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A Comparison between short term (co-seismic) and long term (one year) slip for the Landers earthquake: Measurements from strong motion and SAR interferometry.

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Abstract. The long term relative displacements in the region of the Landers earthquake were measured over a time interval of about one year using SAR interferometry. We have also evaluated the co-seismic slip distribution through a strong motion inversion [*Cotton and Campillo*, 1995] and these results are used to compute the static displacement field associated with the co-seismic slip. We show that the synthetic static and the interferometry measurements are in very good agreement. To give an evaluation of the magnitude of the pre- and post-seismic slip, a residual interferogram between data and synthetic co-seismic slip has been computed. A simple analysis of the residual displacements gives a limiting value of the amplitude of pre- and post-seismic slip integrated over a period of one year and suggests that it is on the order of a few decimeters.

Introduction

As one of the largest events ever recorded on the San Andreas fault system, the 1992 Landers earthquake has been studied using different data sets. The strong motion records have been used for the inversion of the slip distribution by different groups [*Cohee and Beroza*, 1995; *Wald and Heaton*, 1995; *Cotton and Campillo*, 1995]. In spite of the different fault geometries and crustal models used in the inversions, the slip distributions that have been proposed are in good agreement. On the other hand, *Massonnet et al.* [1993, 1994] showed that the deformation of the Earth surface in a wide region surrounding the Landers fault can be obtained from SAR interferometry using ERS-1 satellite data. The technique of interferometry makes it possible to measure the ground displacement between two passings of the satellite. In practice for the data we use here, the displacements were measured at an interval of more than one year. Indeed the displacements measured with such a technique include co-seismic as well as pre- and post-seismic motion. In the case of the inversion of the strong motion data, the analysis considers only the motion during a few tens of seconds after the beginning of the dynamic rupture. Our goal here is to compare the static displacements produced by the dynamic rupture as it is inferred from the strong motion data with the measurements made using radar interferometry. Finally we give a limiting value of what could be the amplitude of pre- and post-seismic slip during the period of measure of the interferogram.

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Comparison between synthetic ('seismological') and observed ground deformation.

We use an interferogram that has been computed using the SAR data collected on 24 April 1992 and on 18 June 1993 by the satellite ERS-1 (Figure 1a). The technique of processing is described by *Massonnet et al.* [1994]. Each fringe corresponds to an interval of displacement of 28 mm in the direction of the satellite (21.44° from vertical in the vicinity of the fault 34.5 N, 116.5 W, satellite travelling to the south-Southwest with heading 191.7°). We also computed the relative displacement by unwrapping the interferogram using a remote reference point. This operation cannot be achieved in the vicinity of the fault where the spatial resolution of the SAR data is not sufficient. At less than about seven kilometers from the fault, the variation of displacement on a pixel can be larger than a wavelength and it is therefore impossible to define continuous lines of equal phase. We obtained the displacement along a series of East-West profiles (Figure 2). The locations of the profiles are shown in Figure 3. Since the Big Bear earthquake (M_w=6.2) which occurred about 3 hours after Landers has a clear influence on the south part of the interferogram, we limited these measurements to its northern half.

To evaluate the part of the static field associated with the Landers event itself, we use the slip distribution obtained by *Cotton and Campillo* [1995]. The data set consists of the records of only 13 accelerometric stations located at distance ranging from about 10 kilometers to about 100 kilometers from the fault. We take into account only the slip that occurred in the first 17 seconds of the rupture process, that is the part that is well resolved in the inversion. Using the slip distribution deduced

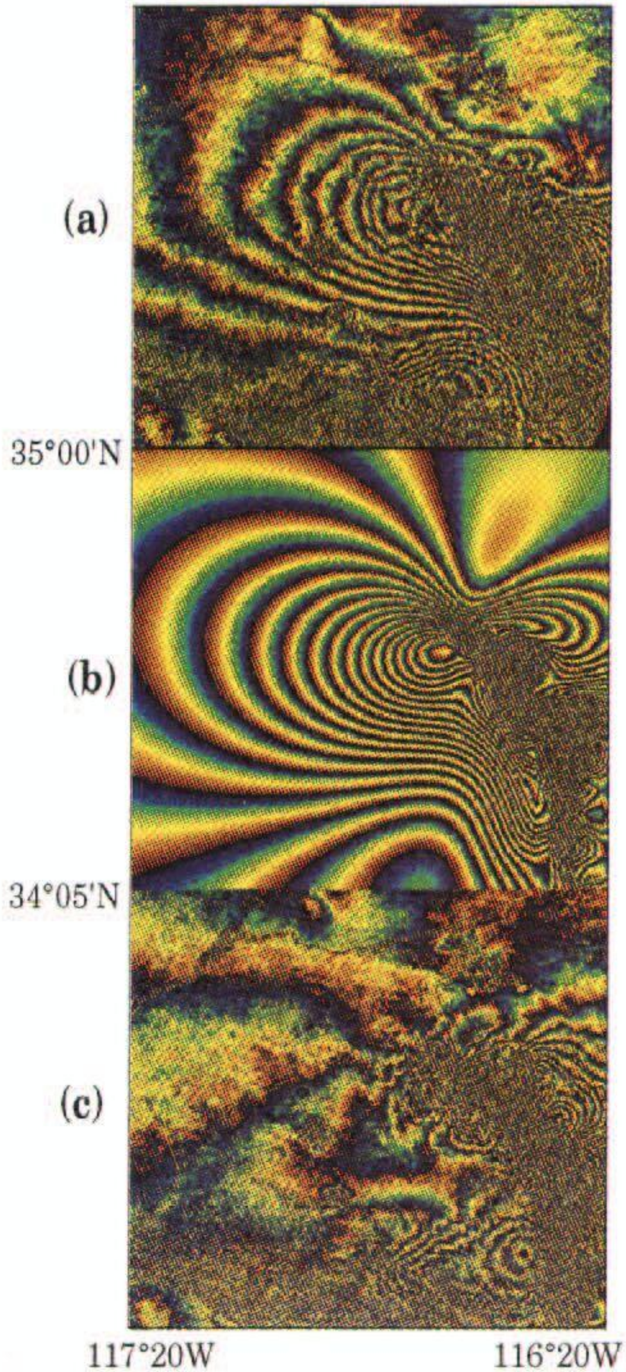

Figure 1. Interferogram constructed from radar images acquired on 24 April 1992 and 18 June 1993. One cycle of color corresponds to one interferometric fringe equivalent to 28 mm of change in the distance between the satellite and the ground. The quality of interferograms is governed principally by the altitude of ambiguity for the pair of satellite orbits. An altitude of ambiguity, several times larger than the 30-m uncertainty in the elevation model, indicates that the interferometric map of the change in range is robust to errors in that model. The altitude of ambiguity is 220 m, implying that a 30 m error in the elevation model would create an error of only 4 mm in the interferogram. Unit vector from ground to satellite (east, south, up) is (0.33, 0.07, 0.94). The interferogram is dominated by the signature of the Landers and the Big Bear earthquake that occurred on 28 June. The four closed fringes in the middle bottom of the interferogram have been interpreted as the displacement due to the magnitude (M_L=5.1) of 4 December 1992 (*Massonnet et al.*, 1994).

b) Synthetic interferogram produced using the strong motion rupture model of *Cotton and Campillo* [1995].

c) residual interferogram obtained by phase subtraction of the ERS-1 observation of Figure 1a and of our synthetics of Figure 1b.

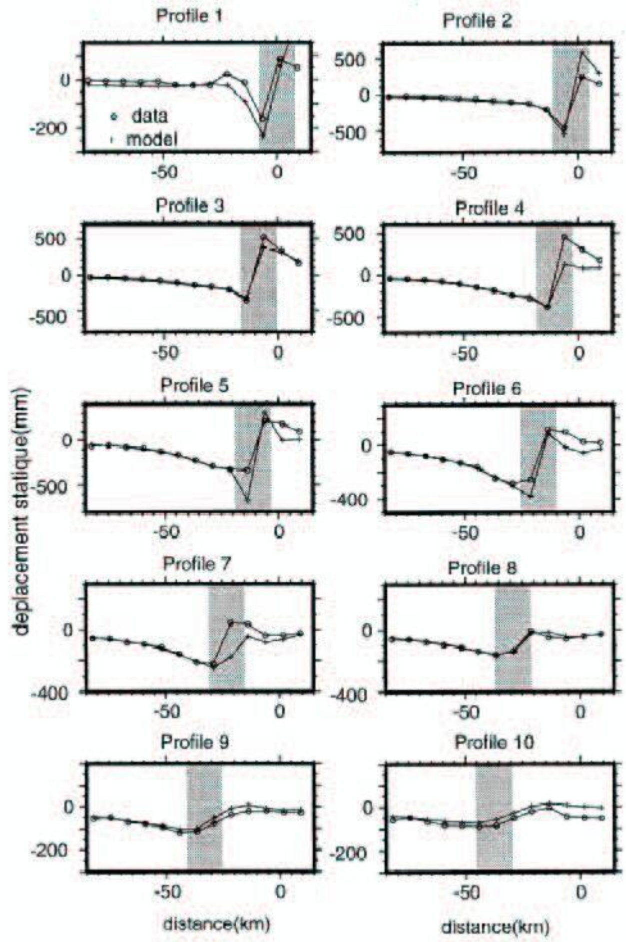

Figure 2. Values of static displacement in the earth-satellite direction along EW profiles (shown in Figure 3). The data (circles) have been obtained by unwrapping the interferogram shown in Figure 1a. The crosses are the values predicted by the rupture model inferred from the strong motion records. The shaded area shows the portions of the profiles where the unwrapping is not reliable (less than 7 kilometers from the fault).

from the accelerograms, we compute the static displacements at a series of about 2000 points evenly covering the region in which the deformation has been measured by radar interferometry. We use the same Green's functions of the layered crust as for the inversion of strong motion and we measure the static on the synthetics far after the arrival of the slowest waves (typically 100 s after the origin time). We convert the component of displacement in the direction of the satellite in phase shift and we obtain a synthetic interferogram (Figure 1b). The agreement between observed and synthetic interferograms is satisfactory except indeed for the effects of the Big Bear event and of the

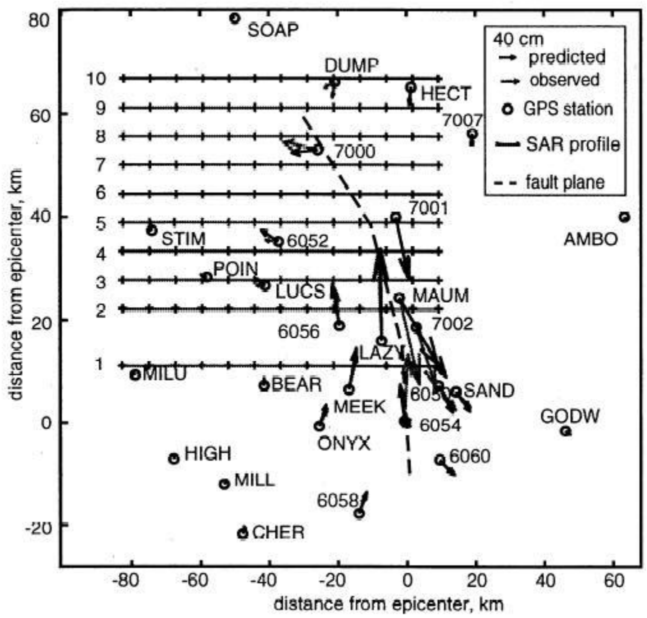

Figure 3. Map of the profiles along which the displacement has been computed from the interferogram. The fault geometry used in the inversions is shown by the dotted lines. The observed (gray) and predicted (black) horizontal displacements at GPS stations are shown by arrows, with the amplitude scaling as shown in the inset.

M_l=5.1 aftershock of Dec, 4 1992 that are not modelled here. In the vicinity of the fault, the motions are very sensitive to the fine geometry of the fault system. Indeed, the strong motion model is obtained using remote observation and assuming a simple geometry (in order to maintain a small number of model parameters). Therefore the details of the ground deformation are not expected to be predicted by the strong motion model. The values of the synthetic displacements are in a good agreement with the ones computed from the interferogram along EW profiles, as shown in Figure 2 where synthetic displacements are denoted by crosses. Since SAR interferometry is most sensitive to the vertical displacement, we present in Figure 3 a comparison between the GPS horizontal displacement measurements of *Hudnut et al.* [1994] with the displacement obtained from the strong motion model. At most sites the agreement is satisfactory. The GPS sites were reobserved shortly after the earthquake and can be considered as characteristic of the co-seismic slip. This shows that in the region where the measurements are the most reliable (good resolution of the fringes and far from Big Bear) the strong motion model predicts quite well the geodetic measurements. This agreement can also be considered with respect to the residual interferogram computed by *Massonnet et al.* [1996b] from a slip model proposed by *Massonnet et al.* [1993] and deduced from slip observed at the surface. Far from the fault, the amplitude of the residuals obtained by *Massonnet et al.* [1996] and these deduced from the strong motion model (Figure 1c) are comparable. West of the fault the results are even better for the strong motion model as indicated by few interferences residuals. This shows the accuracy of the strong motion inversion and shows that pre- and post-seismic displacements are much smaller than the co-seismic displacements.

Can residuals be associated with non-seismic slip ?

An important point is to know if we can infer some conclusions about aseismic slip from the residual between SAR measurements, which cover the deformation of more than one year and strong motion models from which static deformations associated with the 20 seconds of the rupture have been calculated. Different elements can be evoked to explain these residual displacements. First of all, indeed, are the errors both in retrieving the displacement field from the SAR observations and in inverting for the slip distribution from the strong motion records. The numerous aftershocks have a cumulative moment that accounts for no more than a few percent of the main event. Pre- and post-seismic slip occurring before the complete healing of the fault could also play a part since the relative displacements are measured over a period of about 1 year.

To test this last possibility, we computed the residuals along the profiles depicted on Figure 3. The results are presented in Figure 4. We search in the residuals the decay with distance that is expected if they have a physical source on the fault. This effect is illustrated in Figure 4 by the synthetic displacements computed for a 60 cm slip on the fault (model A) and 90 cm slip at a depth between 6 and 11 km (model B). The characteristic decay is not present in the residuals, indicating that we cannot identify the effect of aseismic slip in this data set. On the other hand, the synthetics give an evaluation of the amplitude of the displacement

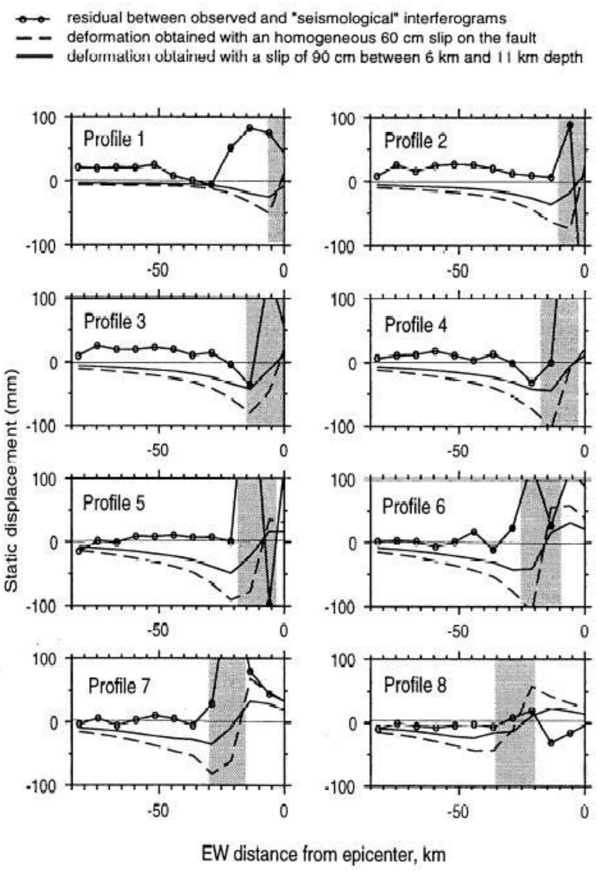

Figure 4. Residuals (circles) along the profiles depicted on Figure 3 compared to synthetic displacements computed for a 60 cm slip on the fault (model A) and 90 cm at a depth between 6 and 11km (model B). The shaded area shows the portions of the profiles where the unwrapping is not reliable (less than 7 kilometers from the fault).

associated with a slip of 60 cm on the entire fault and 90 cm at a depth between 6 and 11 km.
According to synthetic tests, displacement in the earth-satellite direction and then interferograms are much less sensitive to slip occurring on the deeper part of the fault than close to the surface. Therefore, only the occurrence of aseismic slip at moderate depth (less than 11 km) will be discussed in the following. Comparing these synthetics with the residuals shows that, far from the source the residuals fluactuate at a level much smaller than the amplitude variation of the synthetics. Since the amplitude of the synthetics is linear with the slip on the fault, one can realize from Figure 4 that the mean pre- and post-seismic slip integrated over one year cannot be larger than a typical value of a few dm. We must repeat here that we have not shown any evidence of the existence of pre- or post-seismic slip. Such a small limit value of slip reaches both the limits of accuracy of our method and the possible contribution of the aftershocks. Nevertheless, the small value of the residuals, together with the absence of the expected trend of decay with distance shows that the aseismic slip at the top part of the fault has to be small with respect to the slip during the main shock and remain in a range of 10% of the co-seismic slip.

Recently, post-seismic interferograms have been constructed from radar images acquired after the earthquake [*Massonnet et al.*, 1994, 1996; *Peltzer et al.*, 1996]. These post-seismic interferograms are made from radar images acquired on 3 July 1992 (5 days after the earthquake) and other following closely spaced track on the Landers area (2 April 1995 for example). Pushing radar interferometry to near its typical artefact level, maps of the post-seismic deformation field in the three years following the earthquake have been obtained. Those post-seismic interferograms do not include very early post-seismic deformation created by afterslip which could have happened in the hours and 5 first days following the earthquakes. *Massonnet et al.* [1996] however suggest an amount of post-seismic aseismic slip of several decimeters, a value which has also been suggested with a GPS data analysis by *Blewitt et al.* [1993] and *Shen et al.* [1994]. This value is close to the range of possible aseismic slip deduced from our study. All these results suggest that total aseismic slip (including very early post-seismic aseismic slip) appear to be no more than about 10% of co-seismic slip which had an average value of 3 meters and a maximum value of 7 meters.

Conclusion

SAR interferometry made it possible to measure the displacements in the region of the Landers earthquake over a time interval of about one year. We used the results of the strong motion inversion of the slip distribution [*Cotton and Campillo*, 1995] to compute the static displacement field associated with the co-seismic slip. We showed that the synthetic static calculations and the interferometry measurements are in a very good agreement. To give an evaluation of the magnitude of the pre- and post-seismic slip at shallow depth, we computed a residual interferogram between data and synthetic co-seismic slip. A simple analysis of the residual displacements gives a limiting value of the amplitude of pre- and post-seismic slip integrated over a period of one year and suggests it is on the order of a few decimeters.

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