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1 **Time-variable 3D ground displacements from High-Resolution Synthetic**  
2 **Aperture Radar (SAR). Application to La Valette landslide (South French Alps).**

3

4

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6

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12

13 **Abstract**

14 We apply an image correlation technique to multi-orbit and multi-temporal High-Resolution (HR) SAR  
15 data. Image correlation technique has the advantage of providing displacement maps in two  
16 directions; e.g. the Line of Sight direction (LoS) and the Azimuth direction. This information, derived  
17 from the two modes of data acquisition (ascending and descending), can be combined routinely to  
18 infer the three dimensional surface displacement field at different epochs. In this study, a methodology  
19 is developed to characterize the displacement pattern of the large La Valette landslide (South French  
20 Alps) using TerraSAR-X images acquired in 2010. The results allow mapping the dynamics of different  
21 units of the La Valette landslide at high spatial resolution. The study demonstrates the potential of this  
22 new application of High Resolution SAR image correlation technique for landslide ground surface  
23 deformation monitoring.

24

25 **Introduction**

26 Slope movements such as landslides are one of the most significant geo-hazards in terms of socio-  
27 economic costs. Displacement monitoring of unstable slopes is thus crucial for the prevention and the  
28 forecast. In areas where large landslides cannot be stabilized and may accelerate suddenly, remote  
29 monitoring is often the only solution for surveying and early-warning. The choice of an adequate  
30 monitoring system depends on several constraints such as the landslide type, the areal extension, the

31 range of observed velocity, the frequency of data acquisition, the desired accuracy and by the cost of  
32 data acquisition and processing. Techniques based on High Resolution (HR) Space-borne SAR could  
33 provide valuable information in terms of landslide monitoring. In this framework, the availability of HR  
34 SAR such as the German Space Agency (DLR) Terrasar-X (TSX) data with frequent repeat cycle (11  
35 days) represents an opportunity for constructing frequent landslide displacement maps in the  
36 perspective of an operational use.

37 The sub-pixel correlation technique is based on the measurement of sub-pixel offsets between SAR  
38 images acquired at different dates. The method is based on a local correlation analysis that can be  
39 performed in the Fourier domain (as is presented in the current study) or in the spatial domain (e.g.  
40 Delacourt et al., 2004). Once the SAR data are perfectly co-registered, lines and columns (e.g.  
41 azimuth and range directions) offsets between two SAR data are converted in surface displacement  
42 estimates (e.g. Michel & Avouac, 2002; de Michele et al., 2010). Typically, the precision of the  
43 technique can reach about 1/10 of a pixel or even more (e. g. Leprince et al., 2007) depending both on  
44 the characteristics of the data (acquisition geometry, changes that occurred between the acquisitions,  
45 instrumental noise) and the amplitude of ground displacement (e.g. notably its spatial wavelength with  
46 respect to the size of the correlation window). This technique has been successfully applied to optical  
47 and radar data for studying deformation patterns originated from earthquakes (e.g. Michel and  
48 Avouac, 2002; de Michele et al., 2010), glacier kinematics (e.g. Scambos et al., 1992; Wangenstein et  
49 al., 2006) and landslides (Delacourt et al., 2009; Travelletti et al., 2012a). However, in regions  
50 characterized by the presence of persistent cloud cover, passive sensor data have important  
51 limitations preventing the creation of reliable archives of images for long-term monitoring. Data from  
52 active sensors such as HR SAR amplitude can be an alternative to optical imagery. The primary  
53 interests of using such data are threefold. First, the SAR amplitude is little or even not affected by the  
54 cloud cover or the atmospheric disturbances compared to SAR interferometry (InSAR). Second, the  
55 backscatter amplitude is less affected by multi-temporal vegetation changes than the phase of the  
56 signal commonly used in InSAR. Third, SAR amplitude is not affected by signal saturation in the  
57 presence of high displacement gradient.

58 Ionospheric disturbances could, in specific cases (e.g. Quegan & Lamont, 1986), produce anomalous  
59 signatures on the azimuth offset estimations due to azimuth misregistration errors of the processed  
60 images. As the ionosphere is a dispersive medium for microwaves, such an effect mainly concerns the

61 radar data obtained by sensors based on longer wavelength (e.g. L-band sensors). It is thus assumed  
62 that results derived from X-band data are little disturbed by the ionosphere except for the geographic  
63 locations that are affected by very high Total Electron Content (such as the polar regions; Mattar &  
64 Gray, 2002). It has been shown that *a posteriori* comparison of several azimuth offset maps allows  
65 detecting and rejecting offset results affected by ionospheric disturbances (e.g. Raucoules & de  
66 Michele, 2010).

67 A further advantage of using SAR imagery is the high attitude control of the platform, which provides  
68 very similar geometrical conditions for image acquisitions (e.g perpendicular baselines generally  
69 shorter than few hundreds of metres). In such conditions, where the Base to Height ratio (B/H)  $\sim 10^{-3}$ ,  
70 the topographic contribution to the range offsets is rather moderate (for 1m pixel size, a 100 m height  
71 variation would correspond to about 0.1 pixel). By selecting smaller baselines, the topographic  
72 component can even be decreased (in the presence of steep relief, for instance) and in several cases,  
73 as the presented one, there is no need to correct the topographic component.

74 With this basis, the ability of TSX (as well as other HR SAR sensors) of providing amplitude images  
75 with resolution equivalent to optical remote sensing data ( $\sim 1\text{m}$ ) is of major interest. Given the high  
76 spatial resolution of the TSX data, displacements fields in the azimuth and range directions can be  
77 measured with an expected precision of about 0.1 m at different acquisition dates.

78 The objectives of this work are threefold. First, we intend to evaluate the capability of the SAR  
79 amplitude offset technique to obtain landslide displacement maps with TSX data. Second, we explore  
80 the possibility of combining offsets maps into time series using least-square approaches (Usai, 2003;  
81 Le Mouelic et al., 2005; Casu et al., 2011). Third, we intend to combine ascending and descending  
82 modes to retrieve the multi-temporal 3D surface displacement fields,. The study could be of particular  
83 interest for detecting changes in surface displacement rates (e.g. acceleration and deceleration) at  
84 high spatial resolution. This could help for the forecast of large movements. To reach the  
85 aforementioned goals, we have decided to plan the acquisitions of TSX Spotlight data (1m resolution)  
86 at La Valette landslide (South French Alps) during one year, from April 2010 to March 2011. This  
87 landslide is characterized by displacement rates of about a dam/yr (e.g. Colas & Locat, 1992;  
88 Travelletti et al., 2012b). Eight TSX Spotlight data in ascending mode and thirteen in descending  
89 mode have been acquired.

90

91 **Geological setting and history of the landslide**

92 The La Valette landslide is one of the largest and more complex slope movement in the South French  
93 Alps, and has been triggered in March 1982. The landslide features two styles of behaviors; a  
94 translational slide type with the development of a flow tongue in the medium and lower part, and a  
95 slump-type with the development of multiple rotational slides in the upper part at the main scarp. The  
96 landslide extends over a length of 2 km. It features a variable width ranging from 0.2 km in the lower  
97 and medium parts to 0.4 m in the upper part. The maximum depth, estimated by seismic and electrical  
98 resistivity tomography and geotechnical boreholes, varies from 25 m in the lower and middle parts  
99 (e.g. Travelletti et al., 2009; Hibert et al., 2012; Samyn et al., 2012) to 35 m in the upper part  
100 (Le Mignon, 2004; Travelletti et al., 2012b). The mean slope gradient is ca. 30° in the scarp area and  
101 ca. 20° in the translational slide area. The volume of the landslide is estimated at  $3.5 \cdot 10^6 \text{ m}^3$ .

102 The landslide affects a hill slope located uphill of the municipality of St-Pons (Alpes-de-Haute-  
103 Provence Department). It represents a significant threat for the 170 community housings located  
104 downhill (Le Mignon & Cojean, 2002). The occurrence of rapid mudflows triggered in the scarp area in  
105 the 1980s and 1990s has motivated the development of an early-warning system since 1991  
106 composed of benchmark topographical monitoring, optical and infra-red camera monitoring and the  
107 installation debris height detection sensors in the torrent, and the drainage of the lower part of the  
108 landslide.

109 The landslide exhibits a complex style of activity in space and time. It has developed first as a  
110 rotational slide affecting the Autapie sheet thrust in relation to a major fault system (Colas & Locat  
111 1993). The failed mass has progressively loaded the underlying black marls formation, and the  
112 landslide has progressed downhill by a series of rapid mudflows triggered in the marls such as in  
113 March 1982, April 1988, March 1989 and March 1992. The most important acceleration occurred in  
114 1988 when a mudflow of  $50.000 \text{ m}^3$  triggered at the elevation of 1400 m over a distance of ca. 500 m.  
115 For the moment, these mudflows did not generate a cascade mobilization of the entire landslide mass.  
116 The ground displacements are monitored permanently with topometric benchmarks since 1991  
117 (Squarzoni et al. 2005), differential dual-frequency GPS (Malet et al., 2012) and an extensometer  
118 since 2008. At regular periods the monitoring is performed also by digital correlation of terrestrial  
119 photos (Travelletti et al., 2012) and satellite radar interferometry (Squarzoni et al. 2003). Two main  
120 aspects can be pointed out from these past monitoring studies and from the observations by the local

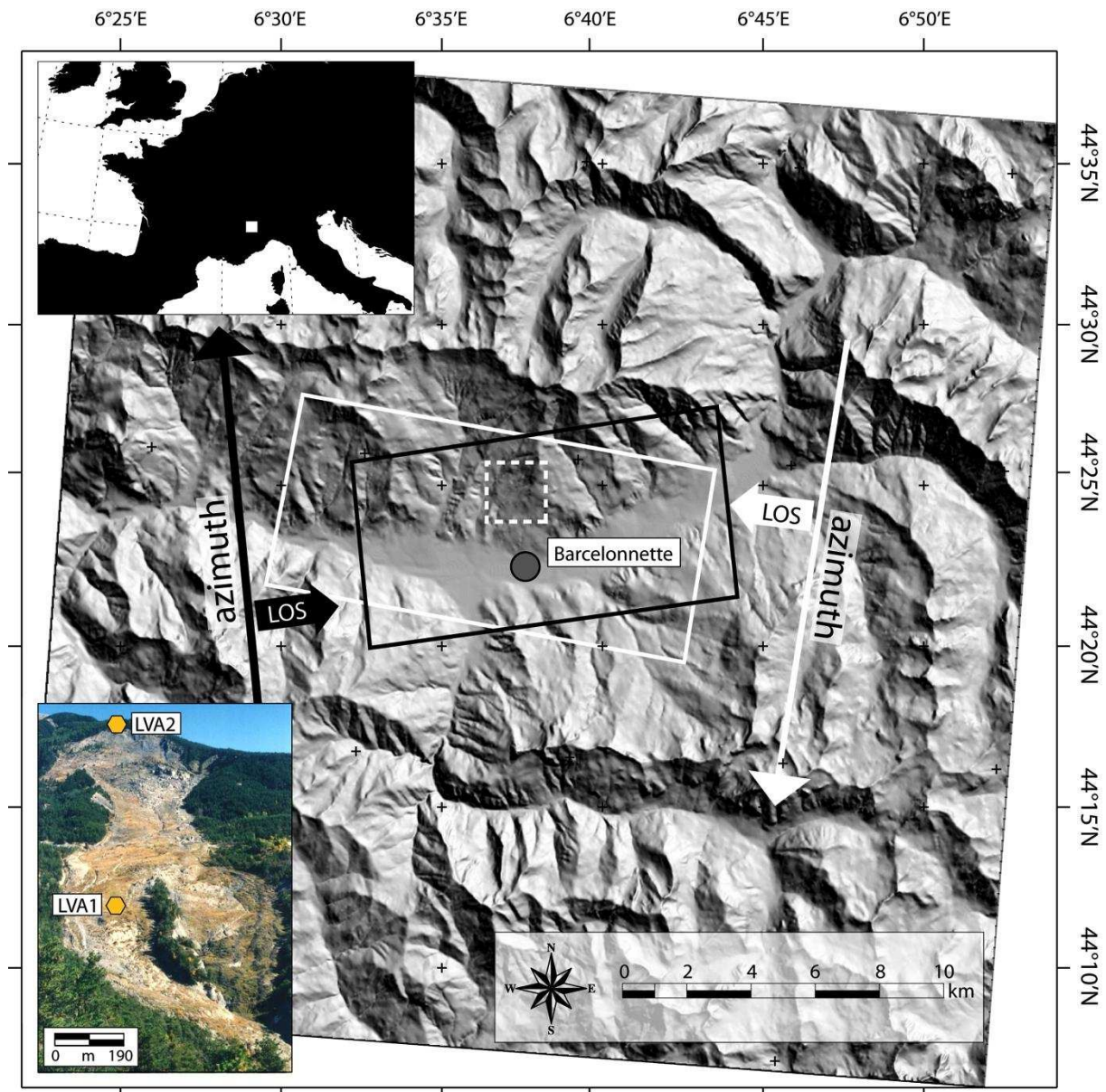
121 risk managers. First, they observed a decrease of velocity (from  $0.4 \text{ m.day}^{-1}$  to about  $0.01 \text{ m.day}^{-1}$ ) in  
122 the middle and lower part of the landslide caused by the local groundwater drawdown since the  
123 installation of a drainage system in the 1990s. Second, they pointed out an important activity of the  
124 upper part at the Soleil Boeuf crest since year 2000. This activity is characterized by a rapid  
125 retrogression of the main scarp towards the North-East and an enlargement of the landslide towards  
126 the North-West. In response to this worrying situation, the RTM Service has installed several  
127 additional benchmarks along profiles both in the unstable and stable parts of the Soleil-Boeuf crest to  
128 monitor the displacements in the crown area. Actually, an accumulation of material and a steepening  
129 of the slope are observed in the upper part because of the retrogression of the scarp (Travelletti et al.,  
130 2012b). Consequently, the possible hazard scenario consists in the untrained loading of underlying  
131 black marls formation and the triggering of new rapid and mobile mudflows.

132

### 133 **High resolution radar dataset**

134 The Table 1 lists the TSX spotlight images used for the analysis. The objective of the satellite  
135 programming was to obtain a sufficient amount of data to estimate the changes in displacement  
136 rates during the study period. Thus the image acquisition rate has been deliberately increased for the  
137 periods between March and June as changes in the displacement regime (due to possible changes in  
138 the sub-surface water circulation in spring) were expected.

139



140

141 Figure 1: The Barcelonnette area of interest in the South French Alps. The white dotted line  
 142 corresponds the location of the La Valette landslide and to the frame of Figures 2 and 3. The  
 143 extension of the TSX acquisition frames are indicated in white (descending mode) and black  
 144 (ascending mode). The bottom right terrestrial photograph presents the morphology of the landslide in  
 145 2009.

146

147 The ascending data set is incomplete due to failure in the data acquisition. However, the period  
 148 between April and November 2010 is globally well covered. We preferred to plan data acquisitions with  
 149 incidence angles of  $41^{\circ}.2$  (ascending mode) and  $49^{\circ}.3$  (descending mode) in order to minimize the  
 150 surface affected by lay-over and shadowing phenomena.

151  
152  
153  
154

Table 1. TerraSAR-X HR spotlight data acquired for the analysis.

| Month          | Ascending  | Descending |
|----------------|------------|------------|
| April 2010     | 2010-04-08 | 2010-04-04 |
| May 2010       | 2010-05-11 | 2010-05-18 |
|                | 2010-05-22 |            |
| June 2010      | 2010-06-02 | 2010-06-09 |
|                | 2010-06-13 | 2010-06-20 |
| July 2010      | 2010-07-05 | 2010-07-01 |
| August 2010    | 2010-08-07 |            |
| September 2010 |            |            |
| October 2010   |            | 2010-10-08 |
| November 2010  | 2010-11-03 | 2010-11-10 |
| December 2010  |            | 2010-12-13 |
| January 2011   |            | 2011-01-15 |
| February 2011  |            | 2011-02-06 |
| March 2011     |            | 2011-03-11 |
|                |            | 2011-03-22 |
| April 2011     |            | 2011-04-13 |

155  
156  
157  
158

## Methodology

### *Sub-pixel image correlation*

159 The objective is to estimate local changes in the position of elements at the ground surface by  
160 comparing two images acquired at different dates. The observed position change on the image is  
161 interpreted as displacement. The estimation of such offsets (both in azimuth and range directions) is  
162 obtained by local correlation processing on the image pair. The method applied to SAR amplitude  
163 images has been firstly described by Michel et al. (1999) and is today widely used in characterization  
164 of tectonic plate movement associated to earthquake (e.g. de Michele et al. 2010 or Pathier et al.  
165



166 2005). For this study, the image correlator implemented in the GAMMA software has been used along  
167 with the “offset-tracking” procedure (Werner et al., 2005). This kind of technique is known to provide  
168 offsets estimation with a precision up to 1/20-1/10 pixel (and thus sometimes named sub-pixel  
169 correlation). Bamler & Eineder (2005) proposed a theoretical estimate of the error standard deviation  
170 for offsets derived from incoherent correlation methods (Eq. 1):

$$171 \quad \sigma \sim \sqrt{\frac{3}{N} \frac{\sqrt{1-\gamma^2}}{\pi\gamma}} \quad (1)$$

172 where  $\gamma$  is the coherence value and N is the number of pixels within the estimation window.

173  
174 The GAMMA software offset-tracking procedure provides SNR estimations for each offset by  
175 comparing the height of the correlation peak relative to the average level of the correlation function.  
176 They are indicators of the confidence in offsets estimates. The average of resulting SNR values on the  
177 landslide is higher than 11 suggesting high coherence levels. The connection between SNR values  
178 produced by the correlation tool and coherence is not straightforward (Wegmuller, personal  
179 communication) but, we such high SNR values, we can expect coherence values ranging at least  
180 between 0.8 and 0.9. Using estimation window sizes (N) of 32 pixels, the resulting expected standard  
181 deviation based on Eq. 1 is about 0.01 pixels. This value is both smaller than the accuracy generally  
182 admitted for such techniques and smaller than the ground measurements further presented. The  
183 formula of Eq.1 should be seen as an estimator of an upper boundary of the performance rather than  
184 an actual accuracy estimator.

185 In a first step, all the images of each time serie (ascending and descending) were co-registered on the  
186 first (reference) image of each series using a two degrees polynomial adjustment model derived from  
187 local correlation estimations. This procedure allows correcting the global shifts between the images  
188 that can be due to slight differences in the acquisition conditions. Then, the local offsets can be  
189 estimated using smaller windows (32 pixels in our case) and on denser grids (spacing of 16 pixels ).

190 Considering the low values of the selected perpendicular baselines (between 1 m and 200 m) and the  
191 rather high displacement rate ( $\sim 1 \text{ m.month}^{-1}$ ), it is assumed that the range offsets due to local  
192 topography can be neglected with respect to ground displacement. In addition, stacking (as carried  
193 out) of offset maps obtained with different values of perpendicular baselines should partially  
194 compensate this topographic bias as it averages topographic components resulting from baselines  
195 with different signs and absolute values: we can suppose that with a large data set, the mean of the

196 perpendicular baselines associated to the different offset maps should much smaller than the maximal  
197 value (e.g. 200m in our case).

198

199 *Multi-temporal processing:*

200 The multi-temporal approach used for obtaining the evolution of the deformation is based on  
201 algorithms initially designed for deriving interferometric Time Series from a set of differential  
202 unwrapped interferograms (Berardino et al., 2002; Usai, 2003; Le Mouelic et al., 2005). Considering N  
203 differential interferograms (phase  $[\Phi_i]$ ) obtained from M SAR images, the phase ( $[\varphi_j]$ ) time series to  
204 be processed has to verify the following relation:

205

$$206 \begin{bmatrix} \Phi_1 \\ \Phi_2 \\ \Phi_3 \\ \dots \\ \Phi_N \end{bmatrix} = A \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \dots \\ \varphi_M \end{bmatrix} \quad (2)$$

207

208 where A is a matrix containing -1, 0 or 1 value according to the generated differential interferograms.  
209 Such over-determined linear system can be solved using a least-square solution. Once re-processed  
210 in Time Series (with respect to the first SAR acquisition), one can compute surface velocity maps on  
211 sub-intervals of the time-span covered by the SAR data set.

212 In SAR interferometry, the phase related to displacement rates can be obtained by linear regression of  
213  $[\varphi_j]$  with respect to the corresponding images acquisition dates on the whole image acquisition time-  
214 span or on shorter time intervals of interest.

215 For the present analysis, the previous algorithm was adapted to correlograms by replacing the phase  
216 ( $[\Phi_i]$ ) values by pixel offsets values in the azimuth direction  $[az_i]$  or in the range direction  $[r_i]$ . We thus  
217 derive times series of surface displacement in 2 directions. Once the azimuth and range time series  
218 are obtained, the deformation rates are calculated along range and azimuth over sub-period by linear  
219 regression. This methodology has been already applied on the C-band ENVISAT Advanced SAR  
220 (ASAR) data to a volcanic areas characterized by large deformation dynamics (Casu et al., 2011).  
221 Here, its applicability for HR X-band SAR monitoring of an active landslide is demonstrated.

222 A first estimate of the precision of the estimated displacement rates consists in dividing the offset  
223 standard deviation error by  $\sqrt{N}$  (where N is the number of independent offset maps) and by  $\langle \Delta T \rangle$

224 (which is the average time span corresponding to the stacked offset maps). For example, in the  
225 ascending mode, only seven offset maps could be considered as independent (the other maps could  
226 be recomputed as linear combinations of these seven maps) with an average time span of 88 days. To  
227 convert the accuracy of individual correlograms (expressed in m) to displacement rates (expressed in  
228  $\text{m.yr}^{-1}$ ), we therefore multiply it by about 1.56. If we assume 0.1 m precision on offset estimates the  
229 resulting precision on the velocity would be about  $15 \text{ cm.yr}^{-1}$ .

230

### 231 *3D displacement estimates*

232

233 In order to produce 3D maps of the ground surface deformation, the combination of ascending and  
234 descending mode of observation is carried out based on the algorithm presented in de Michele et al.  
235 (2010). The basic idea is to retrieve the 3D deformation from four displacement rate components (1  
236 azimuth and 1 LoS directions for the ascending and descending modes) obtained by the correlation  
237 computation for each point of the processing grid, affected by a certain quality (the SNR value  
238 associated with each offset measurement can be an indicator of the measurement precision). To  
239 construct the three component vectors representing the displacements, a least square formulation is  
240 proposed:

241 Let  $\mathbf{d}$  be the vector constructed with the four measured values (e.g. two azimuth and two LoS  
242 components of the displacement rate) for a given point of the processing grid:

243

$$\mathbf{d} = \begin{pmatrix} az_{asc} \\ az_{desc} \\ los_{asc} \\ los_{desc} \end{pmatrix}$$

244

245

246 Let  $\mathbf{A}$ , be a matrix containing the unitary vectors corresponding to the four directions along which the  
247 offsets are measured:

248

$$\mathbf{A} = \begin{pmatrix} u_{az-asc} \\ u_{az-desc} \\ u_{los-asc} \\ u_{los-desc} \end{pmatrix}$$

249

250

251 The three components displacement vector  $\mathbf{v}$  is linked to  $\mathbf{d}$  by:

$$\mathbf{d} = \mathbf{A} \mathbf{v} \tag{3}$$

253

254 The vector  $\mathbf{v}$  can thus be derived from  $\mathbf{d}$  by inverting Eq. 2 using a weighted (by the SNR values) least  
 255 squares formulation. Considering both the unitary vectors used for the test site/sensor (and therefore  
 256 the  $\mathbf{A}$  matrix form) and the estimation of the standard deviation of the error on  $\mathbf{d}$  resulting from Eq. 1,  
 257 the standard deviation error on  $\mathbf{v}$  derived from a pair of displacement rate maps (ascending and  
 258 descending) is of the same order than the input rates.

259 The hypothesis behind this approach is that the 3D surface displacement rate that controls the  
 260 measured pixel offsets is sufficiently similar among the epochs corresponding to the ascending and  
 261 descending offsets maps to be merged. In an ideal situation, the ascending and descending time  
 262 sampling should be identical (e.g. the same acquisition date), and displacement time series could be  
 263 directly derived. In our case, the processing was performed with displacement rates that are less  
 264 affected by time-span differences between correlograms and do not need rescaling.

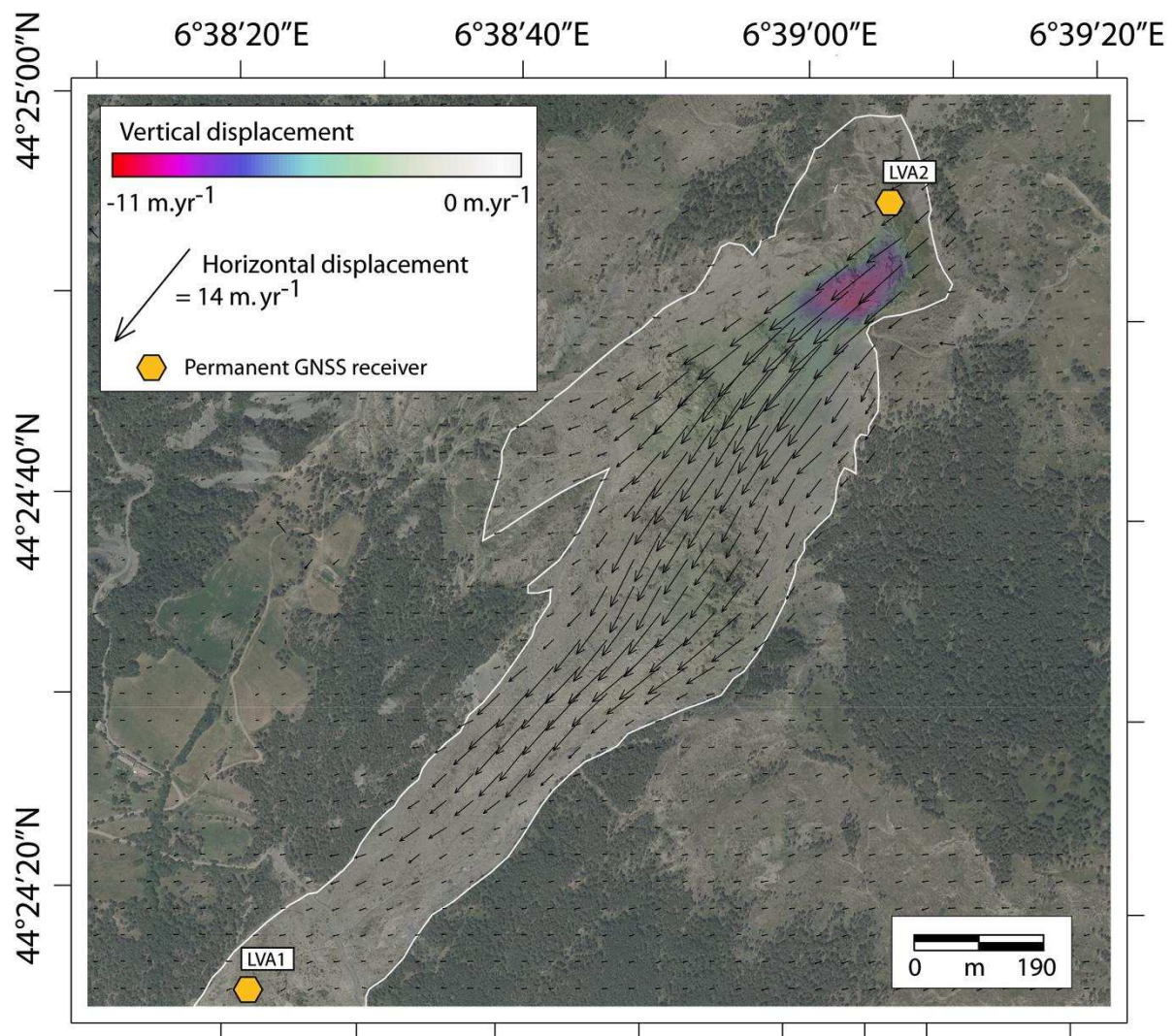
265

266 **Results: kinematic analysis of the La Valette landslide**

267

268 Figures 2 presents the estimated 3D displacement map for the complete investigated period (April  
 269 2010 – November 2010). The map indicates that the most active part of the landslide is the upper part,  
 270 and that the displacement rates decrease downslope. The maximum measured horizontal  
 271 displacement rate is  $14 \text{ m.yr}^{-1}$ , while the maximum measured vertical velocity is  $11 \text{ m.yr}^{-1}$ .

272



273

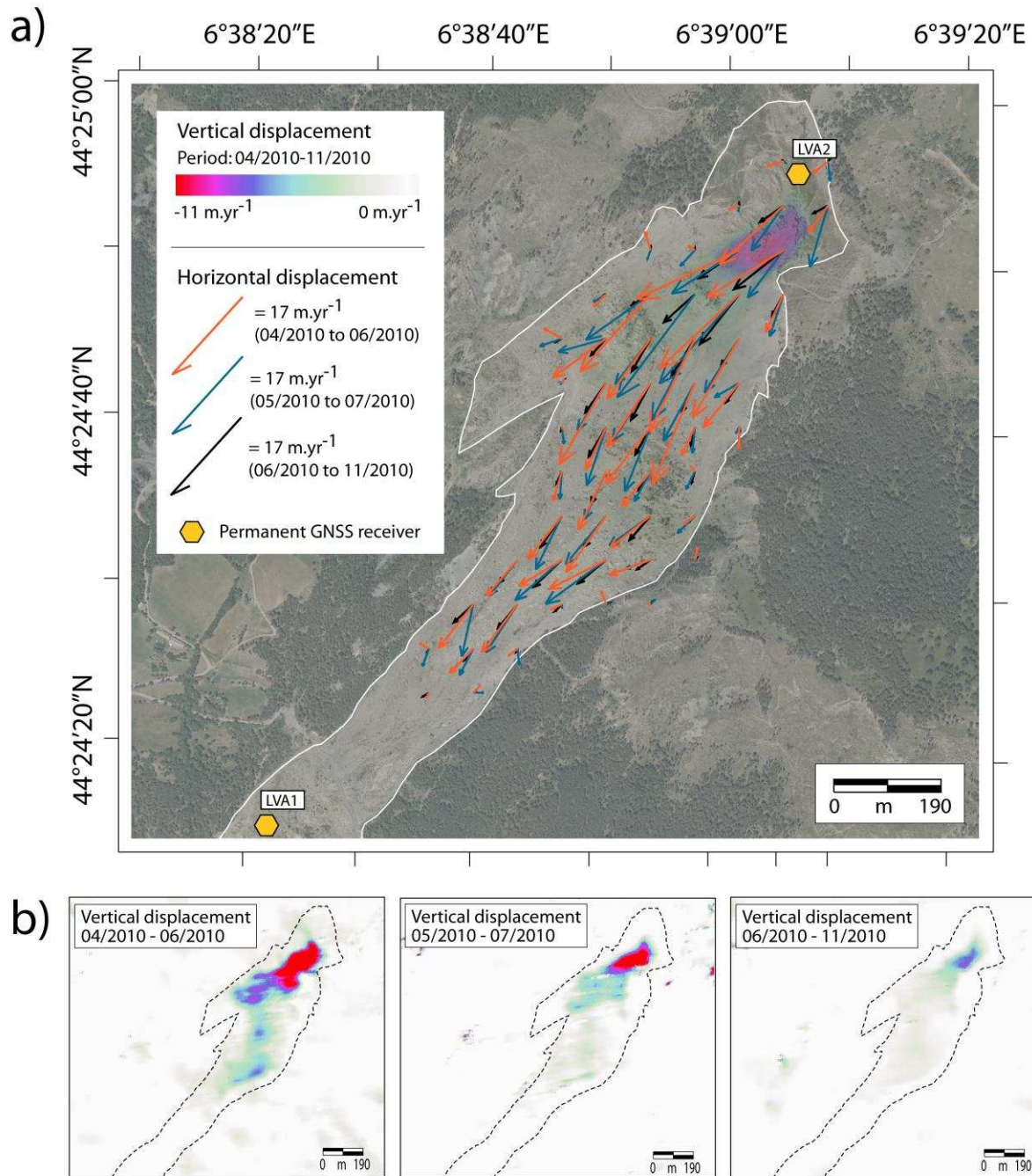
274 Figure 2: 3D displacement map of the La Valette landslide for the April–November 2010 period. Color represents  
 275 the vertical displacements and arrows the horizontal displacements.

276

277 For identifying temporal variations in the behavior of the landslide, displacement rate maps were  
 278 produced for three periods (April–June 2010, May–July 2010, July–November 2010; Fig. 3). We  
 279 produced two maps for the period April–July, because it corresponds to the period of major potential  
 280 changes in the kinematic regime. Noteworthy is the fact that – for this period - the offset estimation in  
 281 descending mode is only based on three acquisitions for each sub-period. We can notice that the  
 282 landslide displacement field is measured with high spatial details, and that spatial resolution of the  
 283 results is fine enough to characterize the spatial variability of the displacement rates.

284 The three displacement rates maps show temporal changes in the velocity pattern, with higher  
 285 displacements rates during the April–July period (up to about 20 m.yr<sup>-1</sup>) and lower displacement rates

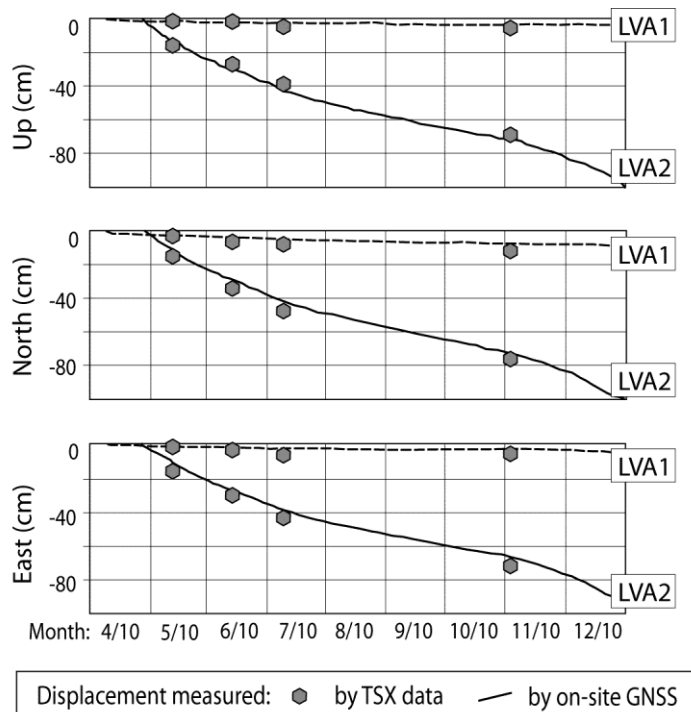
286 during the July-November period. Noteworthy, the upper part of the landslide seems to be globally  
 287 affected by higher horizontal displacement rates between April and June 2010 than during the May-  
 288 July period whereas the lower part seems to slightly accelerate between May and July.  
 289



290  
 291 Figure 3: 3D displacement map on the La Valette landslide for the three sub-periods. a) Color represents the  
 292 vertical displacements for the whole data set period, and arrows the horizontal displacement field per sub-period.  
 293 b) vertical displacement for each period (same color scale).  
 294

295 We can notice that the descending mode data set covers a period of about five months longer than the  
 296 ascending one. In the present analysis, this supplementary data was not used.

297



298

299 Figure 4: GNSS displacement time series at locations LVA1 (downslope) and LVA2 (upslope) for the period April-  
 300 December 2010 and associated cumulated displacements measured in May, June, July and November 2010 by  
 301 the TSX data for the three component of the displacement (Up, North, East). The displacements are cumulated  
 302 from 8 April 2010 for the GNSS LVA1, and from 27 April 2010 for the GNSS LVA2.

303

304 Further, the accuracy of the displacement rates measured from the TSX data is quantified through a  
 305 comparison (at the two locations LVA1 and LVA2; Figs. 2 & 3) with the displacements measured on-  
 306 site by two permanent dual-frequency GNSS receivers (Trimble NetR9) of the French National  
 307 Landslide Observatory OMIV (<http://omiv.unistra.fr/>). The GNSS observations (acquired at a frequency  
 308 of 30s for 24h sessions) are processed daily using the GAMIT/GLOBK software. To compute the  
 309 cumulated displacement from the TSX data based on maps at different time-spans but having time  
 310 overlaps between them (e.g., for descending mode, time spans are  $t_0-t_3$ ,  $t_1-t_5$ ,  $t_4-t_7$ , where  $t_0, \dots, t_7$  are  
 311 the TSX acquisition dates on the full period of interest chronologically ordered. The periods  $t_1-t_3$  and  
 312  $t_5-t_7$ , therefore correspond to overlaps. The following procedure has been used. The displacements are  
 313 cumulated starting from the date of the first TSX image acquisition (e.g.  $t_0$  is 8 April 2010). The

314 cumulated displacement at the starting date of the second time span is estimated using the velocity  
315 estimation of the first time span (e.g. for descending mode data,  $d(t_1)=d(t_0)+V_0(t_1-t_0)$  where  $V_0$  is the  
316 first velocity estimate). By iterating to the three displacement rate maps (and taking  $t_0$  as reference  
317 date), we were able to compute four estimates of the cumulated displacement to be compared to the  
318 GNSS observations. Figure 4 presents the GNSS displacement time series obtained for the period  
319 April-December 2010 and the corresponding amount of cumulated displacement measured from the  
320 TSX data. For the three components (Up, North, East), the accuracy of the TSX displacements is in  
321 the range of  $\pm 12$  cm for the North and East components and  $\pm 8$  cm for the Up component in  
322 comparison to the GNSS cumulated displacements. The landslide kinematic pattern is therefore well  
323 identified by the TSX data.

324

### 325 **Conclusions and perspectives**

326 This work demonstrates the interest of sub-pixel image correlation techniques applied to series of HR  
327 X-band SAR images for mapping and quantifying landslide displacement patterns. The characteristics  
328 of these data in terms of spatial resolution, geometry, repetitiveness and low dependence to the  
329 weather conditions are very suitable for landslide monitoring. It appears as a performing alternative to  
330 optical HR image correlation whose data can be hampered by atmospheric conditions.

331 In the case of the La Valette landslide, the displacements observed for the period 2010-2011 are well  
332 depicted and are in agreement with the ground-based displacement observations. Displacement rates  
333 of up to  $16 \text{ m.yr}^{-1}$  are mapped and changes in the kinematic regime are detected with a decrease of  
334 the displacement rates between the months of July to November.

335 The procedure for deriving such maps has revealed to be simple (and therefore easily automatable)  
336 and robust (no biases were detected during the processing). Noteworthy is the fact that the  
337 displacement rates are much higher than the expected accuracy with the reduced data set (seven  
338 images in ascending mode): in fact, the image acquisition was planned according to a *priori*  
339 knowledge on the foreseen displacement. Therefore, for landslides characterized by a different  
340 kinematic regime, a different data acquisition strategy should be used.

341 In particular, for faster landslides (with displacement rates of  $\text{m.month}^{-1}$ ), the high repetitiveness of the  
342 current HR X-band space-borne sensors (TSX or Cosmo-Skymed) would allow to adjust (by  
343 increasing the acquisition rate) the inter-acquisition time span to higher displacement rates. As well,



344 the accuracy of the method is also sufficient for monitoring slower landslides (with displacement rates  
345 of  $\text{dm.yr}^{-1}$ ) if longer time spans (e.g. years and more) are used. The proposed monitoring technique  
346 can therefore be applied to a wide range of landslide types.

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