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# 1 3D displacement field of the 2015 $M_w$ 8.3 Illapel 2 earthquake (Chile) from across- and along-track 3 Sentinel-1 TOPS interferometry

R. Grandin<sup>1</sup>, E. Klein<sup>2</sup>, M. Métois<sup>3</sup>, and C. Vigny<sup>2</sup>

## Abstract

4 Wide-swath imaging has become a standard acquisition mode for radar missions aiming at  
5 applying SAR interferometry at global scale with enhanced revisit frequency. Increased swath  
6 width, compared to classical Stripmap imaging mode, is achieved at the expense of azimuthal  
7 resolution. This makes along-track displacements, and subsequently north-south displacements,  
8 difficult to measure using conventional split-beam (multiple-aperture) InSAR or cross-correlation  
9 techniques. Alternatively, we show here that the along-track component of ground motion can  
10 be deduced from the double-difference between backward- and forward-looking interferograms  
11 within regions of burst overlap. “Burst overlap interferometry” takes advantage of the large  
12 squint angle diversity of Sentinel-1 ( $\sim 1^\circ$ ) to achieve sub-decimeter accuracy on the along-track  
13 component of ground motion. We demonstrate the efficiency of this method using Sentinel-1 data  
14 covering the 2015  $M_w$ 8.3 Illapel earthquake (Chile) for which we retrieve the full 3D displacement  
15 field and validate it against observations from a dense network of GPS sensors.

## 1. Introduction

16 Since the pioneering contributions of the 1990s, monitoring of large-scale ground motion  
17 using Interferometric Synthetic Aperture Radar (InSAR) has made spectacular progress.  
18 Thanks to improvement of the phased array technology, advances in orbitography, in-  
19 creasing computational power as well as the launch of multiple civilian SAR missions  
20 since the 2000s, a broad range of natural and anthropogenic processes can be routinely  
21 monitored today [see *Simons and Rosen*, 2007, for a recent review]. Among these pro-  
22 cesses, the InSAR technique has proved extremely valuable in mapping the displacement

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<sup>1</sup>Institut de Physique du Globe de Paris,  
Sorbonne Paris Cité, Université Paris  
Diderot, UMR 7154 CNRS, Paris, France.

<sup>2</sup>Laboratoire de Géologie, École Normale  
Supérieure, UMR 8538 CNRS, Paris,  
France.

<sup>3</sup>Laboratoire de Géologie de Lyon: Terre,  
Planètes, Environnement (LGLTPE), École  
Normale Supérieure de Lyon, Université  
Claude Bernard, UMR 5276 CNRS, Lyon,  
France.

23 field induced by large plate-boundary events, such as earthquakes or magmatic intrusions,  
24 especially in geographical areas where GPS measurements are lacking [e.g. *Peltzer et al.*,  
25 1999; *Grandin et al.*, 2009].

26 One limitation of InSAR is that only the component of deformation in the sensor line-of-  
27 sight (LOS), i.e. the across-track component, can be resolved. Acquisitions from ascending  
28 and descending passes are usually combined to provide two different viewing geometries.  
29 Even so, due to the near-polar orbit of SAR satellites, resolution on the north-south com-  
30 ponent remains poor [*Wright et al.*, 2004].

31 Therefore, in complement to conventional InSAR, a number of signal processing tech-  
32 niques have been proposed to retrieve the horizontal component of displacement parallel  
33 to the satellite track. These methods, which rely either on the amplitude (incoherent  
34 cross-correlation, also termed offset tracking [*Michel et al.*, 1999; *Fialko et al.*, 2001]) or  
35 on the phase (multiple-aperture InSAR, also termed split-beam interferometry [*Bechor*  
36 *and Zebker*, 2006; *Barbot et al.*, 2008; *Jung et al.*, 2009]), typically allow for resolving  
37 displacements exceeding  $\sim 10\%$  of the azimuth pixel size. Hence, for classical Stripmap  
38 mode (azimuth pixel size of the order of a few meters), displacements greater than a few  
39 decimeters can be resolved. As a consequence, the resolution that can be achieved with  
40 such methods restricts their applicability to the study of intermediate to large earthquakes  
41 ( $M_w > 6$ ).

42 Recent advances in SAR technology and processing have allowed for the emergence of a  
43 new generation of sensors entirely dedicated to wide-swath imaging. Wide-swath modes  
44 allow for global mapping with an increased revisit frequency, as exemplified by the two

45 satellites Sentinel-1 and ALOS-2, respectively operating TOPS and ScanSAR as stan-  
46 dard acquisition modes. Unfortunately, the increase of the swath breadth by a factor  
47 3 to 5 comes at the expense of reduced azimuthal resolution by an equivalent factor.  
48 Trading azimuth resolution for increased swath width, hence shortened revisit interval, is  
49 arguably advantageous for studying large-scale tectonic deformation, whether coseismic,  
50 postseismic or interseismic [e.g. *Grandin et al.*, 2015]. On the other hand, split-beam and  
51 offset-tracking techniques become limited to sensing along-track displacement exceeding  
52  $\sim 50$  cm, hence restricting their potential usefulness [*Jung et al.*, 2014].

53 Alternatively, we propose here to take advantage of wide-swath burst-modes, especially  
54 TOPS, by applying along-track interferometry in regions where successive bursts over-  
55 lap in the azimuth direction (Figure 1). This technique, whose original objective was  
56 to improve the coregistration of a slave image against its master [*Scheiber and Moreira*,  
57 2000; *Prats-Iraola et al.*, 2012], is used here for another purpose. We show that burst-  
58 overlap interferometry allows for resolving subtle motion along the azimuth direction. The  
59 technique is particularly efficient for Sentinel-1 TOPS data, as beam steering in azimuth  
60 provides an increased squint angle diversity within burst overlaps, hence a better resolu-  
61 tion on horizontal motion compared to split-beam interferometry applied to Stripmap or  
62 ScanSAR images.

63 In this paper, focusing on the case study of the Illapel earthquake (Chile, 16 September  
64 2015,  $M_w 8.3$ ), we use Sentinel-1 wide-swath data to retrieve the full 3D surface displace-  
65 ment field. Independent measurements acquired by a continuous GPS network allow for  
66 validating the method and estimating its uncertainty.

## 2. Method

### 2.1. TOPS along-track interferometry

67 Sentinel-1 is the first SAR mission to implement the TOPS mode as a standard acqui-  
68 sition mode for interferometry (Figure 1) [*Torres et al.*, 2012]. Similar to ScanSAR, an  
69 extended swath is achieved in TOPS mode by electronically steering the beam in eleva-  
70 tion periodically so as to cover several adjacent sub-swaths (three in the case of Sentinel-1  
71 “Interferometric Wide-swath” mode, IW) [*De Zan and Guarnieri*, 2006]. Each sub-swath  
72 is imaged in a succession of bursts, typically consisting of a thousand pulses. Because a  
73 given ground pixel is only illuminated during a fraction of the standard Stripmap-mode  
74 synthetic aperture duration, the resulting azimuth bandwidth of burst-modes, hence the  
75 achievable azimuth resolution, is decreased accordingly. On the other hand, the range  
76 properties of the images (bandwidth and resolution) are unchanged.

77 In ScanSAR mode, the beam angle with respect to zero-Doppler direction (also termed  
78 “squint” angle) is held fixed. In TOPS mode, a steady drift of the squint angle, from  
79 backward to forward, is introduced over the course of the burst transmission in order  
80 to broaden the size of the illuminated area in the azimuth direction (Figure 1a). As a  
81 result, TOPS achieves improved image quality both in terms of phase (reduced azimuth  
82 ambiguity) and amplitude (decreased “scaloping” effect) [*Meta et al.*, 2008]. Nevertheless,  
83 both ScanSAR and TOPS require accurate burst synchronization to warrant sufficient  
84 azimuth spectral overlap for interferometry [*Holzner and Bamler*, 2002].

85 In wide-swath mode, a small overlap region occurs between the bursts to ensure that  
86 the final processed image will be devoid of any gap (Figure 1a). In these “burst overlap  
87 regions”, ground pixels are observed twice from two slightly different angles, or equiva-

88 lently with two different Doppler centroid frequencies (Figure 1b). In ScanSAR mode, this  
89 azimuth angular separation is limited by beam aperture, which usually does not exceed  
90  $0.25^\circ$ . In TOPS mode, the Doppler centroid difference is much greater, as a direct conse-  
91 quence of the squinted view introduced by beam steering in azimuth. For Sentinel-1, the  
92 difference in squint angle is typically of the order of  $1^\circ$ , with overlap regions corresponding  
93 to  $\sim 10\%$  of the burst length.

94 When processing TOPS data for interferometry, it is possible to take advantage of the  
95 slight difference in squint angles within overlap regions in order to retrieve the horizontal  
96 component of ground motion parallel to the satellite track. Akin to Multiple Aperture  
97 InSAR (MAI), a double difference of the phase within overlap regions is computed as  
98 follows (Figure 1b) : (1) calculate the interferogram using only the phase deduced from  
99 the forward view  $\Delta\Phi_{\text{fw}}$ , (2) calculate the interferogram in the backward view  $\Delta\Phi_{\text{bw}}$ ,  
100 (3) compute the difference between forward-looking and backward-looking interferograms  
101  $\Delta\Phi_{\text{ovl}} = \Delta\Phi_{\text{fw}} - \Delta\Phi_{\text{bw}}$  (see Appendix A for details). This technique will be thereafter  
102 referred to as “burst-overlap interferometry”.

103 The final double-difference interferogram corresponds to the temporal variation of the  
104 difference in slant range from two slightly different squint angles. In observation scenarios  
105 devoid of any ground motion, the double-difference phase  $\Delta\Phi_{\text{ovl}}$  only includes the effect  
106 of slight errors in coregistration between the master and slave images [*Scheiber and Mor-*  
107 *eira, 2000*]. Hence, this procedure is commonly used to refine coregistration during TOPS  
108 InSAR processing, a method known as “enhanced spectral diversity” (ESD) [e.g. *Prats-*  
109 *Iraola et al., 2012*]. On the other hand, when significant ground motion has occurred

110 between two acquisitions, phase jumps across burst boundaries in TOPS interferograms  
111 are diagnostic of horizontal ground motion along the satellite track [e.g. *De Zan et al.*,  
112 2014; *González et al.*, 2015]. The double-difference procedure allows for directly measur-  
113 ing this phase difference on a pixelwise basis within overlap regions. Topographic and  
114 tropospheric contributions are largely cancelled by the double-difference, which results in  
115 better phase quality than in the across-track interferogram.

## 2.2. Data set

116 In order to map the 3D displacement field of the 2015  $M_w$ 8.3 Illapel earthquake, we  
117 use SAR data acquired by Sentinel-1A in IW TOPS mode. Images before the earthquake  
118 were acquired on 08/24/2015 and 08/26/2015 for the descending and ascending passes,  
119 respectively. Post-earthquakes acquisitions were performed on 09/17/2015 (+11 hours  
120 after quake) and 09/19/2015 (+3 days). Interferograms are computed using the method  
121 of *Grandin* [2015], starting from Level 1 Single Look Complex (SLC) products distributed  
122 by ESA. Precise orbits (<https://qc.sentinel1.eo.esa.int>) and SRTM 1-arcsecond DEM are  
123 used for orbital and topographic corrections. Azimuth phase deramping is calculated  
124 using precise coregistration derived from pixel offsets, and further refined by means of  
125 ESD within burst overlaps [*Prats-Iraola et al.*, 2012; *Grandin*, 2015]. Interferograms are  
126 multilooked by a factor 12 in range and 4 in azimuth, resulting in a ground pixel of  
127  $\sim 60$  m. Unwrapping is performed using the cut-tree algorithm [*Goldstein et al.*, 1988]  
128 and corrected manually when necessary.

129 Azimuth displacements are retrieved using the burst overlap interferometry technique  
130 (see Appendix A for details). Flat-Earth, topographic correction and multilooking are



131 applied to the forward and backward interferograms prior to computation of the double-  
132 difference interferogram [De Zan *et al.*, 2015]. A spatial coherence mask with a threshold  
133 of 0.4 is applied to discard unreliable phase values. Pixels are low-pass filtered using 1 km-  
134 wide maximum likelihood estimator. Flattening of interferograms is performed by fitting  
135 a bilinear polynomial surface on the difference between, on one hand, GPS measurements  
136 from a local geodetic network [Ruiz *et al.*, 2016] projected onto the appropriate unit vector  
137 (along- or across-track) and, on the other hand, the nearest pixel in the interferogram.  
138 Finally, interpolation by a Laplacian operator is applied in order to fill the gaps between  
139 the bursts.

### 3. Results and discussion

#### 3.1. Along-track InSAR

140 Across-track interferograms show a maximum line-of-sight displacement of  $\pm 150$  cm,  
141 picturing the semi-circular fringe pattern typical of subduction earthquakes in Chile [e.g.  
142 Pritchard *et al.*, 2006] (Figure 2, top). Displacement occurs exclusively away from the  
143 satellite in the descending pass and toward the satellite in the ascending pass. This  
144 is consistent with seaward motion reaching  $\gtrsim 1$  m in the coastal area combined with  
145 moderate vertical displacement (within the range  $\pm 50$  cm) due to the offshore earthquake  
146 location. Furthermore, we notice that peak displacement in the descending across-track  
147 interferogram occurs  $\sim 30$  km to the north of the peak in the ascending interferogram.  
148 This suggests that displacement vectors experience substantial rotation, either about a  
149 vertical or horizontal axis, at  $31^\circ\text{S}$ . However, as a result of the acquisition geometry of  
150 InSAR, the vertical and north-south components cannot be distinguished in the across-

151 track interferograms. Hence, all the details of the actual ground displacement field cannot  
152 be restituted solely from these two across-track interferograms.

153 In contrast, along-track interferograms show a more complex displacement pattern with  
154 both negative and positive displacements peaking at  $\pm 40$  cm (Figure 2, bottom). Dis-  
155 placements vary smoothly over distances exceeding  $\sim 20$  km, which is twice the distance  
156 separating two consecutive burst overlap regions. This demonstrates that interpolation  
157 between burst overlaps did not lead to significant aliasing of the displacement field. Due  
158 to the near-polar orbit, along-track interferograms are strongly sensitive to the north-  
159 south component of motion, whereas across-track interferograms are least sensitive to  
160 this component. In the particular case of the Illapel earthquake, horizontal displacement  
161 occurs mostly trench-normal, i.e. with an azimuth of  $N260^\circ$ . The ascending along-track  
162 interferogram, which is nearly insensitive to the trench-normal displacement, shows a sign  
163 reversal consistent with trench-parallel, southward motion in the north, shifting to trench-  
164 parallel, northward motion in the south. In the along-track descending interferogram,  
165 peak displacement occurs in the northern part, at  $30.7^\circ S$ , which is also compatible with  
166 a significant component of southward displacement in that area. These trench-parallel  
167 displacements are consistent with a radial, centripetal pattern of horizontal displacement  
168 vectors pointing toward the centroid of the earthquake. This effect is most pronounced  
169 toward the north and south edges of the main slip area, a feature that can be used to  
170 refine source models of the earthquake.

### 3.2. Comparison with GPS data

171 Projection of GPS displacements in the line-of-sight and along the direction of the  
172 satellite track allows for validating the accuracy of the interferometric products for across-  
173 track and along-track interferograms, respectively (Figure 3). This comparison yields a  
174 root mean square (RMS) residual of 7.8 cm and 7.0 cm for ascending and descending  
175 across-track interferograms, respectively. This residual is close to the fluctuations of 1–2  
176 fringes usually observed within across-track C-band interferograms in north-central Chile  
177 [Ducret, 2013]. Linear regression between across-track InSAR and GPS projected in the  
178 LOS shows an excellent mutual agreement, with a coefficient of correlation above 0.98  
179 and a proportionality factor within 10% of unity.

180 For the along-track component, the RMS equals 3.5 cm and 5.9 cm for ascending and  
181 descending geometries, respectively. This sub-decimeteric misfit is in agreement with theo-  
182 retical expectations (see Appendix A for details). The slope of the linear regression is close  
183 to 0.8 in either case. This value departs from unity, which may be due to bias on the slope  
184 determination imparted by misfits on the few points located in the area of maximum dis-  
185 placement along the coast. In particular, maximum misfit in the descending along-track  
186 interferogram chiefly occurs at site EMAT, which has recorded a peak westward displace-  
187 ment of 220 cm. Due to instrument malfunction, the GPS-derived coseismic displacement  
188 at EMAT includes 2 days of post-seismic displacement that are largely absent in the  
189 descending interferogram (post-quake image acquired +11 hours after mainshock). Yet,  
190 significant post-seismic motion, likely resulting from rapid afterslip, is evident in time-  
191 series from cGPS sites located along the coast (6–7 cm eastward displacement is recorded

192 in the 24 hours following the mainshock at sites CMBA and PFRJ). Therefore, significant  
193 residual post-seismic motion may explain part of the misfit at EMAT.

### 3.3. 3D displacement field

194 The 3D displacement field can be deduced from the four components of ground motion  
195 sensed by across- and along-track interferograms on both ascending and descending geome-  
196 tries (Figure 4). This is achieved by solving an overdetermined linear system involving 3  
197 unknowns and 4 equations, consisting in the LOS and azimuth displacements in ascending  
198 and descending passes. The agreement between GPS- and InSAR-derived displacements  
199 is below 3 cm for the vertical and east-west components, which are best resolved. The  
200 RMS is only slightly higher (5.3 cm) for the north-south component, which would other-  
201 wise remain unresolved by standard across-track InSAR. The rotation of displacement  
202 vectors along the shoreline is well reproduced, as well as the shift from coastal subsidence  
203 to coastal uplift at  $31.1^{\circ}\text{S}$ . This change is consistent with vertical motion recorded by  
204 intertidal fauna [Ruiz *et al.*, 2016]. Coseismic slip extending below the continent near the  
205 epicenter, and remaining offshore further to the north, explains this feature [Ruiz *et al.*,  
206 2016; Melgar *et al.*, 2016].

## 4. Conclusion

207 This study demonstrates the capability of the Sentinel-1 system, operating in wide-  
208 swath TOPS mode, to capture the full 3D displacement field of large subduction earth-  
209 quakes at sub-decimeter accuracy for all three components. In the particular case of  
210 an earthquake where horizontal displacement is predominantly east-west, and displace-  
211 ments vary smoothly, such as large subduction earthquakes in South America, Japan or

212 Cascadia, Sentinel-1 allows for quickly and exhaustively mapping surface displacement.  
 213 For shallower and/or smaller earthquakes, the method may partly miss the variability  
 214 of the displacement over length scales smaller than 10 km, as along-track interferometry  
 215 is only practicable in burst overlap regions. Nevertheless, within burst overlap regions,  
 216 the along-track component of displacement is available at dense spatial sampling, and is  
 217 not influenced by tropospheric phase screen. This is similar to having a densely-spaced  
 218 campaign GPS transect at disposal, which already represents a substantial improvement.  
 219 Between these sparse burst overlap regions, conventional split-beam and/or offset-tracking  
 220 can provide a background measurement, albeit with less accuracy [*Jung et al.*, 2014;  
 221 *Scheiber et al.*, 2015]. Future development of agile SAR antennas and innovative acquisi-  
 222 tion modes, such as Bi-Directional SAR or SuperSAR, should provide two simultaneous  
 223 squinted views with continuous spatial sampling [*Mittermayer et al.*, 2013; *Jung et al.*,  
 224 2015], thereby truly extending the InSAR technique towards full 3D capability.

## Appendix A: Along-track ground displacement from TOPS interferometry

### A1. Principle of “burst overlap interferometry”

In along-track double-difference interferograms, the azimuth displacement  $\Delta x_{az}$  is pro-  
 portional to the azimuth time shift induced by target displacement along the azimuth  
 time axis  $\Delta t_{az}$  (or equally the azimuth misregistration) and to the difference in instanta-  
 neous Doppler frequency  $\Delta f_{ovl}$  between forward and backward view in the overlap region  
 [*Scheiber and Moreira*, 2000]:

$$\Delta\Phi_{ovl} = 2\pi\Delta f_{ovl}\Delta t_{az} = 2\pi\Delta f_{ovl}\frac{\Delta x_{az}}{\Delta x_s}\Delta t_s \quad (\text{A1})$$

where  $\Delta t_s$  is the azimuth sampling and  $\Delta x_s$  is the azimuth pixel size. In TOPS wide-swath mode, the frequency difference  $\Delta f_{\text{ovl}}$  is the product of the effective Doppler rate  $K_t$  and the duration of a full TOPS cycle  $T_{\text{cycle}}$  [Prats-Iraola et al., 2012]:

$$\Delta f_{\text{ovl}} = |K_t| T_{\text{cycle}} \quad (\text{A2})$$

The effective Doppler rate  $K_t$  results from the combination of the classical Doppler rate induced by platform motion  $K_a$  and the supplemental effect  $K_s$  induced by beam steering at a rate  $k_\Psi$  from the aft to the fore [De Zan and Guarnieri, 2006]:

$$K_t = \frac{K_a K_s}{K_a - K_s} \quad ; \quad K_a = -\frac{2v_s^2}{\lambda R_o} \quad ; \quad K_s \approx \frac{2v_s}{\lambda} k_\Psi \quad (\text{A3})$$

The same result can be deduced equivalently by considering the difference between line-of-sight (LOS) vectors for the two observation directions available in burst overlaps. The azimuth displacement is the projection of ground motion  $\vec{u}_{\text{displ}}$  onto the difference, within the overlap region, between the LOS vectors  $\vec{k}_{\text{fw}}$  and  $\vec{k}_{\text{bw}}$  of the forward interferogram and the backward interferogram, respectively (Figure 1b) :

$$\begin{aligned} \Delta \Phi_{\text{ovl}} = (\Delta \Phi_{\text{fw}} - \Delta \Phi_{\text{bw}}) &= \frac{4\pi}{\lambda} \vec{u}_{\text{displ}} \cdot (\vec{k}_{\text{fw}} - \vec{k}_{\text{bw}}) \\ &= \frac{4\pi}{\lambda} \Delta x_{\text{az}} \cdot \|\vec{j}_{\text{diff}}\| \end{aligned} \quad (\text{A4})$$

$$\text{with} \quad : \quad \vec{j}_{\text{diff}} = \vec{k}_{\text{fw}} - \vec{k}_{\text{bw}} \approx \Delta \Psi_{\text{ovl}} \cdot \vec{j}_{\text{along-track}} \quad (\text{A5})$$

where  $\vec{j}_{\text{along-track}}$  is a horizontal unit vector parallel to the satellite track. In TOPS mode, the squint angle difference  $\Delta \Psi_{\text{ovl}}$  between two consecutive overlaps for a given sub-swath can be deduced from the beam steering rate  $k_\Psi$  and the time separation between overlaps  $\Delta \eta_{\text{ovl}}$ :

$$\Delta \Psi_{\text{ovl}} = \Delta \eta_{\text{ovl}} k_\Psi \quad (\text{A6})$$

225 Typical numerical values of the above parameters for Sentinel-1 TOPS IW mode are pro-  
 226 vided in Table A1. Ultimately, the along-track displacement  $\Delta x_{az}$  (in cm) is obtained by  
 227 multiplying the double-difference phase  $\Delta\Phi_{ovl}$  (in radian) by a factor  $\sim 21 - 25$  cm/rad,  
 228 meaning that a full along-track fringe represents an along-track displacement of  $\sim 130$  cm  
 229 (for comparison, the radian-to-cm conversion factor equals  $\sim 0.44$  cm/rad for the  $\sim 2.8$  cm  
 230 across-track fringe).

## A2. Uncertainty assessment

From a signal processing point-of-view, the theoretical accuracy achieved by the double-difference interferogram in burst overlaps is given by the error standard deviation [Bamler and Eineder, 2005; Prats-Iraola et al., 2012] :

$$\sigma_{ovl} = \frac{1}{2\pi\Delta f_{ovl}} \frac{1}{\sqrt{N}} \frac{\sqrt{1-\gamma^2}}{\gamma} \frac{1}{\Delta t_s}, \quad (\text{A7})$$

here provided in units of resolution elements. In this expression,  $N$  is the number of pixels used in the spatial averaging,  $\gamma$  is the coherence and  $\Delta f_{ovl}$  is the spectral separation in the overlap region ( $\sim 4$  kHz for Sentinel IW). As shown in Figure A1, the expected accuracy strongly depends on the number of independent pixels used in the averaging, but less so on the coherence. In case of a uniform shift across the whole burst overlap region (i.e. no deformation),  $N$  may exceed a million pixels, so that an accuracy better than 0.1 cm can be reached. However, the accuracy decreases to 0.3–1 cm if displacement changes over distances of the order of 1 km, and up to 10 cm for 100 m posting in adverse coherence conditions. These estimates are in rough agreement with the residual fit to the GPS measured for the Illapel earthquake data set (RMS=3–5 cm, Section 3.2), which corresponds to relatively good coherence conditions ( $\gamma > 0.5$ ). For comparison, the standard devia-

tions from Coherent cross-correlation (CCC) [*Bamler and Eineder, 2005; De Zan, 2011*] and Incoherent (amplitude) cross-correlation (ICC) [*De Zan, 2014*] are, respectively :

$$\sigma_{ICC} = \sqrt{\frac{3}{2N} \frac{\sqrt{1-\gamma^2}}{\pi\gamma}} \quad ; \quad \sigma_{CCC} = \sqrt{\frac{3}{10N} \frac{\sqrt{2+5\gamma^2-7\gamma^4}}{\pi\gamma^2}} \quad (\text{A8})$$

231 For a given number of averaged pixels, the performance of the present method is better,  
232 by one order of magnitude, than that of ICC and CCC (Figure A1).

233 From a practical point of view, the double-difference along-track phase is not contami-  
234 nated by atmospheric phase screen, which is the main source of error for multi-temporal  
235 InSAR [e.g. *Zebker et al., 1997; Hanssen, 2001*]. Nevertheless, along-track InSAR being  
236 a relative measurement, it can be affected by long-spatial-wavelength nuisance stemming  
237 from residual large-scale misregistration due to geometric approximations and/or orbit er-  
238 rors. This effect translates locally into a bias that may reach several centimeters. This bias  
239 can be mitigated by adjustment of a planar or higher order polynomial trend in distant  
240 regions unaffected by the tectonic signal, or accounted for as an unknown during source  
241 modeling. Alternatively, external data, such as GPS, can be used to provide a reference.  
242 Interpolation between burst overlaps can also lead to aliasing of the displacement field.  
243 The induced errors depend on the smallest spatial wavelength of the deformation. In par-  
244 ticular, a complex displacement field (e.g. induced by shallow faulting) will significantly  
245 jeopardize the validity of the interpolation.

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247 The Sentinel-1 data used for this study are provided by ESA / Copernicus. Interfero-  
248 metric processing was carried out using a modified version of ROIPAC software [*Rosen*  
249 *et al., 2004*]. Most figures were designed and some processing steps (filtering, interpola-



tion) were performed with help of GMT software [Wessel and Smith, 1991]. The GPS  
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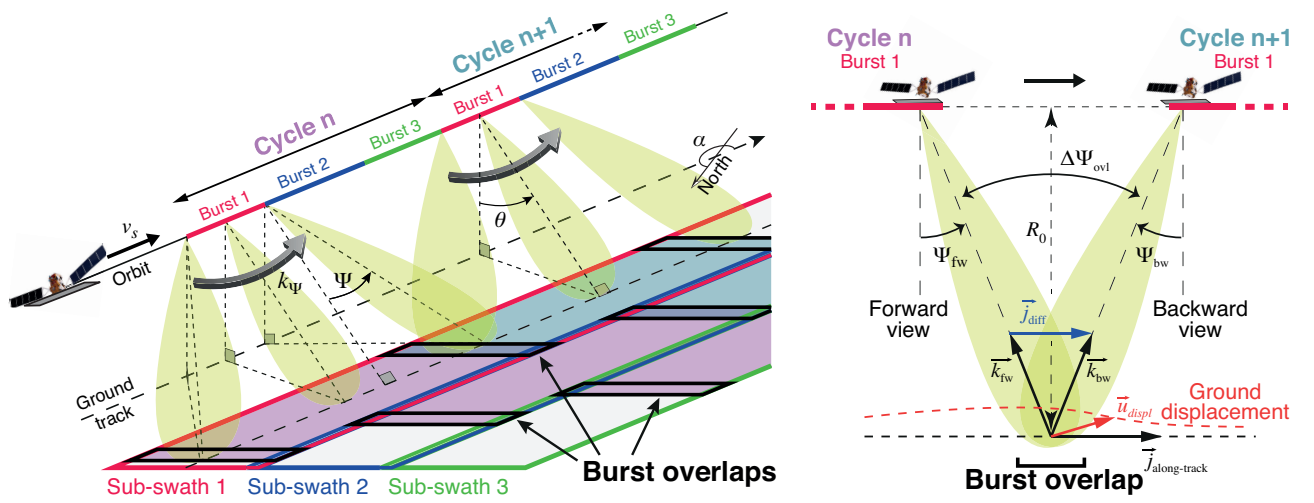
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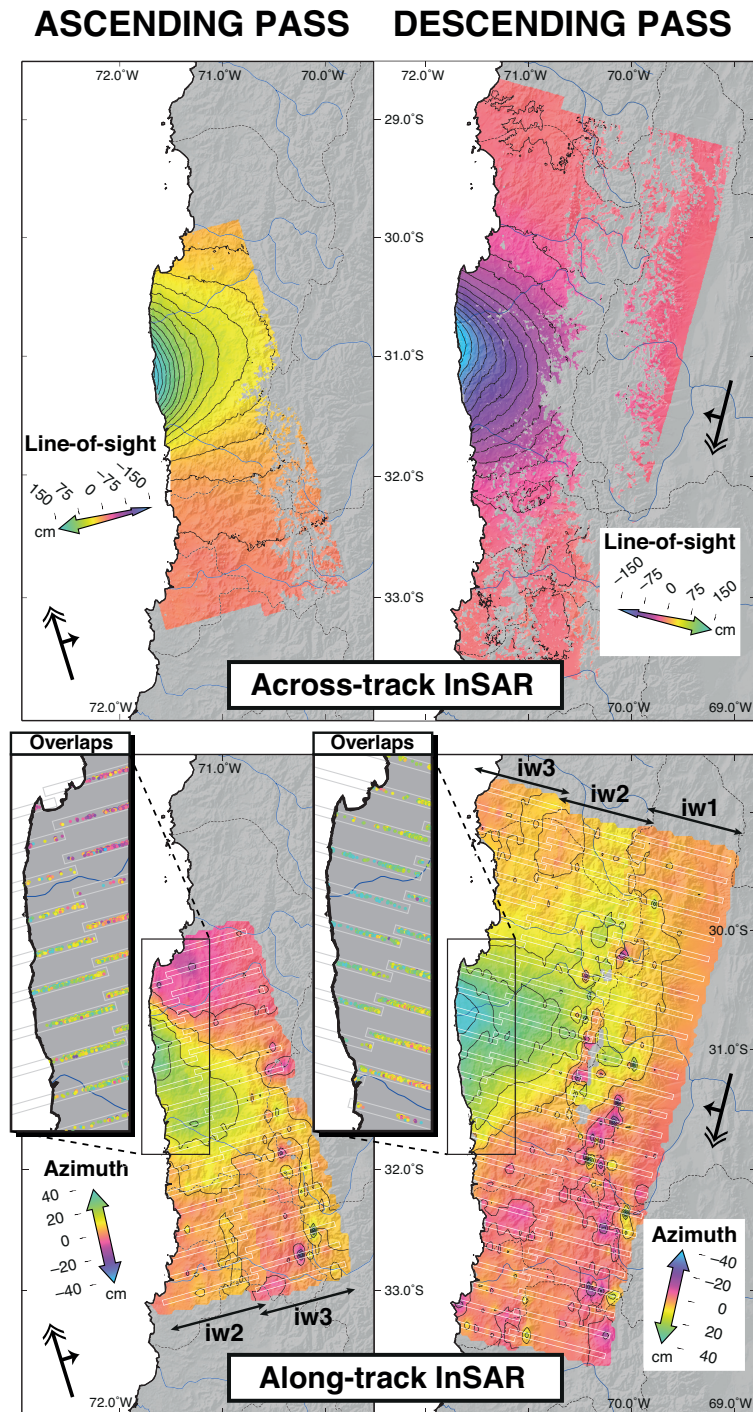
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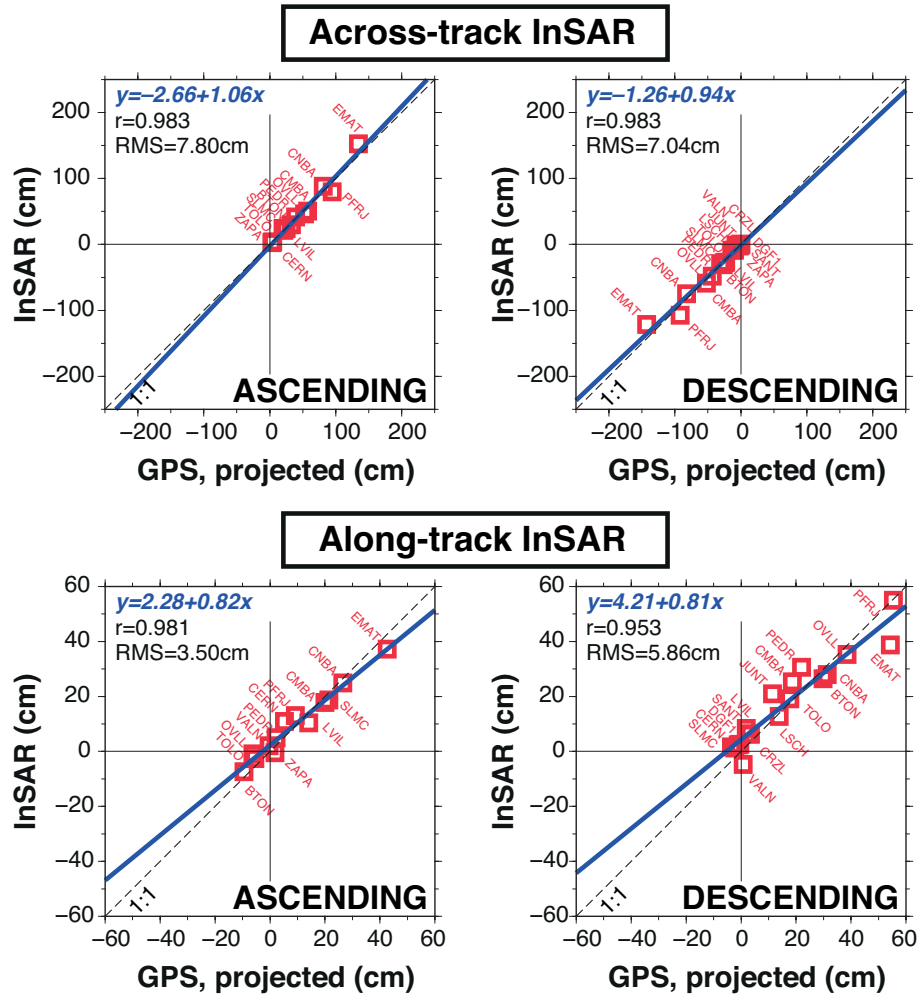
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**Figure 1.** Left: principle of TOPS imaging mode. Right: squint angle diversity in burst overlap regions.

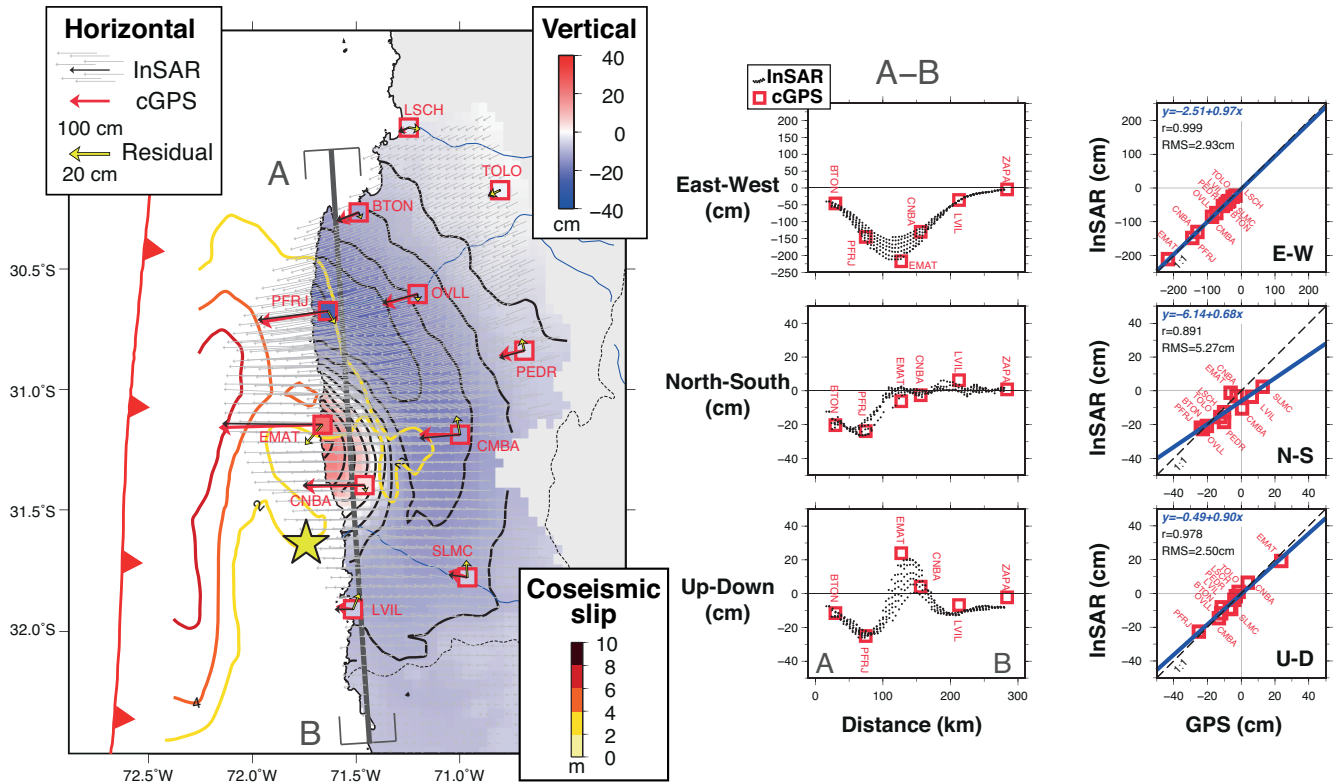


**Figure 2.** Across-track (top) and along-track (bottom) displacement field from Sentinel-1 InSAR. Note the different color scaling for across-track and along-track InSAR. The left and right panels correspond to ascending and descending passes, respectively. Double headed arrow shows direction of flight of the platform. White rectangles in bottom panels indicate regions of burst overlaps. The along-track displacement field was filtered and interpolated between regions

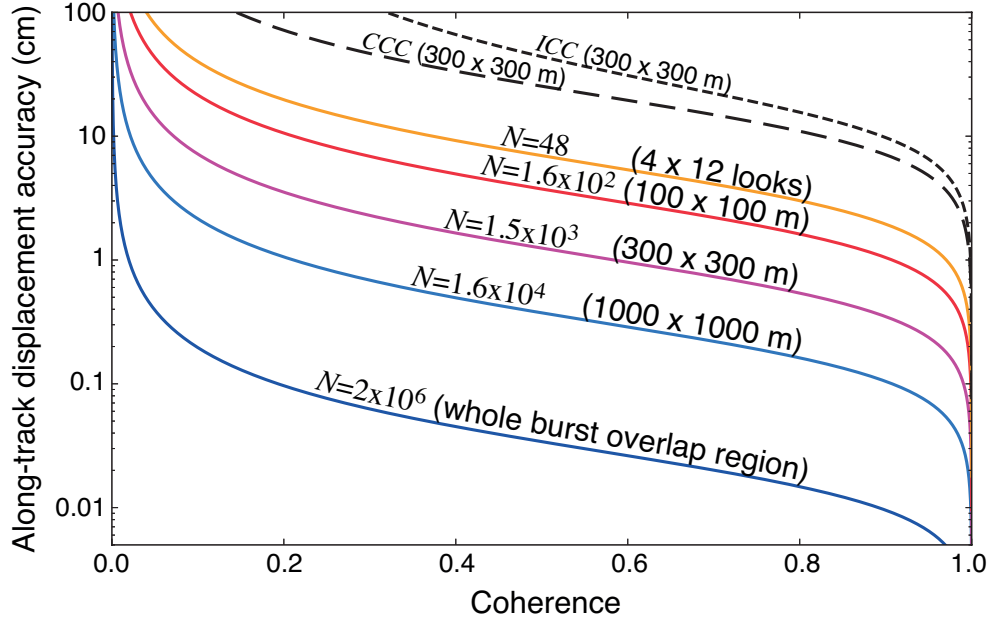


**Figure 3.** Linear regression between GPS and (top) across-track InSAR or (bottom) along-track InSAR. Left panels are for the ascending pass, right panels for the descending pass (same ordering as in Figure 2). Note the different scaling for across-track and along-track InSAR.





**Figure 4.** Left: 3D surface displacement reconstructed from Sentinel-1 InSAR. Red arrows show displacement at continuous GPS sites (cGPS), while color fill in red squares interior represents the vertical component of displacement from GPS [Ruiz et al., 2016]. Black arrows show displacement deduced from Sentinel-1 InSAR at locations of GPS benchmarks. Residuals are shown in yellow, with enhanced scaling. Grey arrows show horizontal displacement sampled on a regular grid. The colored grid in the background shows the vertical component of displacement on the same regular grid, with contours at 5 cm interval overlaid. Coseismic slip contours from USGS are shown for comparison ([http://earthquake.usgs.gov/earthquakes/eventpage/us20003k7a#scientific\\_finitefault](http://earthquake.usgs.gov/earthquakes/eventpage/us20003k7a#scientific_finitefault)). Center: transect showing comparison between Sentinel-1 InSAR and GPS. Location of the profile is shown in left panel. Top row: east-west component; middle row: north-south component; bottom row: vertical component. Sign convention is right-handed ENU. Note the different scaling for the east-west component. Right: linear regression between Sentinel-1 InSAR and GPS displacements at GPS sites.



**Figure A1.** Theoretical accuracy of the along-track displacement achieved by Sentinel-1 burst-overlap interferometry, as a function of coherence  $\gamma$ , for an azimuth pixel size  $\Delta x_s = 14$  m (color lines, Equation A7). Several cases are distinguished, depending on the number of full-resolution pixels  $N$  used for the averaging. The accuracy of coherent and incoherent cross-correlation techniques (respectively CCC and ICC) at  $300 \times 300$  m posting is shown for comparison (black dashed lines, Equation A8).

**Table A1.** Parameters of Sentinel-1 IW data used in this study (descending pair)

Parameter		1	2	3
Sub-swath				
Range <sup>a</sup>	$R_o$	829 km	879 km	933 km
Incidence angle <sup>a</sup>	$\theta$	34°	39°	44°
Antenna steering rate	$k_\Psi$	1.59 deg.s <sup>-1</sup>	0.98 deg.s <sup>-1</sup>	1.40 deg.s <sup>-1</sup>
Time separation between overlaps	$\Delta\eta_{ovl}$	0.80 s	0.96 s	0.82 s
Squint difference in overlap region	$\Delta\Psi_{ovl}$	1.28°	0.94°	1.15°
Doppler rate due to platform motion <sup>a</sup>	$K_a$	-2260 Hz	-2131 Hz	-2008 Hz
Doppler rate due to antenna steering <sup>a</sup>	$K_s$	7593 Hz	4679 Hz	6672 Hz
Doppler rate in focused SLC <sup>a</sup>	$K_t$	1742 Hz	1464 Hz	1544 Hz
Wavelength	$\lambda$		5.55 cm	
Platform heading (clockwise w.r.t. north)	$\alpha$		-167.2°	
Platform velocity	$v_S$		7211 m.s <sup>-1</sup>	
Azimuth sampling	$\Delta t_s$		0.002056 s	
Azimuth pixel size	$\Delta x_s$		14.07 m	
Burst cycle duration	$T_{cycle}$		2.75 s	

<sup>a</sup> At mid-range