment*, vol. 111,  
641 pp. 172–181, 2007.
- 642 [31] F. Vernier, R. Fallourd, J. M. Friedt, Y. Yan, E. Trouvé, J. Nicolas, and L. Moreau, “Fast Correlation  
643 Technique for Glacier Flow Monitoring by Digital Camera and Space-borne SAR Images,” *EURASIP*  
644 *Journal on Image and Video Processing*, 2011.
- 645 [32] J. Avouac, F. Ayoub, S. Leprince, O. Konca, and D. V. Helmberger, “The 2005,  $M_w$ 7.6 Kashmir  
646 earthquake: Sub-pixel correlation of ASTER images and seismic waveforms analysis,” *Earth and*  
647 *Planetary Science Letters*, vol. 249, no. 3-4, pp. 514–528, 2006.
- 648 [33] Z. Li, J. Elliott, W. Feng, J. Jackson, B. Parsons, and R. Walters, “The 2010 Mw 6.8 Yushu (Qing-  
649 hai, China) earthquake: Constraints provided by InSAR and body wave seismology,” *Journal of*  
650 *Geophysical Research*, vol. 116, no. B10302, pp. 1–16, 2011.
- 651 [34] Y. Yan, V. Pinel, E. Trouvé, E. Pathier, J. Perrin, P. Bascou, and F. Jouanne, “Coseismic displace-  
652 ment field and slip distribution of the 2005 kashmir earthquake from SAR amplitude image correlation  
653 and differential interferometry,” *Geophysical Journal International*, vol. 193, no. 1, pp. 29–46, 2013.
- 654 [35] X. Hu, T. Wang, and M. Liao, “Measuring coseismic displacements with point-like targets offset  
655 tracking,” *IEEE Geoscience and Remote Sensing Letters*, vol. 11, no. 1, pp. 283–287, 2014.
- 656 [36] G. Liu, H. Jia, R. Zhang, H. Zhang, H. Jia, B. Yu, and M. Sang, “Exploration of Subsidence  
657 Estimation by Persistent Scatterer InSAR on Time Series of High Resolution TerraSAR-X Images,”



- 658 *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 4, no. 1,  
659 pp. 159 – 170, 2011.
- 660 [37] R. Zhang, G. Liu, T. Li, L. Huang, B. Yu, Q. Chen, and Z. Li, “An Integrated Model for Extract-  
661 ing Surface Deformation Components by PSI Time Series,” *IEEE Geoscience and Remote Sensing*  
662 *Letters*, vol. 11, no. 2, pp. 544 – 548, 2014.
- 663 [38] O. Cavalié, E. Pathier, M. Radiguet, M. Vergnolle, N. Cotte, A. Walpersdorf, V. Kostoglodov, and  
664 F. Cotton, “Slow slip event in the mexican subduction zone: Evidence of shallower slip in the guerrero  
665 seismic gap for the 2006 event revealed by the joint inversion of InSAR and GPS data,” *Earth and*  
666 *Planetary Science Letters*, vol. 367, pp. 52–60, 2013.
- 667 [39] R. Goldstein, H. Englehardt, B. Kamb, and R. Frolich, “Satellite radar interferometry for monitoring  
668 ice sheet motion : application to an Antarctic Ice Stream,” *Science*, vol. 262, no. 1, pp. 525–530,  
669 1993.
- 670 [40] J. Mohr, N. Reeh, and S. Madsen, “Three-dimensional glacial flow and surface elevation measured  
671 with radar interferometry,” *Nature*, vol. 391, pp. 273–276, 1998.
- 672 [41] E. Trouvé, G. Vasile, M. Gay, L. Bombrun, P. Grussenmeyer, T. Landes, J. Nicolas, P. Bolon,  
673 I. Petillot, and A. Julea, “Combining airborne photographs and spaceborne sar data to monitor  
674 temperate glaciers: Potentials and limits,” *IEEE Transactions on Geoscience and Remote Sensing*,  
675 *IEEE Transactions*, vol. 45, pp. 905–924, 2007.
- 676 [42] A. Ferretti, C. Prati, and F. Rocca, “Permanent scatterer in SAR interferometry,” *IEEE Transactions*  
677 *on Geoscience and Remote Sensing*, vol. 39, no. 1, pp. 8–20, 2001.
- 678 [43] C. Werner, U. Wegmuller, T. Strozzi, and A. Wiesmann, “Interferometric point target analysis for  
679 deformation mapping,” in *Geoscience and Remote Sensing Symposium*, vol. 7, pp. 4362–4364, 2003.
- 680 [44] B. M. Kampes, *Radar interferometry : persistent scatterer technique*. Springer, 2006.
- 681 [45] A. Hooper, P. Segall, and H. Zebker, “Persistent scatterer interferometric synthetic aperture radar for  
682 crustal deformation analysis with application to Volcan Alcedo, Galapagos,” *Journal of Geophysical*  
683 *Research*, vol. 112, no. B07407, 2007.
- 684 [46] P. Rosen, I. J. S. Hensley, F. Li, S. Madsen, E. Rodriguez, and R. Goldstein, “Synthetic aperture  
685 radar interferometry,” *Proceedings of the IEEE*, vol. 88, no. 3, pp. 333–382, 2000.

- 686 [47] P. Berardino, G. Fornaro, R. Lanari, and E. Santosti, “A new algorithm for surface deformation  
687 monitoring based on small baseline differential sar interferograms,” *IEEE Transactions on Geoscience  
688 and Remote Sensing*, vol. 40, no. 11, pp. 2375–2383, 2002.
- 689 [48] D. A. Schmidt and R. Bürgmann, “Time-dependent land uplift and subsidence in the santa clara val-  
690 ley, california, from a large interferometric synthetic aperture radar data set,” *Journal of Geophysical  
691 Research*, vol. 108, no. B9, pp. ETG4.1–ETG4.13, 2003.
- 692 [49] S. Usai, “A least squares database approach for sar interferometric data,” *IEEE Transactions on  
693 Geoscience and Remote Sensing*, vol. 41, no. 4, pp. 753–760, 2003.
- 694 [50] R. Lanari, O. Mora, M. Manunta, J. Mallorqui, P. Berardino, and E. Sansosti, “A Small-Baseline  
695 Approach for Investigating Deformations on Full-Resolution Differential SAR Interferograms,” *IEEE  
696 Transaction on Geoscience and Remote Sensing*, vol. 42, no. 7, pp. 1377–1386, 2004.
- 697 [51] Y. Yan, M. P. Doin, P. Lopez-Quiroz, F. Tupin, B. Fruneau, V. Pinel, and E. Trouvé, “Mexico  
698 city subsidence measured by Insar time series: Joint analysis using PS and SBAS approaches,”  
699 *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 5, no. 4,  
700 pp. 1312–1326, 2012.
- 701 [52] G. Liu, H. Jia, Y. Nie, T. Li, R. Zhang, and B. Yu, “Detecting subsidence in coastal areas by ultrashort  
702 baseline TCPInSAR on time series of high resolution TerraSAR-X images,” *IEEE Transactions on  
703 Geoscience and Remote Sensing*, 2013.
- 704 [53] S, “Measuring two-dimensional movements using a single InSAR pair,” *Geophysical Research Letter*,  
705 vol. 33, no. L16311, pp. 1–5, 2006.
- 706 [54] H. Jung, S. Yun, and M. Jo, “An Improvement of Multiple-Aperture SAR Interferometry Performance  
707 in the Presence of Complex and Large Line-of-Sight Deformation,” *IEEE Journal of Selected Topics  
708 in Applied Earth Observations and Remote Sensing*, vol. 8, no. 4, pp. 1743 – 1752, 2015.
- 709 [55] O. Monserrat, M. Crosetto, M. Cuevas, and B. Crippa, “The thermal expansion component of Persis-  
710 tent Scatterer Interferometry observations,” *IEEE GEOSCIENCE AND REMOTE SENSING LET-  
711 TERS*, vol. 8, no. 5, pp. 864 – 868, 2011.
- 712 [56] G. Fornaro, D. Reale, and S. Verde, “Bridge thermal dilation monitoring with millimeter sensitivity  
713 via multidimensional SAR imaging,” *IEEE GEOSCIENCE AND REMOTE SENSING LETTERS*,  
714 vol. 10, no. 4, pp. 677 – 681, 2010.

- 715 [57] D. Reale, G. Fornaro, and A. Pauciuolo, “Extension of 4-D SAR imaging to the monitoring of ther-  
716 mally dilating scatterers,” *IEEE Transactions on Geoscience and Remote Sensing*, vol. 51, no. 12,  
717 pp. 5296–5306, 2013.
- 718 [58] H. Matsuda and N. Shimizu, “Assessment of rock slope stability based on the three-dimensional  
719 continuous displacement monitoring by Global Positioning System,” *International Journal of the*  
720 *JCRM*, vol. 2, no. 1, pp. 17–20, 2006.
- 721 [59] F. Jouanne, A. Awan, A. Madji, A. Pêcher, M. Latif, A. Kausar, J. Mugnier, I. Khan, and N. Khan,  
722 “Post-seismic deformation in Pakistan after the October 8, 2005 earthquake: evidence of afterslip  
723 along a flat north of the Balakot-Bagh trust,” *Journal of Geophysical Research*, vol. 116, no. B07401,  
724 2011.
- 725 [60] T. Reverso, J. Vandemeulebrouck, F. Jouanne, V. Pinel, T. Villemin, E. Sturkell, and P. Bascou, “A  
726 two-magma chamber model as a source of deformation at grímsvötn volcano, Iceland,” *Journal of*  
727 *Geophysical Research*, vol. 119, pp. 4666–4683, 2014.
- 728 [61] F. Ponton, E. Trouvé, M. Gay, A. Walpersdorf, R. Fallourd, J. Nicolas, F. Vernier, and J. Mugnier,  
729 “Observation of the argentière glacier flow variability from 2009 to 2011 by TerraSAR-X and GPS  
730 displacement measurements,” *Journal of Selected Topics in Applied Earth Observations and Remote*  
731 *Sensing*, vol. 7, no. 8, 2014.
- 732 [62] E. Calais, J. Han, C. DeMets, and J. Noquet, “Deformation of the North American plate interior from  
733 a decade of continuous GPS measurements,” *Journal of Geophysical Research*, vol. 111, no. B06402,  
734 pp. 1–23, 2006.
- 735 [63] P. Capuano, G. D. Natale, P. Gasparini, F. Pingue, and R. Scarpa, “A model for the 1908 Messina  
736 Straits (Italy) earthquake by inversion of levelling data,” *Bulletin of the Seismological Society of*  
737 *America*, vol. 78, no. 6, pp. 1930 – 1947, 1988.
- 738 [64] R. Bürgmann, P. Segall, M. Lisowski, and J. Svarc, “Postseismic strain following the 1989 Loma  
739 Prieta earthquake from GPS and leveling measurements,” *Journal of Geophysical Research*, vol. 102,  
740 no. B3, pp. 4933 – 4955, 1997.
- 741 [65] M. Motagh, Y. Djamour, T. Walter, H. Wetzell, J. Zschau, and S. Arabi, “Land subsidence in Mashhad  
742 Valley, northeast Iran: Results from InSAR, levelling and GPS,” *Geophysical Journal International*,  
743 vol. 168, no. 2, pp. 518–526, 2007.

- 744 [66] K. Chen, M. Yang, Y. Huang, K. Ching, and R. Rau, "Vertical displacement rate field of taiwan  
745 from geodetic levelling data 2000-2008," *Survey Review*, vol. 43, no. 321, pp. 296–302, 2011.
- 746 [67] R. Fallourd, O. Harant, E. Trouvé, J. M. Nicolas, M. Gay, A. Walpersdorf, J. L. Mugnier, J. Serafini,  
747 D. Rosu, L. Bombrun, G. Vasile, N. Cotte, F. Vernier, F. Tupin, L. Moreau, and P. Bolon, "Mon-  
748 itoring Temperate Glacier Displacement by Multi-Temporal TerraSAR-X Images and Continuous  
749 GPS Measurements," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote*  
750 *Sensing*, vol. 4, no. 2, pp. 372–386, 2011.
- 751 [68] E. Burgess, R. Forster, and C. Larsen, "Flow velocities of alaskan glaciers," *Nature communications*,  
752 vol. 4, 2013.
- 753 [69] O. Cavalié, M. P. Doin, C. Lasserre, and P. Briole, "Ground motion measurement in the lake Mead  
754 area, Nevada, by differential synthetic aperture radar interferometry time series analysis: Probing  
755 the lithosphere rheological structure," *Journal of Geophysical Research*, vol. 112, no. B03403, 2007.
- 756 [70] E. Trouvé, J. M. Nicolas, and H. Maitre, "Improving Phase Unwrapping Techniques by the Use of  
757 Local Frequency Estimates," *IEEE Transaction on Geoscience and Remote Sensing*, vol. 36, no. 6,  
758 pp. 1963–1972, 1998.
- 759 [71] R. B. Lohman and M. Simons, "Some thoughts on the use of InSAR data to constrain models of sur-  
760 face deformation: Noise structure and data downsampling," *Geochemistry, Geophysics, Geosystems*,  
761 vol. 6, no. 1, pp. Q01007.1–Q01007.12, 2005.
- 762 [72] H. Sudhaus and S. Jónsson, "Improved source modelling through combined use of InSAR and GPS  
763 under consideration of correlated data errors: application to the June 2000 Kleifarvatn earthquake,  
764 Iceland," *Geophysical Journal International*, vol. 176, no. 2, pp. 389–404, 2009.
- 765 [73] J. Zhang, Y. Bock, H. Johnson, P. Fang, S. Williams, J. Genrich, S. Wdowinski, and J. Behr,  
766 "Southern California Permanent GPS Geodetic Array: Error analysis of daily position estimates and  
767 site velocities," *Journal of Geophysical Research*, vol. 102, no. B8, pp. 18035–18055, 1997.
- 768 [74] T. Arnadóttir, P. Segall, and M. Matthews, "Resolving the discrepancy between geodetic and seismic  
769 fault models for the 1989 Loma Prieta, California, earthquake," *Bulletin of the Seismological Society*  
770 *of America*, vol. 82, no. 5, pp. 2248 – 2255, 1992.
- 771 [75] A. Amoruso and L. Crescentini, "Inversion of levelling data: how important is error treatment?,"  
772 *Geophysical Journal International*, vol. 171, no. 3, pp. 1352–1362, 2007.

- 773 [76] T. Wright, B. Parsons, and E. Fielding, "Measurement of interseismic strain accumulation across the  
774 north anatolian fault by satellite radar interferometry," *Geophysical Research Letters*, vol. 28, no. 10,  
775 pp. 2117–2120, 2001.
- 776 [77] S. Lyons and D. Sandwell, "Fault creep along the southern san andreas from interferometric synthetic  
777 aperture radar, permanent scatterers, and stacking," *Journal of Geophysical Research*, vol. 108,  
778 no. B1, 2003.
- 779 [78] D. A. Schmidt, R. Bürgmann, R. M. Nadeau, and M. d'Alessio, "Distribution of aseismic slip rate  
780 on the Hayward fault inferred from seismic and geodetic data," *Journal of Geophysical Research*,  
781 vol. 110, no. B08406, pp. 1–15, 2005.
- 782 [79] O. Cavalié, C. Lasserre, M.-P. Doin, G. Peltzer, J. Sun, X. Xu, and Z.-K. Shen, "Measurement of  
783 interseismic strain across the Haiyuan fault (Gansu, China), by InSAR," *Journal of Geophysical*  
784 *Research*, vol. 275, no. 3-4, pp. 246 – 257, 2008.
- 785 [80] A. Hooper, H. Zebker, P. Segall, and B. Kampes, "A new method for measuring deformation on vol-  
786 canoes and other natural terrains using InSAR persistent scatterers," *Geophysical Research Letters*,  
787 vol. 31, 2004.
- 788 [81] F. Casu, S. Elefante, P. Imperatore, I. Zinno, M. Manunta, C. D. Luca, and R. Lanari, "Sbas-dinsar  
789 Parallel Processing for Deformation Time-Series Computation," *IEEE Journal of Selected Topics in*  
790 *Applied Earth Observations and Remote Sensing*, vol. 7, no. 8, pp. 3285–3296, 2014.
- 791 [82] A. Ferretti, A. Fumagalli, F. Novali, C. Prati, F. Rocca, and A. Rucci, "A New Algorithm for  
792 Processing Interferometric Data-Stacks: SqueeSAR," *IEEE Transactions on Geoscience and Remote*  
793 *Sensing*, vol. 49, no. 9, pp. 3460–3470, 2011.
- 794 [83] F. Lombardini, "Differential tomography: a new framework for sar interferometry," *IEEE Transactions*  
795 *on Geoscience and Remote Sensing*, vol. 43, no. 1, pp. 37–44, 2005.
- 796 [84] G. Fornaro, D. Reale, and F. Serafino, "Four-dimensional SAR imaging for height estimation and  
797 monitoring of single and double scatterers," *IEEE Transactions on Geoscience and Remote Sensing*,  
798 vol. 47, no. 1, pp. 224–237, 2009.
- 799 [85] G. Fornaro, F. Serafino, and D. Reale, "4D SAR imaging: The case study of Rome," *IEEE GEO-*  
800 *SCIENCE AND REMOTE SENSING LETTERS*, vol. 7, no. 2, pp. 236 – 240, 2010.
- 801 [86] X. Zhu and R. Bamler, "Very high resolution spaceborne SAR tomography in urban environment,"  
802 *IEEE Transactions on Geoscience and Remote Sensing*, vol. 48, no. 12, pp. 4296–4308, 2010.

- 803 [87] D. Reale, G. Fornaro, A. Pauciuolo, X. Zhu, and R. Bamler, “Tomographic imaging and monitoring  
804 of buildings with very high resolution SAR data,” *IEEE GEOSCIENCE AND REMOTE SENSING*  
805 *LETTERS*, vol. 8, no. 4, pp. 661 – 665, 2011.
- 806 [88] Y. Fialko, M. Simons, and D. Agnew, “The complete (3-D) surface displacement field in the epicentral  
807 area of the 1999 Mw 7.1 Hector Mine earthquake, California, from space geodetic observations,”  
808 *Geophysical Research Letters*, vol. 28, no. 16, p. 3063–3066, 2001.
- 809 [89] T. J. Wright, B. E. Parsons, and Z. Lu, “Toward mapping surface deformation in three dimensions  
810 using InSAR,” *Geophysical Research Letters*, vol. 31, no. L01607, pp. 1–5, 2004.
- 811 [90] T. Wang and S. Jonsson, “Improved SAR amplitude image offset measurements for deriving three-  
812 dimensional coseismic displacements,” *IEEE Journal of Selected Topics in Applied Earth Observa-*  
813 *tions and Remote Sensing*, vol. 8, no. 7, pp. 3271 – 3278, 2015.
- 814 [91] D. Dubois and H. Prade, *Possibility theory: An Approach to Computerized Processing of Uncertainty*.  
815 Plenum Press, 1988.
- 816 [92] D. Dubois, L. Foulloy, G. Mauris, and H. Prade, “Probability-possibility transformations, triangular  
817 fuzzy sets and probabilistic inequalities,” *International Journal on Reliable Computing*, vol. 10, no. 4,  
818 pp. 273–297, 2004.
- 819 [93] L. A. Zadeh, “Fuzzy sets as a basis for a theory of possibility,” *Fuzzy Sets and Systems*, vol. 1, no. 1,  
820 pp. 3–28, 1978.
- 821 [94] Y. Yan, E. Trouvé, V. Pinel, G. Mauris, E. Pathier, and S. Galichet, “Fusion of D-InSAR and  
822 sub-pixel image correlation measurements for coseismic displacement field estimation: Application  
823 to the Kashmir earthquake (2005),” *International Journal of Image and Data Fusion*, vol. 3, no. 1,  
824 pp. 71–92, 2012.
- 825 [95] Y. Okada, “Surface deformation due to shear and tensile faults in a half-space,” *Bulletin of the*  
826 *Seismological Society of America*, vol. 75, no. 4, pp. 1135–1154, 1985.
- 827 [96] K. Mogi, “Relations between the Eruptions of Various Volcanoes and the Deformations of the Ground  
828 Surfaces around them,” *Bulletin of the Earthquake Research Institute*, vol. 36, pp. 99–134, 1958.
- 829 [97] M. Simons, Y. Fialko, and L. Rivera, “Coseismic deformation from the 1999  $m_w$  7.1 Hector Mine,  
830 California, Earthquake as Inferred from InSAR and GPS observations,” *Bulletin of the Seismological*  
831 *Society of America*, vol. 92, no. 4, pp. 1390–1402, 2002.

- 832 [98] S. Jónsson, H. Zebker, P. Segall, and F. Amelung, “Fault Slip Distribution of the 1999  $M_w$ 7.1 Hector  
833 Mine, California, Earthquake, Estimated from Satellite Radar and GPS Measurements,” *Bulletin of*  
834 *the Seismological Society of America*, vol. 92, no. 4, pp. 1377–1389, 2002.
- 835 [99] R. Pedersen, S. Jónsson, T. Arnadóttir, F. Sigmundsson, and K. L. Feigl, “Fault slip distribution of  
836 two June 2000  $M_w$ 6.5 earthquake in South Iceland estimated from joint inversion of InSAR and GPS  
837 measurements,” *Earth and Planetary Science Letters*, vol. 213, no. 3-4, pp. 487–502, 2003.
- 838 [100] G. J. Funning, B. Parsons, and T. J. Wright, “Surface displacements and source parameters of the  
839 2003 Bam (Iran) earthquake from Envisat advanced synthetic aperture radar imagery,” *Journal of*  
840 *Geophysical Research*, vol. 110, no. B09406, pp. 1–23, 2005.
- 841 [101] S. Wei, E. Fielding, S. Leprince, A. Sladen, J. Avouac, D. Helmberger, E. Hauksson, R. Chu, M. Si-  
842 mons, K. Hudnut, T. Herring, and R. Briggs, “Superficial simplicity of the 2010 Elmayor–Cucapah  
843 earthquake of Baja California in Mexico,” *Nature Geoscience*, vol. 4, pp. 615 –618, 2011.
- 844 [102] J. Beavan, E. Fielding, M. Motagh, S. Samsonov, and N. Donnelly, “Fault location and slip distribu-  
845 tion of the 22 February 2011  $M_w$  6.2 Christchurch, New Zealand, earthquake from geodetic data,”  
846 *Seismological Research Letters*, vol. 82, no. 6, pp. 789 – 799, 2011.
- 847 [103] E. Fielding, M. Simons, S. Owen, P. Lundgren, H. Hua, P. Agram, Z. Liu, A. Moore, P. Milillo,  
848 J. Polet, S. Samsonov, P. Rosen, F. Webb, and G. Milillo, “Rapid imaging of earthquake ruptures  
849 with combined geodetic and seismic analysis,” *Procedia Technology*, vol. 16, pp. 876 – 885, 2014.
- 850 [104] W. Barnhart, J. R. Murray, S.-H. Yun, J. L. Svarc, S. V. Samsonov, E. J. Fielding, B. A. Brooks, and  
851 P. Milillo, “Geodetic constraints on the 2014  $M$  6.0 South Napa earthquake,” *Seismological Research*  
852 *Letters*, vol. 86, no. 2A, pp. 335 –343, 2015.
- 853 [105] Y. Fialko, “Interseismic strain accumulation and the earthquake potential on the southern San An-  
854 dreas fault system,” *Nature*, vol. 441, pp. 968–971, 2006.
- 855 [106] D. Massonnet, K. Feigl, M. Rossi, and F. Adragna, “Radar interferometric mapping of deformation  
856 in the year after the Landers earthquake,” *Nature*, vol. 369, pp. 227–230, 1994.
- 857 [107] Y. Fialko, “Evidence of fluid-filled upper crust from observations of postseismic deformation due  
858 to the 1992  $M_w$ 7. 3 Landers earthquake,” *Journal of Geophysical Research*, vol. 109, no. B08401,  
859 pp. 1–17, 2004.

- 860 [108] L. Bruhat, S. Barbot, and J. Avouac, “Evidence for postseismic deformation of the lower crust fol-  
861 lowing the 2004 Mw6.0 parkfield earthquake,” *Journal of Geophysical Research*, vol. 116, no. B08401,  
862 pp. 1–10, 2011.
- 863 [109] D. Sandwell, D. Myer, R. Mellors, and M. Shimada, “Accuracy and resolution of ALOS interfer-  
864 ometry: vector deformation maps of the father’s day intrusion at Kilauea,” *IEEE Transactions on*  
865 *Geoscience and Remote Sensing*, vol. 46, no. 11, pp. 3524–3534, 2008.
- 866 [110] G. Evensen, “The Ensemble Kalman Filter: theoretical formulation and practical implementaion,”  
867 *Ocean Dynamics*, vol. 53, pp. 343–367, 2003.
- 868 [111] Y. Yan, E. Trouvé, and V. Pinel, “Fusion of prior information and multi-scales local frequencies to  
869 facilitate D-InSAR phase unwrapping,” in *IEEE International Symposium on Geoscience and Remote*  
870 *Sensing*, (Munich), pp. 1888–1891, 2012.
- 871 [112] S. Yun, H. Zebker, P. Segall, A. Hooper, and M. Poland, “Interferogram formation in the presence  
872 of complex and large deformation,” *Geophysical Research Letter*, vol. 34, no. L12305, pp. 1–6, 2007.
- 873 [113] S. Atzori, I. Hunstad, M. Chini, S. Salvi, C. Tolomei, C. Bignami, S. Stramondo, E. Trasatti,  
874 A. Antonioli, and E. Boschi, “Finite fault inversion of DInSAR coseismic displacement of the 2009  
875 L’Aquila earthquake (central Italy),” *Geophysical Research Letter*, vol. 36, no. L15305, pp. 1–6, 2009.
- 876 [114] K. L. Feigl and C. H. Thurber, “A method for modelling radar interferograms without phase un-  
877 wrapping: application to the M 5 Fawnskin, California earthquake of 1992 December 4,” *Geophysical*  
878 *Journal International*, vol. 176, no. 2, pp. 491–504, 2009.
- 879 [115] G. Fornaro, S. Atzori, F. Calò, D. Reale, and S. Salvi, “Inversion of wrapped differential interfer-  
880 ometric SAR data for fault dislocation modeling,” *IEEE Transactions on Geoscience and Remote*  
881 *Sensing*, vol. 50, no. 6, pp. 2175 – 2184, 2012.
- 882 [116] D. Baù, M. Ferronato, G. Gambolati, P. Teatini, and A. Alzraiee, “Ensemble smoothing of land  
883 subsidence measurements for reservoir geomechanical characterization,” *INTERNATIONAL JOUR-*  
884 *NAL FOR NUMERICAL AND ANALYTICAL METHODS IN GEOMECHANICS*, vol. 39, no. 2,  
885 pp. 207–228, 2015.
- 886 [117] H. Wang, L. Ge, C. Xu, and Z. Du, “3-d coseismic displacement field of the 2005 Kashmir earthquake  
887 inferred from satellite radar imagery,” *Earth Planets Space*, vol. 59, no. 5, pp. 343 – 349, 2007.



888 [118] A. Manconi and F. Casu, “Joint analysis of displacement time series retrieved from SAR phase and  
889 amplitude: Impact on the estimation of volcanic source parameters,” *Geophysical Research Letters*,  
890 vol. 39, no. 14, 2012.

891 **List of Figures**

892 1 (a) Linear range change rate (b) standard deviation of the linear range change rate obtained  
893 from stacking of 13 independent interferograms in the San Francisco Bay Area from 1992 to  
894 2000 (from [78]). . . . . 35

895 2 Ice flow velocity magnitude obtained from feature-tracking of Landsat images over the  
896 Karakoram for (a) a single annual pair (b) the fusion of 29 annual pairs over the period  
897 1999-2001. White gaps correspond to areas where no measurements are available. In (a)  
898 the spatial coverage is 70%, while it is increased to 94% in (b). Insets show histograms of  
899 the velocity in stable areas for each component. . . . . 36

900 3 Example of displacement time series obtained with SBAS and P0-SBAS for Fernandina (a-  
901 c) and Sierra Negra (d-f) (from [118]). (a) LOS mean deformation velocity map computed  
902 through the SBAS approach and the displacement time series relevant to a point located in  
903 the inner caldera denoted by the black square (b-c) Displacement during the period of 2003 -  
904 2007 computed through the PO-SBAS approach along the range and the azimuth directions  
905 and the displacement time series of representative points located within the inner caldera.  
906 (d) Same as (a) but for Sierra Negra (e) Same as (b) but for Sierra Negra (f) Same as (c)  
907 but for Sierra Negra. The displacement time series is relevant to the relative displacement  
908 between two points located across the caldera, identified by the black boxes. Red lines refer  
909 to the Fernandina May 2005 eruption and to the Sierra Negra October 2005 eruption. . . . 37

910 4 The Up component of the 3D displacement obtained with joint inversion (a) and the associ-  
911 ated uncertainty obtained with (b) joint inversion, probabilistic approach (c) joint inversion,  
912 possibilistic approach (d) pre-fusion, probabilistic approach (e) pre-fusion, possibilistic ap-  
913 proach in the case of the Kashmir earthquake in 2005. . . . . 38

914 5 Slip distribution on the fault plane obtained with (a) pre-fusion (b) joint inversion for the  
915 Kashmir earthquake in 2005. The color represents the magnitude and the arrows represent  
916 the direction. Artefact is observed in depth in model (b) because of the difficulty in adjusting  
917 a model to a large number of noisy measurements. . . . . 39

918 6 Example of distribution and correlation of geometrical parameters of a fault rupture model  
919 of the 2003 BAM (Iran) earthquake obtained by noise realisation (from [100]). Histograms  
920 show uncertainties in individual model parameters. Scatterplots show degrees of correlation  
921 (trade-off) between pairs of model parameters. (Strike, dip, and rake are in degrees; slip is  
922 in m; X and Y coordinates (of the centre of the fault plane projected updip to the surface)  
923 are in UTM km (zone 40); length, width, and centroid (Cd) depth are in km; and moment  
924 is in units of  $10^{18}$  N m.) . . . . . 40

925 7 Slip model for the 2006 slow slip events in the Guerrero seismic gap inferred from (a) GPS  
926 measurement alone (b) InSAR measurements alone (c) joint minimisation of residual of  
927 both GPS and InSAR measurements (from [38]). GPS stations are represented by open  
928 black triangles and InSAR track by black box. Dashed thin gray lines indicate the changes  
929 in the dip of the model subduction plane. Dashed thick gray line represents the Middle  
930 American Trench (MAT) and thick continuous gray lines correspond to fracture zones. The  
931 location of the Guerrero gap (G.gap) is shown in red. . . . . 41

932	8	(a) A priori deformation model in LOS direction, negative value for displacement towards the	
933		satellite. (b) Scale image for phase gradient estimation deduced from the a priori deforma-	
934		tion model. $S_0$ corresponding to the full resolution SLC image and $S_n$ to the multi-looking	
935		image after a complex average of $n$ looks in range and $5n$ looks in azimuth. (c) Original	
936		differential interferogram (d) Filtered interferogram by multi-scale phase gradient (e)	
937		Unwrapped interferogram using multi-scale phase gradient by a least squares method (f)	
938		Wrapped phase residual in the case of the Kashmir earthquake (2005) (from [34]). . . . .	42
939	9	(a) Geometrical parameters of the Paganica fault estimated in [113] (b) Coseismic and (c)	
940		post-seismic slip distributions of the Paganica fault and the Campotosto fault using the	
941		Paganica fault geometry in (a) and the Campotosto fault geometry derived from geological	
942		mapping and InSAR, GPS and levelling data (from [15]). The white star indicates the April	
943		6th Mw 6.3 L'Aquila mainshock, while the green stars are the three Mw > 5 aftershocks on	
944		the Campotosto fault. The Paganica fault is in green and the Campotosto fault is in red.	
945		The gray arrows show the slip direction. . . . .	43

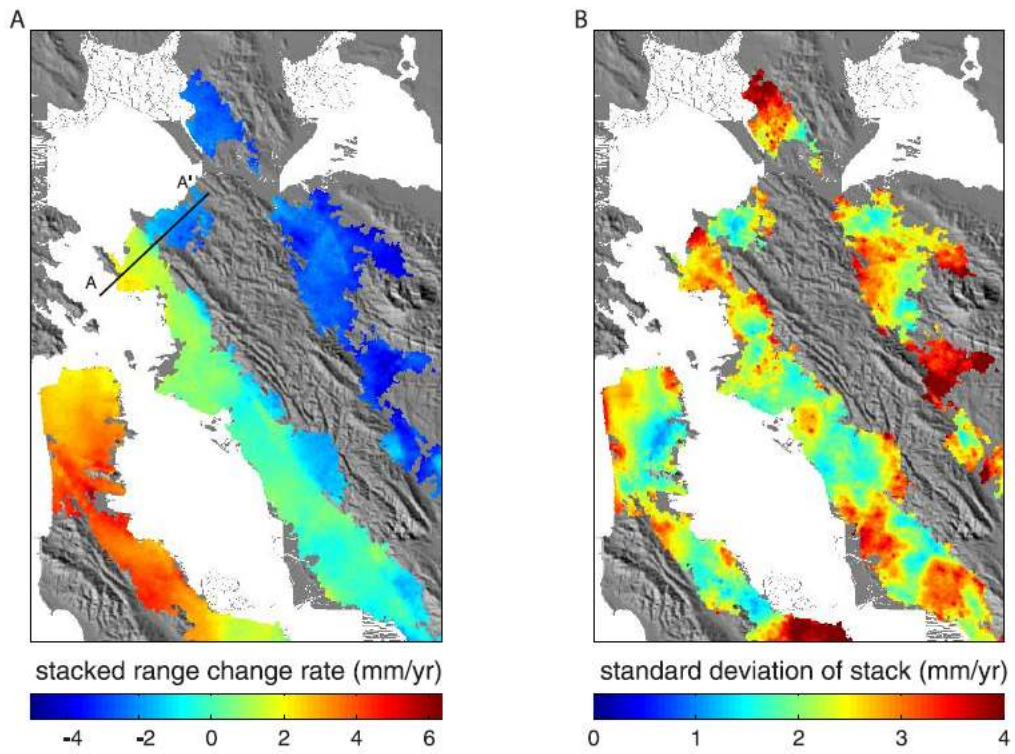
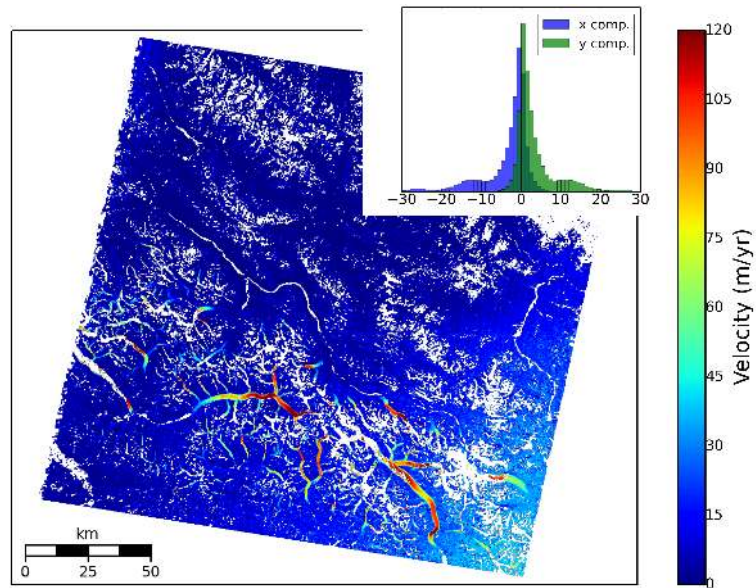
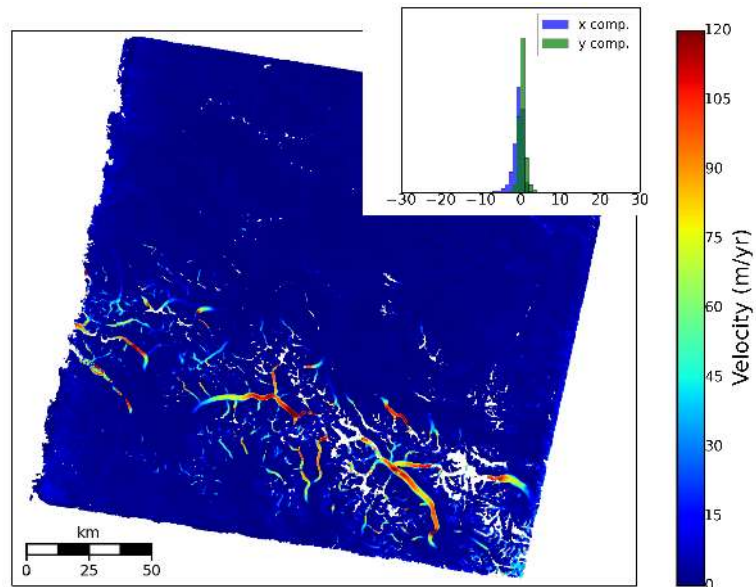


Figure 1: (a) Linear range change rate (b) standard deviation of the linear range change rate obtained from stacking of 13 independent interferograms in the San Francisco Bay Area from 1992 to 2000 (from [78]).



(a)



(b)

Figure 2: Ice flow velocity magnitude obtained from feature-tracking of Landsat images over the Karakoram for (a) a single annual pair (b) the fusion of 29 annual pairs over the period 1999-2001. White gaps correspond to areas where no measurements are available. In (a) the spatial coverage is 70%, while it is increased to 94% in (b). Insets show histograms of the velocity in stable areas for each component.

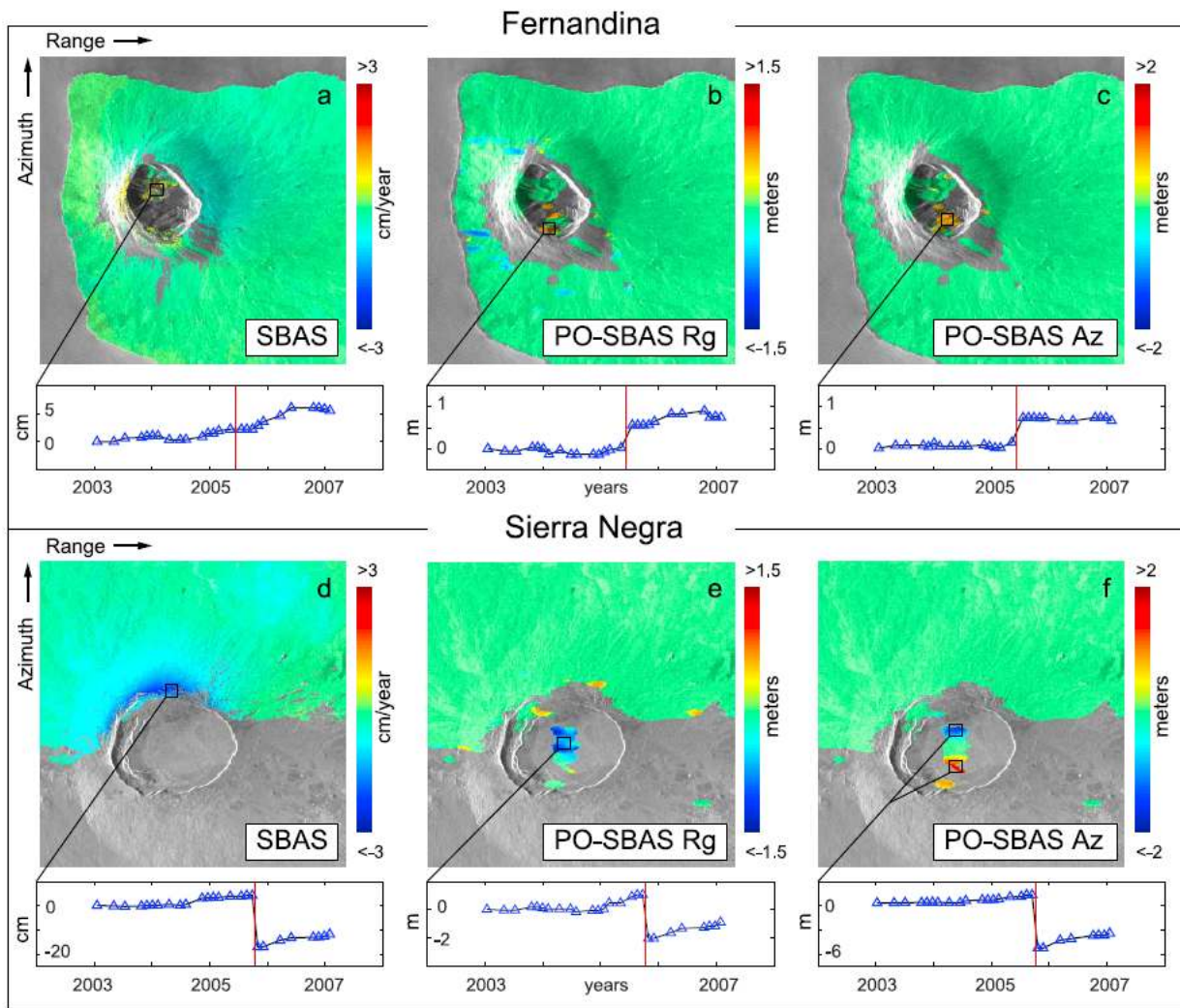


Figure 3: Example of displacement time series obtained with SBAS and P0-SBAS for Fernandina (a-c) and Sierra Negra (d-f) (from [118]). (a) LOS mean deformation velocity map computed through the SBAS approach and the displacement time series relevant to a point located in the inner caldera denoted by the black square (b-c) Displacement during the period of 2003 - 2007 computed through the PO-SBAS approach along the range and the azimuth directions and the displacement time series of representative points located within the inner caldera. (d) Same as (a) but for Sierra Negra (e) Same as (b) but for Sierra Negra (f) Same as (c) but for Sierra Negra. The displacement time series is relevant to the relative displacement between two points located across the caldera, identified by the black boxes. Red lines refer to the Fernandina May 2005 eruption and to the Sierra Negra October 2005 eruption.

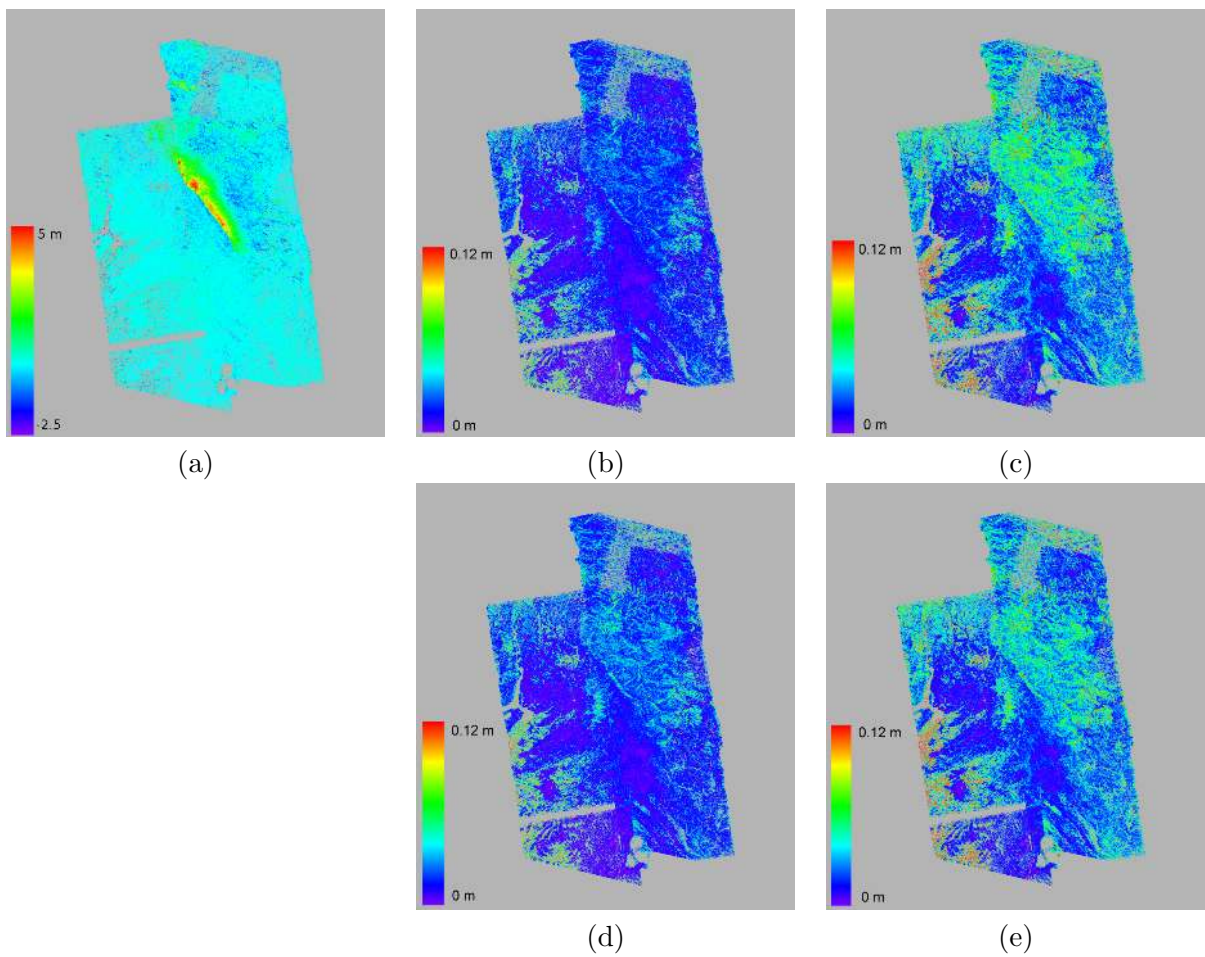


Figure 4: The Up component of the 3D displacement obtained with joint inversion (a) and the associated uncertainty obtained with (b) joint inversion, probabilistic approach (c) joint inversion, possibilistic approach (d) pre-fusion, probabilistic approach (e) pre-fusion, possibilistic approach in the case of the Kashmir earthquake in 2005.

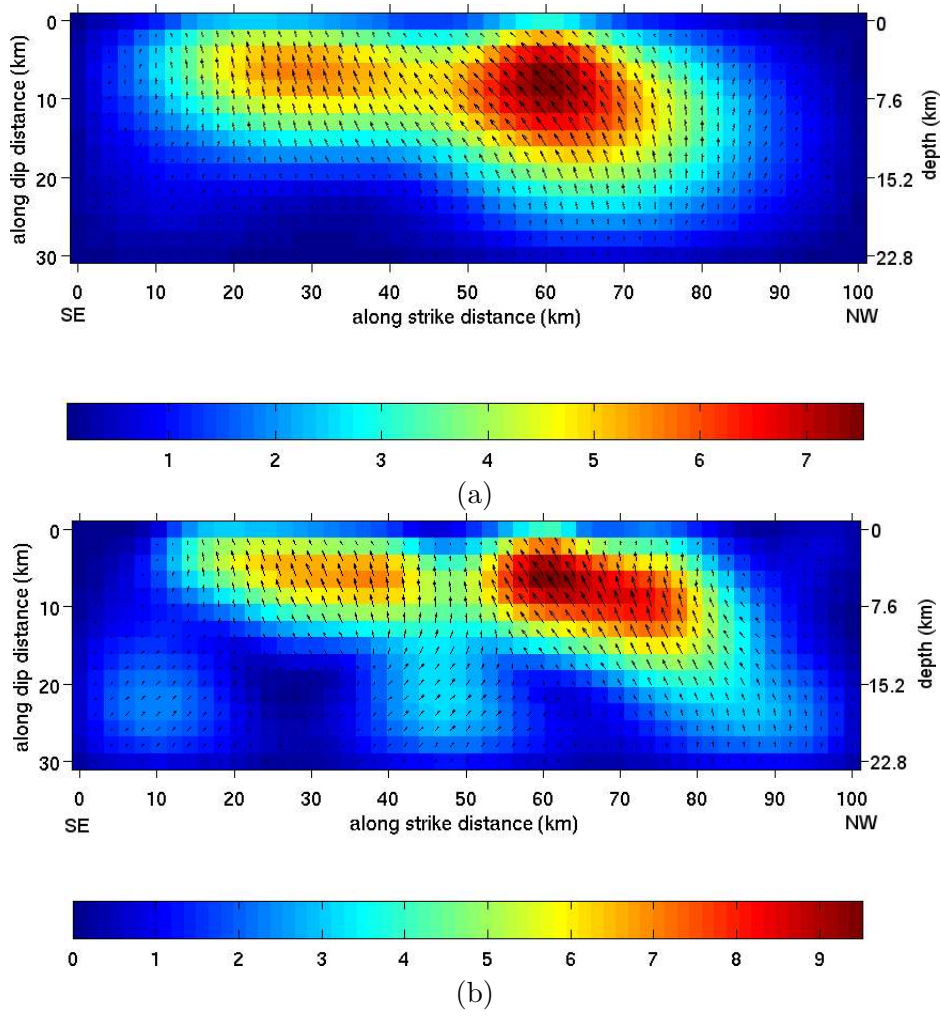


Figure 5: Slip distribution on the fault plane obtained with (a) pre-fusion (b) joint inversion for the Kashmir earthquake in 2005. The color represents the magnitude and the arrows represent the direction. Artefact is observed in depth in model (b) because of the difficulty in adjusting a model to a large number of noisy measurements.



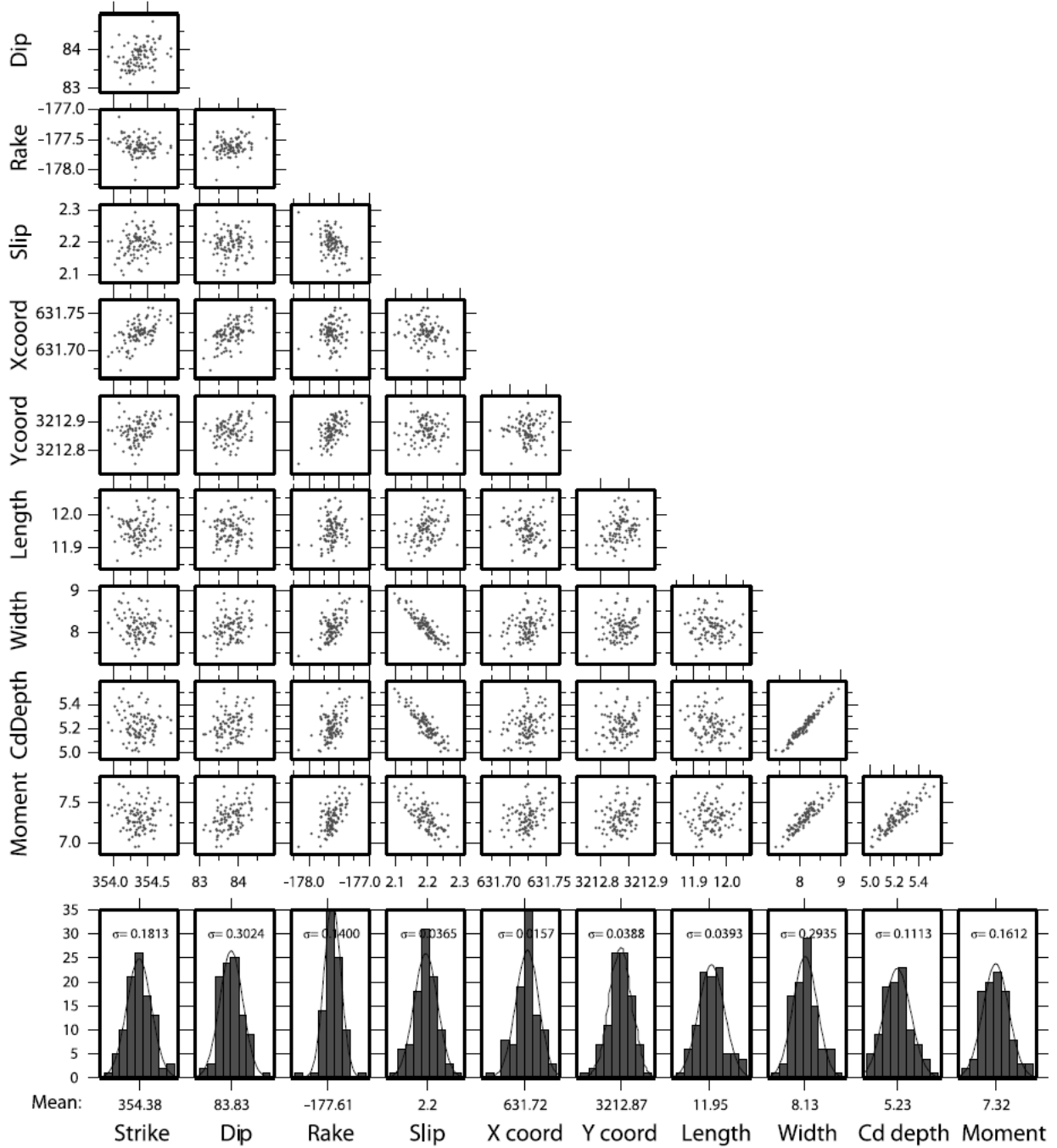


Figure 6: Example of distribution and correlation of geometrical parameters of a fault rupture model of the 2003 BAM (Iran) earthquake obtained by noise realisation (from [100]). Histograms show uncertainties in individual model parameters. Scatterplots show degrees of correlation (trade-off) between pairs of model parameters. (Strike, dip, and rake are in degrees; slip is in m; X and Y coordinates (of the centre of the fault plane projected updip to the surface) are in UTM km (zone 40); length, width, and centroid (Cd) depth are in km; and moment is in units of  $10^{18}$  N m.)

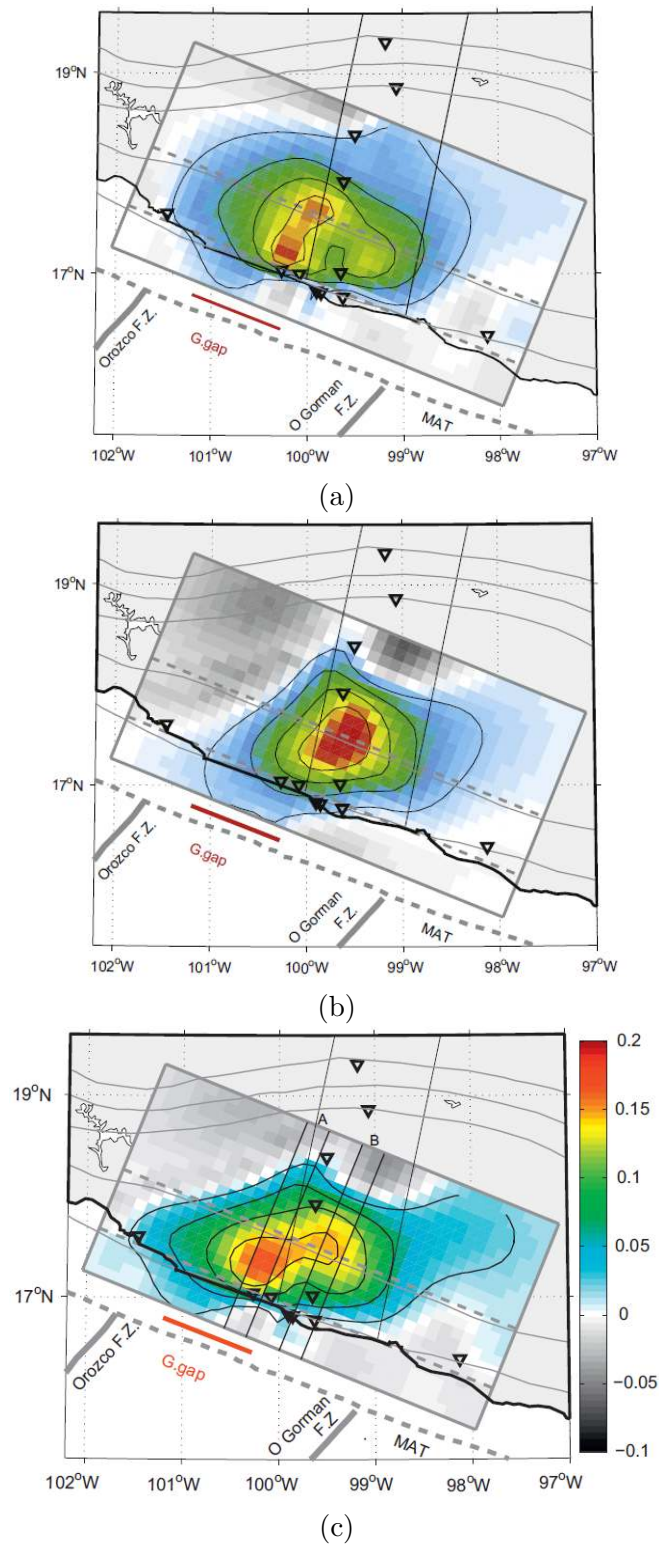


Figure 7: Slip model for the 2006 slow slip events in the Guerrero seismic gap inferred from (a) GPS measurement alone (b) InSAR measurements alone (c) joint minimisation of residual of both GPS and InSAR measurements (from [38]). GPS stations are represented by open black triangles and InSAR track by black box. Dashed thin gray lines indicate the changes in the dip of the model subduction plane. Dashed thick gray line represents the Middle American Trench (MAT) and thick continuous gray lines correspond to fracture zones. The location of the Guerrero gap (G.gap) is shown in red.

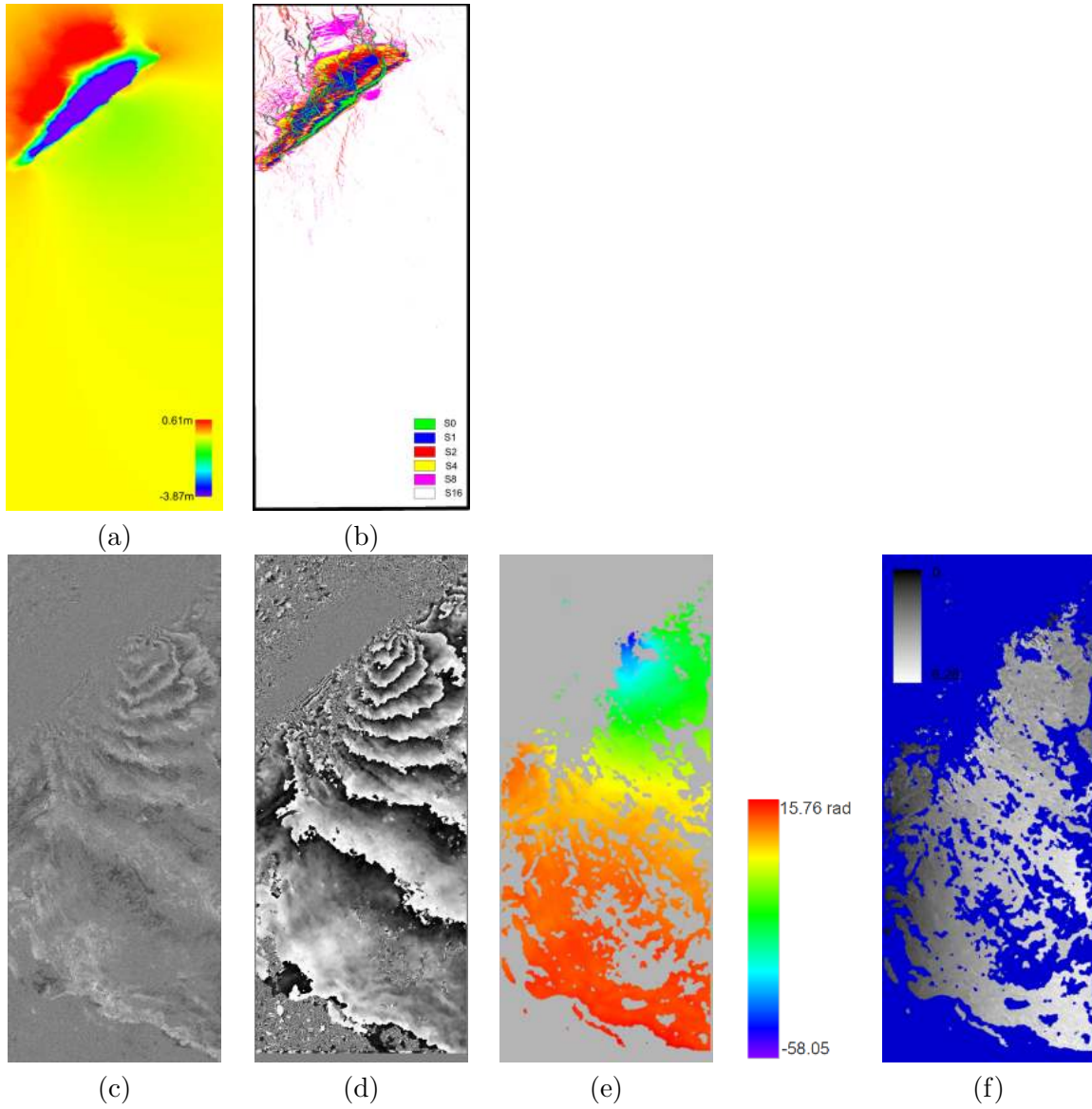


Figure 8: (a) A priori deformation model in LOS direction, negative value for displacement towards the satellite. (b) Scale image for phase gradient estimation deduced from the a priori deformation model.  $S_0$  corresponding to the full resolution SLC image and  $S_n$  to the multi-looking image after a complex average of  $n$  looks in range and  $5n$  looks in azimuth. (c) Original differential interferogram (d) Filtered interferogram by multi-scale phase gradient (e) Unwrapped interferogram using multi-scale phase gradient by a least squares method (f) Wrapped phase residual in the case of the Kashmir earthquake (2005) (from [34]).

Length (km)	Width (km)	Top Depth <sup>a</sup> (km)	Strike (deg)	Dip (deg)	East <sup>b</sup> (km)	North <sup>b</sup> (km)	Rake (deg)	Slip (cm)
12.2 (0.4)	14.1 (0.7)	1.9 (0.2)	133 (2)	47 (1)	373.83 (1.38)	4691.29 (1.58)	-103 (2)	56 (2)

<sup>a</sup>Vertical depth of the fault top edge.

<sup>b</sup>East and North coordinates are in UTM-WGS84, zone 33, and refers to the center of the fault trace.

(a)

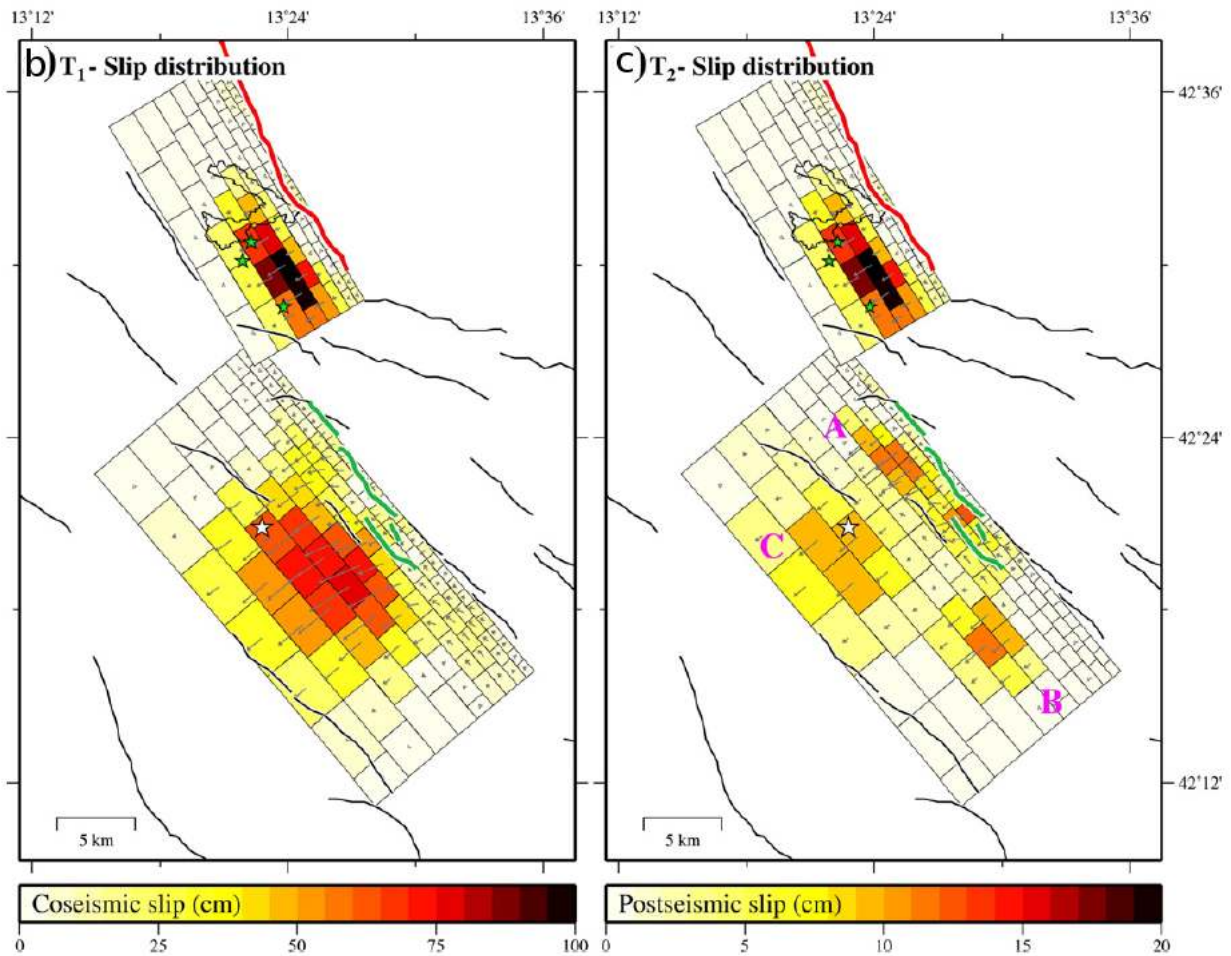


Figure 9: (a) Geometrical parameters of the Paganica fault estimated in [113] (b) Coseismic and (c) post-seismic slip distributions of the Paganica fault and the Campotosto fault using the Paganica fault geometry in (a) and the Campotosto fault geometry derived from geological mapping and InSAR, GPS and levelling data (from [15]). The white star indicates the April 6th Mw 6.3 L'Aquila mainshock, while the green stars are the three Mw > 5 aftershocks on the Campotosto fault. The Paganica fault is in green and the Campotosto fault is in red. The gray arrows show the slip direction.