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Fusion of remotely sensed displacement measurements: current status and challenges

Y. Yan¹, A. Dehecq^{1,2}, E. Trouvé¹, G. Mauris¹, N. Gourmelen², F. Vernier¹

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

Email: ya.jing.yan@univ-smb.fr

2: School of Geosciences, University of Edinburgh, UK

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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 Σ_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 φ azimuth of the**
291 **satellite trajectory and θ the incident angle.** R corresponds to the vector of displacement measured
292 by correlation and/or DInSAR. Σ_R and Σ_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 2π 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.

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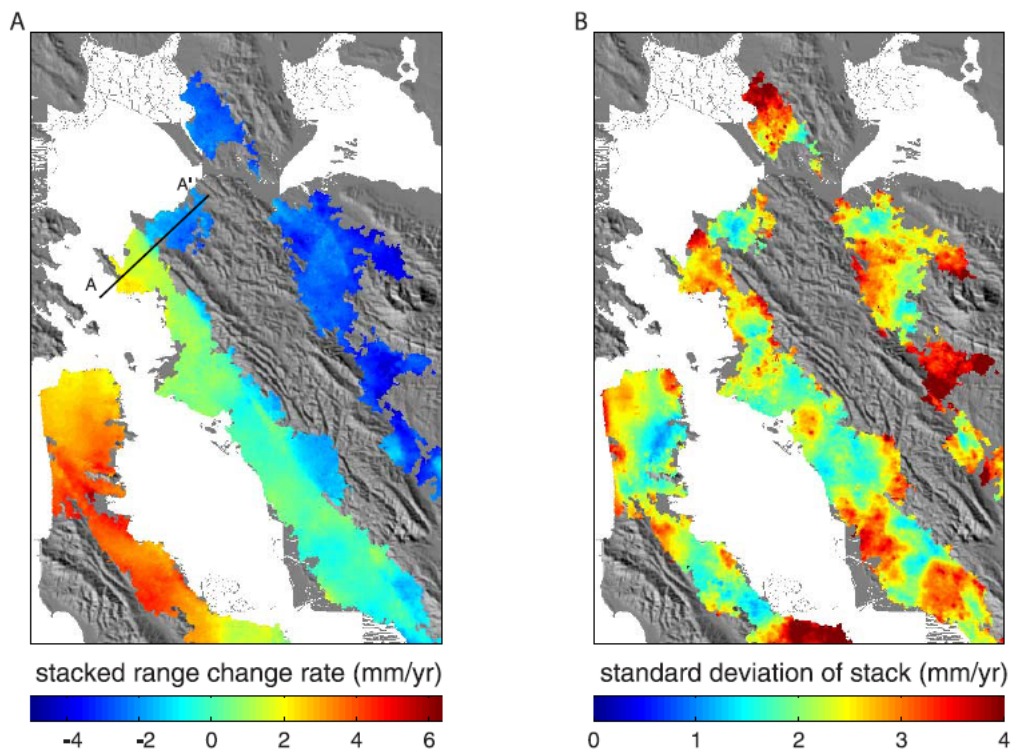
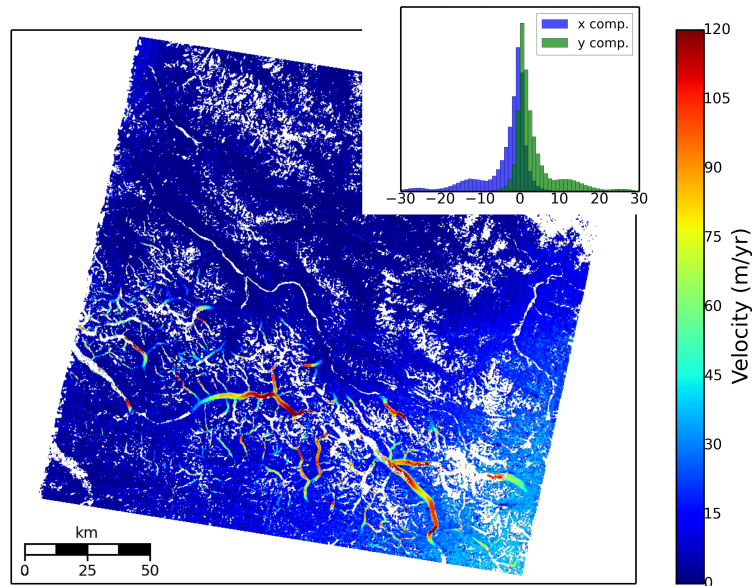
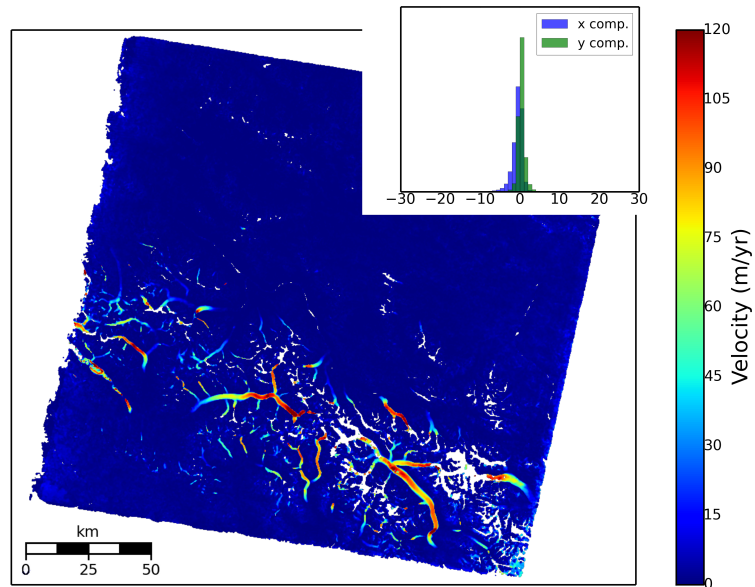


Figure 1: (a) Linear range change rate (b) standard deviation of the linear range change rate obtained from stacking of 13 independent interferograms in the San Francisco Bay Area from 1992 to 2000 (from [78]).



(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.

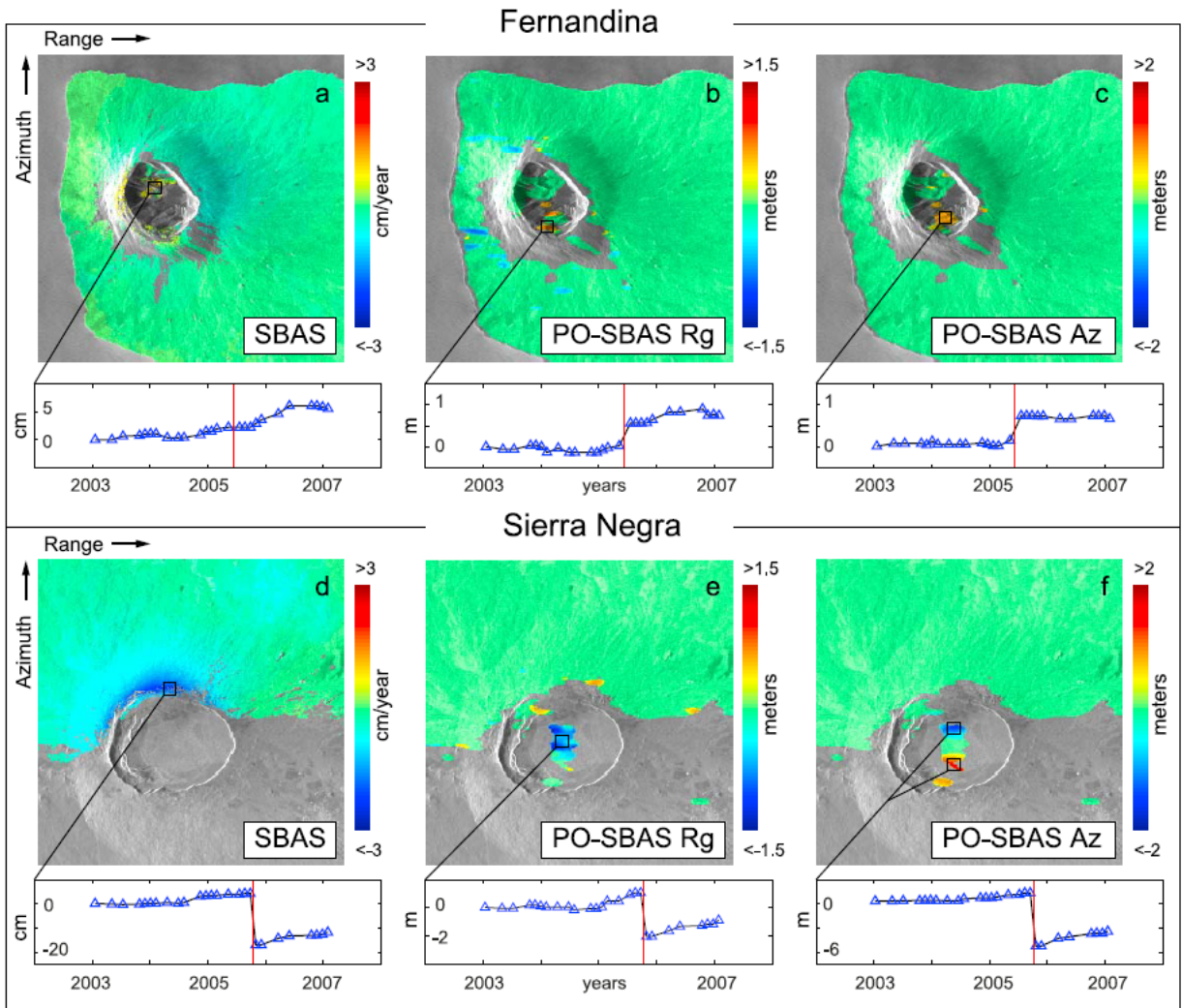


Figure 3: Example of displacement time series obtained with SBAS and PO-SBAS for Fernandina (a-c) and Sierra Negra (d-f) (from [118]). (a) LOS mean deformation velocity map computed through the SBAS approach and the displacement time series relevant to a point located in the inner caldera denoted by 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.

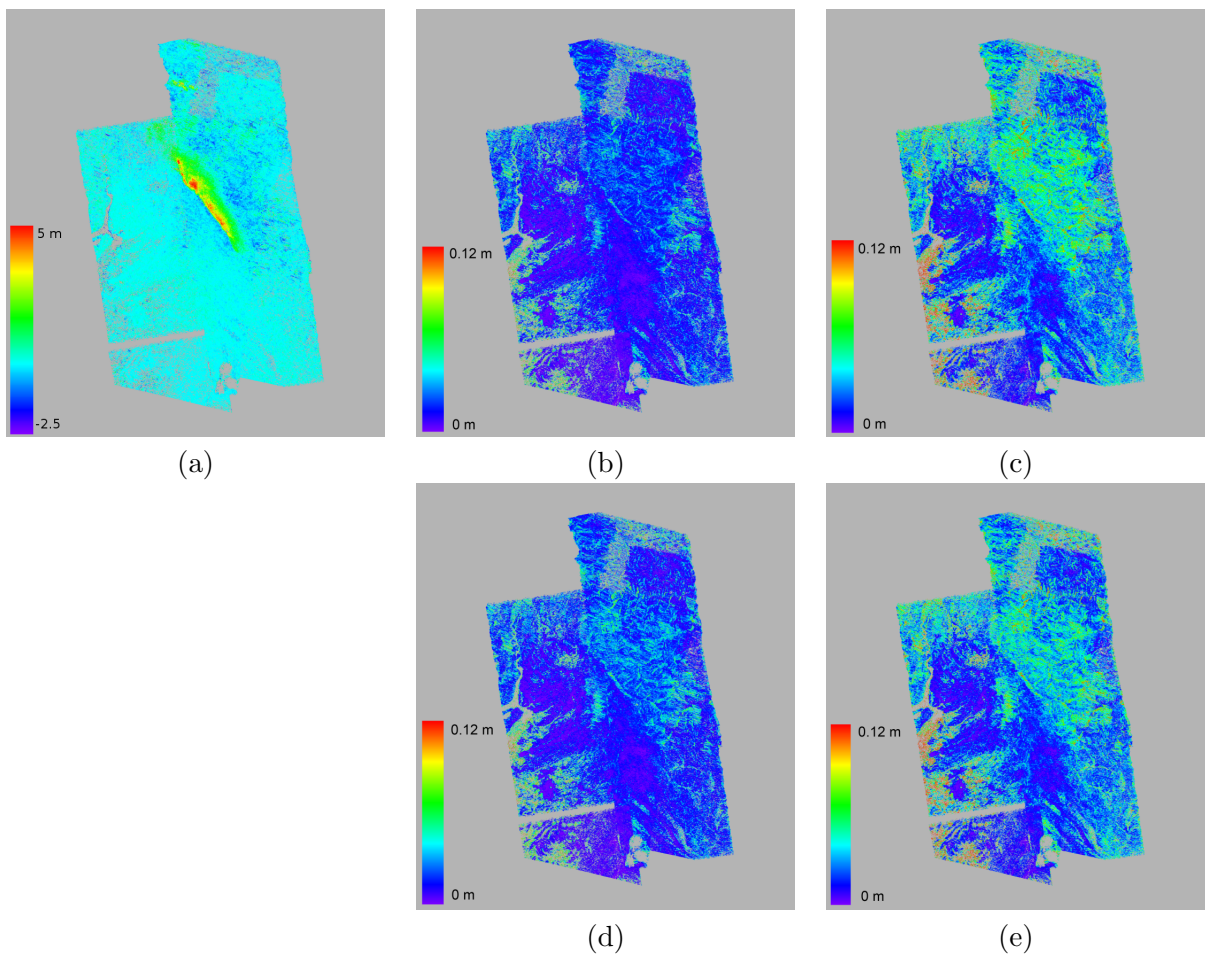


Figure 4: The Up component of the 3D displacement obtained with joint inversion (a) and the associated uncertainty obtained with (b) joint inversion, probabilistic approach (c) joint inversion, possibilistic approach (d) pre-fusion, probabilistic approach (e) pre-fusion, possibilistic approach in the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

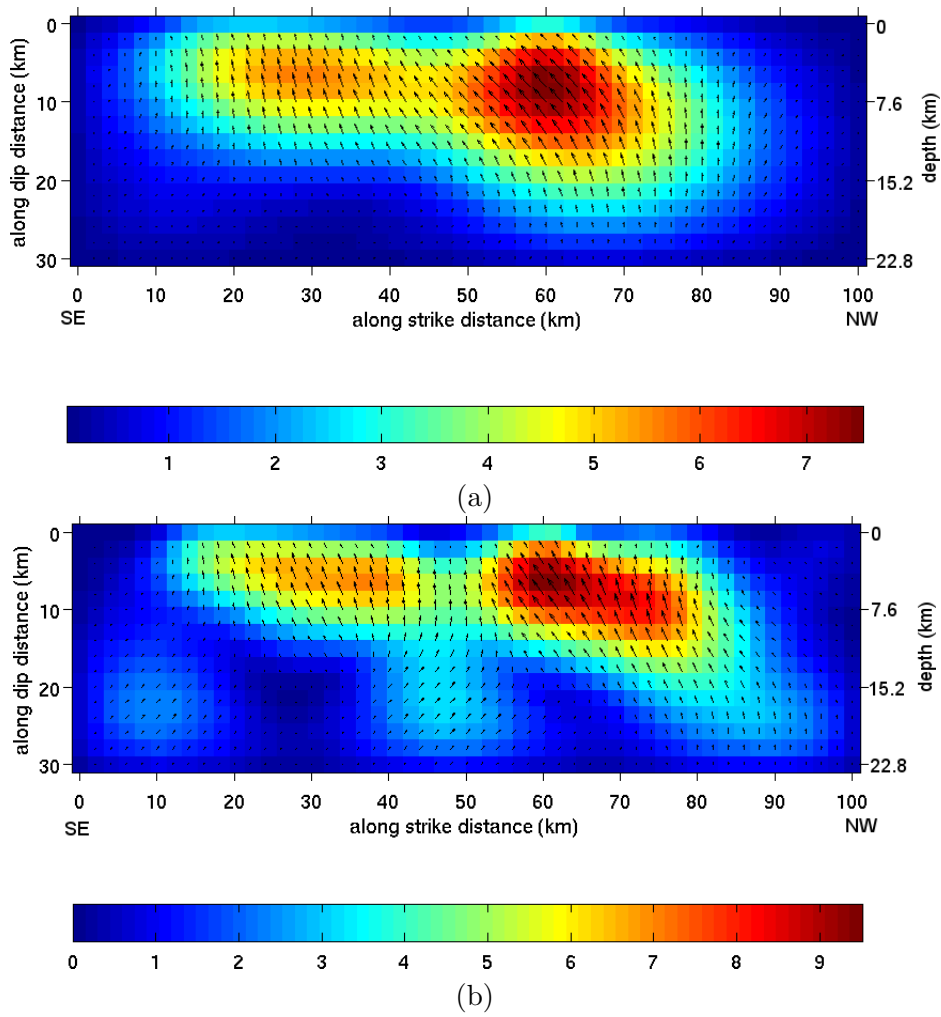


Figure 5: Slip distribution on the fault plane obtained with (a) pre-fusion (b) joint inversion for the Kashmir earthquake in 2005. The color represents the magnitude and the arrows represent the direction. Artefact is observed in depth in model (b) because of the difficulty in adjusting a model to a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

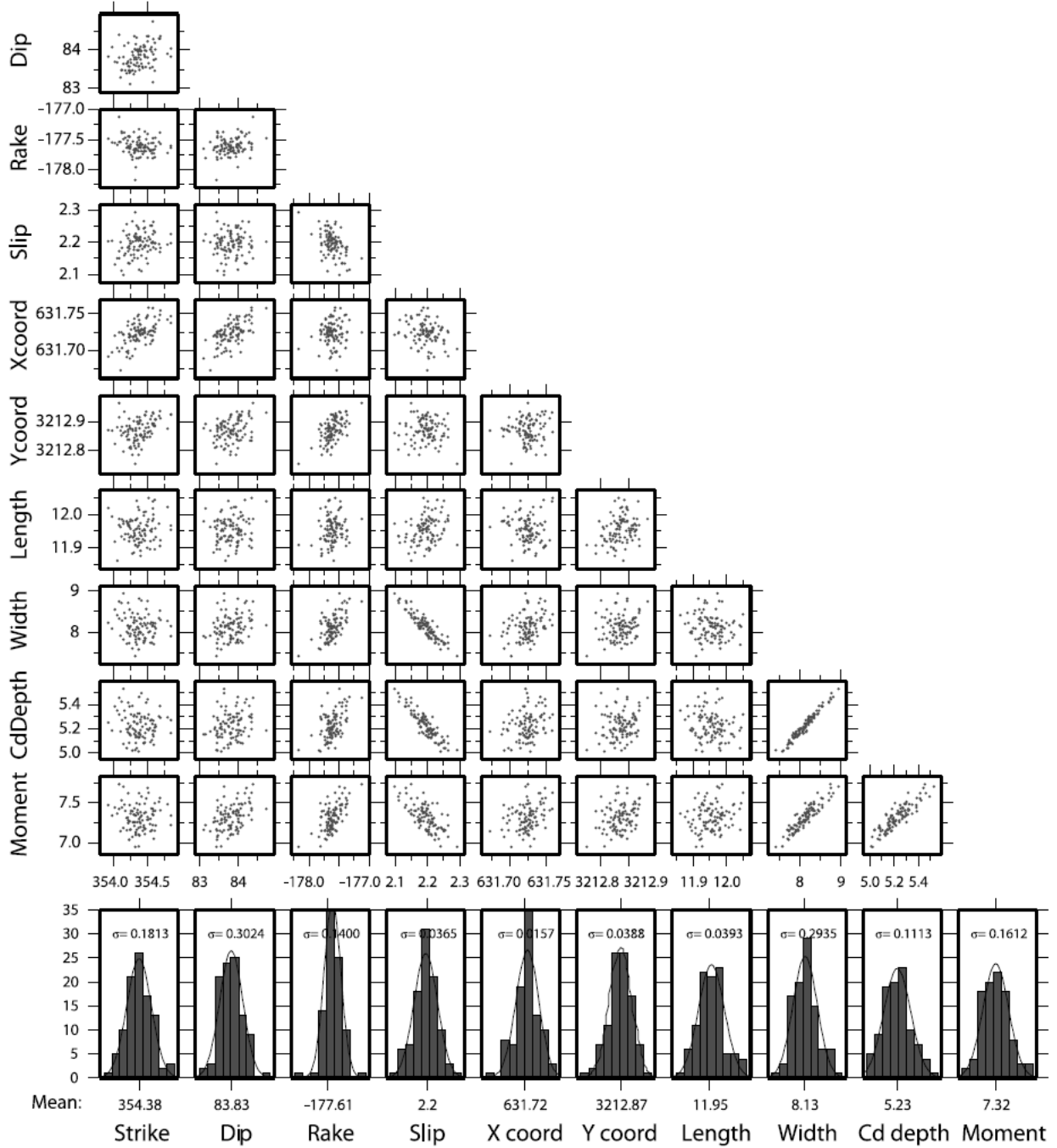


Figure 6: Example of distribution and correlation of geometrical parameters of a fault rupture model of the 2003 BAM (Iran) earthquake obtained by noise realisation (from [100]). Histograms show uncertainties in individual model parameters. Scatterplots show degrees of correlation (trade-off) between 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.)

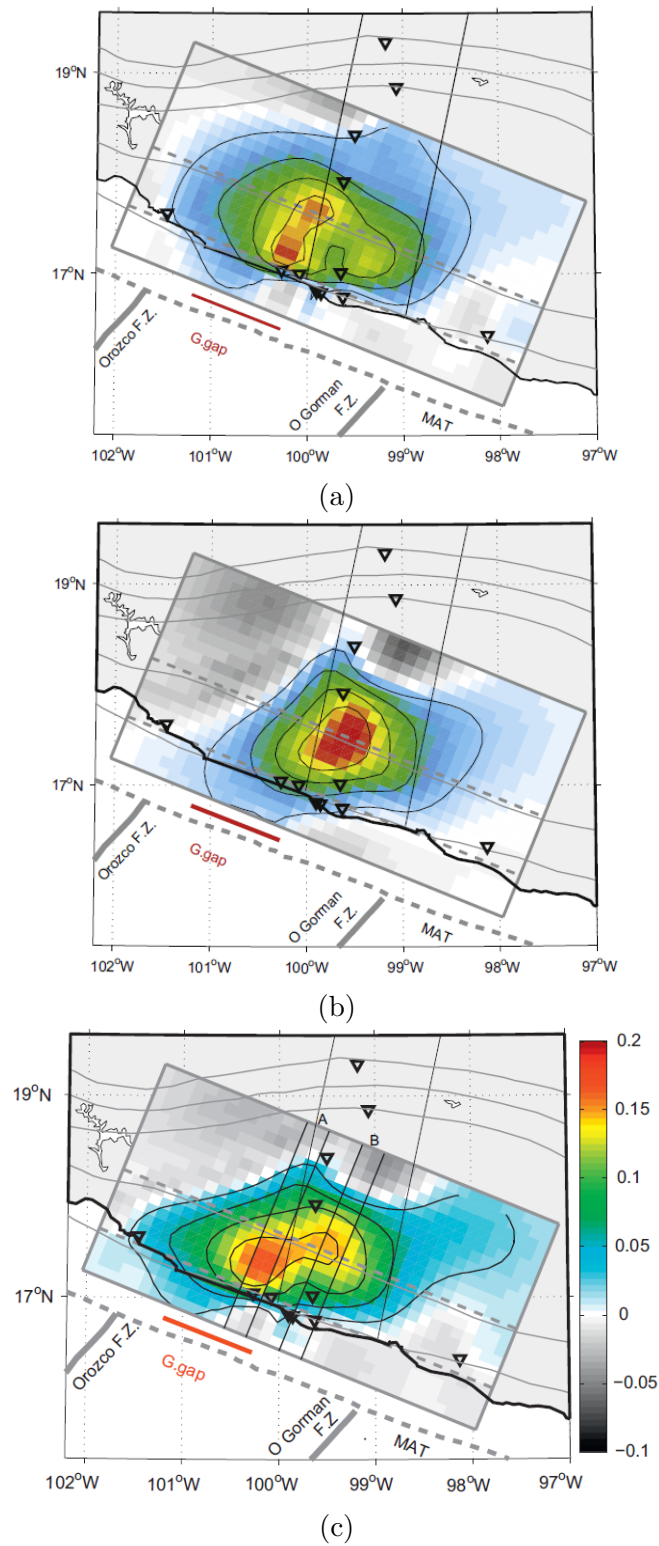


Figure 7: Slip model for the 2006 slow slip events in the Guerrero seismic gap inferred from (a) GPS measurement alone (b) InSAR measurements alone (c) joint minimisation of residual of both GPS and InSAR measurements (from [38]). GPS stations are represented by open black triangles and InSAR track by 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.

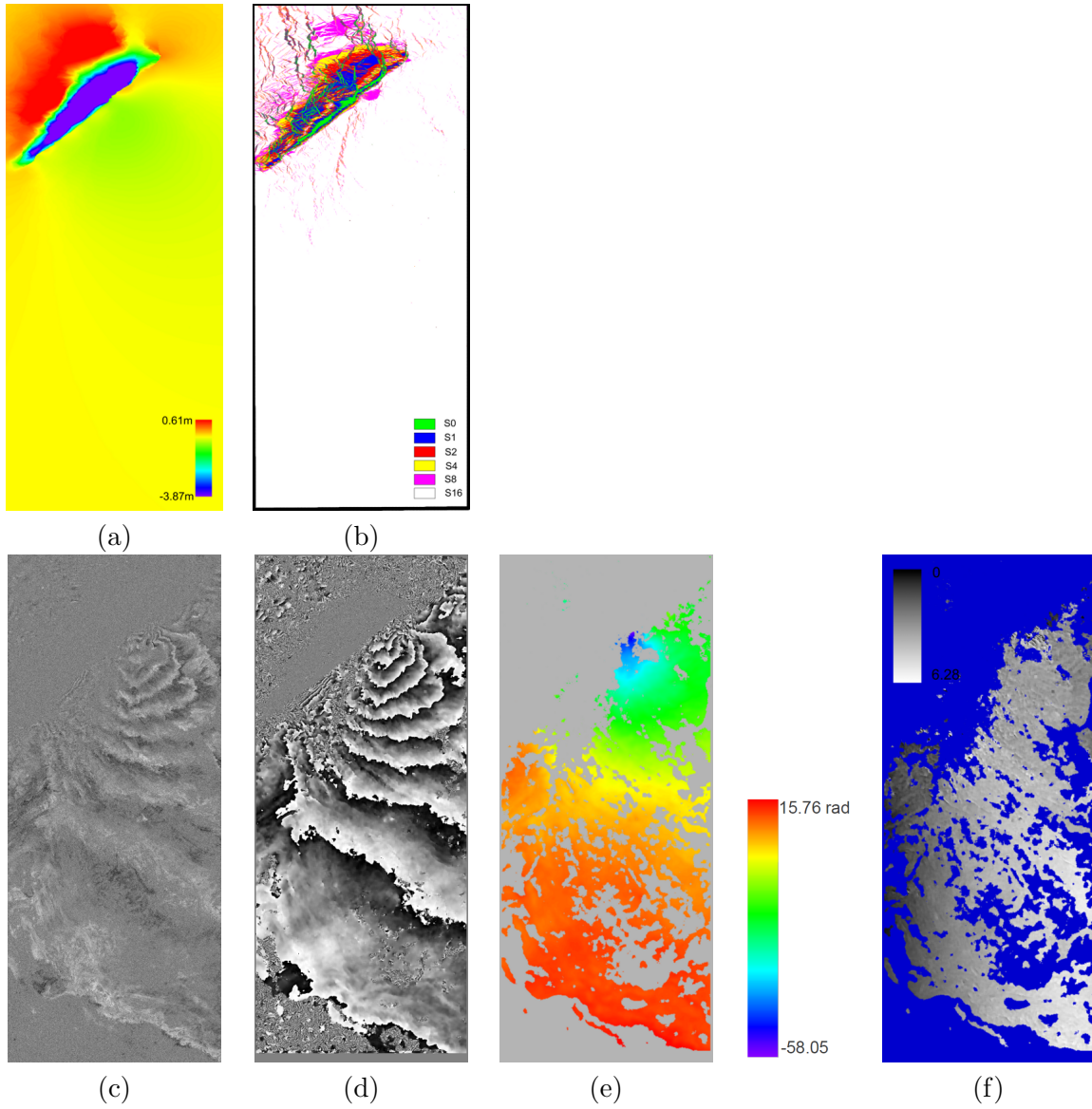


Figure 8: (a) A priori deformation model in LOS direction, negative value for displacement towards the satellite. (b) Scale image for phase gradient estimation deduced from the a priori deformation model. S_0 corresponding to the full resolution SLC image and S_n to the multi-looking image after a complex 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 ^a (km)	Strike (deg)	Dip (deg)	East ^b (km)	North ^b (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)

^aVertical depth of the fault top edge.

^bEast and North coordinates are in UTM-WGS84, zone 33, and refers to the center of the fault trace.

(a)

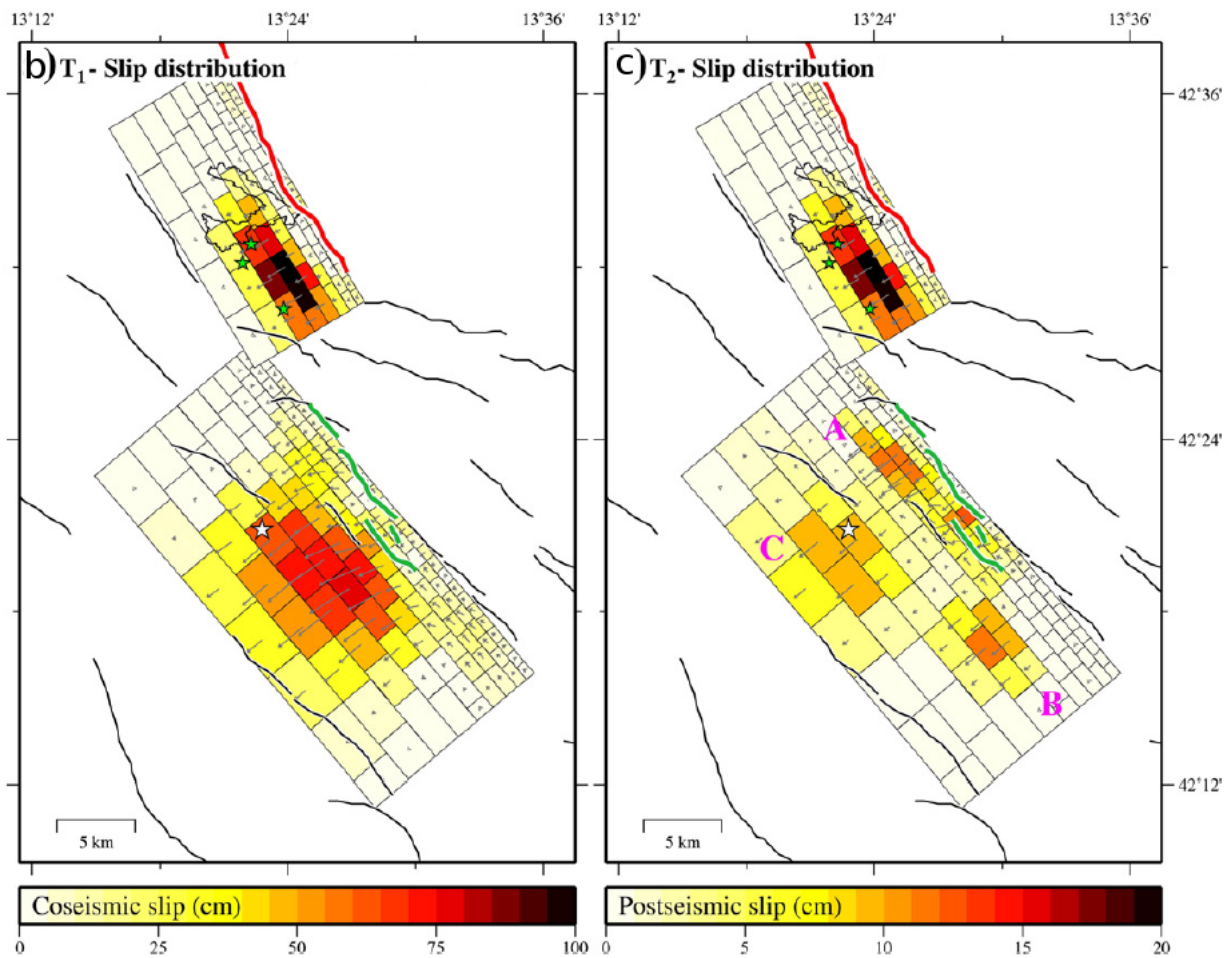


Figure 9: (a) Geometrical parameters of the Paganica fault estimated in [113] (b) Coseismic and (c) post-seismic slip distributions of the Paganica fault and the Campotosto fault using the Paganica fault geometry in (a) and the Campotosto fault geometry derived from geological mapping and InSAR, GPS 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.