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S. Stramondo, M. Tesauro, Pierre Briole, E. Sansosti, S. Salvi, et al.. The September 26, 1997 Colfiorito, Italy, earthquakes: Modeled coseismic surface displacement from SAR interferometry and GPS. *Geophysical Research Letters*, 1999, 26 (7), pp.883-886. 10.1029/1999GL900141 . hal-03215376

HAL Id: hal-03215376

<https://hal.science/hal-03215376>

Submitted on 3 May 2021

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The September 26, 1997 Colfiorito, Italy, earthquakes: modeled coseismic surface displacement from SAR interferometry and GPS

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Abstract. The largest events of the 1997 Umbria-Marche seismic sequence were the two September 26 earthquakes of Mw=5.7 (00:33 GMT) and Mw=6.0 (09:40 GMT), which caused severe damage and ground cracks in a wide area around the epicenters. We created an ERS-SAR differential interferogram, where nine fringes are visible in and around the Colfiorito basin, corresponding to 25 cm of coseismic surface displacement. GPS data show a maximum horizontal displacement of (14 ± 1.8) cm and a maximum subsidence of (24 ± 3) cm. We used these geodetic data and the seismological parameters to estimate geometry and slip distribution on the fault planes. Modeled fault depths and maximum slip amplitudes are 6.5 km and 47 cm for the first event and 7 km and 72 cm for the second one, in good agreement with those derived from the seismological data.

1. Introduction

Starting September 1997, a large area of the Umbria-Marche Apennines in Central Italy was struck by a strong seismic sequence. Activity began on September 3 with a Mw= 4.5 earthquake, then, on September 26 at 00:33 GMT, a Mw 5.7 earthquake occurred near the village of Colfiorito, followed at 09:40 GMT by a Mw 6.0 event [Amato *et al.*, 1998]. The focal mechanisms for these events are all consistent with purely normal faulting with a NE-SW T axis (CMT solutions, [Ekström *et al.*, 1998]). Most of the aftershocks were precisely located at depths ranging between 10 and 3 km, suggesting SW-dipping fault planes [Amato *et al.*, 1998]. Field observations [Cinti *et al.*, 1998; Basili *et al.*, 1998], allowed the identification of diffuse surface deformation features (mostly ground breaks with centi-

metric throw), along a 10 km wide belt coincident with the epicentral area. Even if the strain release during the Colfiorito shocks did not originate large tectonic surface ruptures, the seismic moment values (Table 2), the shallow depth of the seismicity and the aftershock distribution, all suggest that a diffuse zone of surface displacement had occurred. In this paper we present preliminary results of a GPS and SAR interferometry investigation for the two September 26, Colfiorito main shocks.

2. The SAR interferometric fringes

The Differential Interferometry technique, using Synthetic Aperture Radar data (DInSAR), has already been demonstrated to be an important tool for coseismic crustal displacement analysis [Massonnet *et al.*, 1993]. We applied SAR interferometry to the epicentral area and obtained a good final interferogram using a high resolution DEM acquired from the Italian Istituto Geografico Militare (20 m spatial resolution, height accuracy of 10-20 m), to eliminate the effect of the topography.

We used a set of 30 ERS-1/ERS-2 images (from ascending and descending orbits) acquired from July 1993 to October 1997. To minimize the effects of errors in the DEM, we chose interferometric pairs with a high ambiguity height (i.e. the altitude variation producing a phase change of 2π). Our most coherent interferogram was obtained from a 35-day ERS-2 pair; the pre-seismic image was acquired on September 7, 1997 and the post-seismic one on October 12. For these two images the ambiguity height is 79 m, the orthogonal baseline 130 m and the parallel baseline 70 m; according to the estimated accuracy of the DEM, the maximum expected error due to the topography is thus about 1/4 of a fringe, (i.e. less than 7 mm).

The differential interferogram shows (Figure 1) a pattern of concentric fringes with two clear relative minima in the areas of the Annifo and Colfiorito plains (zone of maximum damage). The general pattern elongation agrees with the strike of the mainshock fault planes as determined from the CMT solutions ($140^\circ - 150^\circ$, [Ekström *et al.*, 1998]). The fringe pattern also shows a marked asymmetry, with closer fringes (i.e. a higher displacement gradient) towards the NE; its extension is

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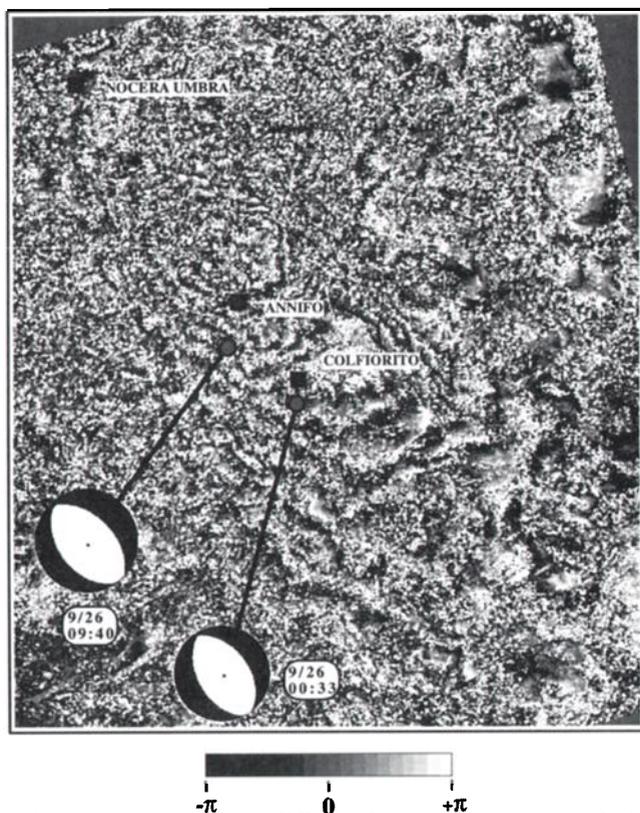


Figure 1. SAR differential interferogram of the Colfiorito area showing the total surface displacement occurred between September 7 and October 12, 1997. Each fringe represents a full phase cycle ($+\pi - \pi$) caused by a displacement increment of -28 mm in the slant range; the direction of the increment is from the outermost fringe inward. Also shown are the epicentral location of the two September, 26, shocks and the CMT focal mechanisms (after *Ekström et al.*, [1998]). To better retain the details of the fringe pattern, the image is not geocoded (SAR geometry). The small residual fringes visible towards the extreme right of the image are presumably related to propagation delays due to tropospheric turbulence.

about 14 km N-S and 10 km W-E. Given the limited temporal baseline (35 days), it likely represents the total coseismic displacement of both the 00:33 and 9:40 GMT, September 26, main-shocks. The displacement increases constantly towards the Annifo plain, where a maximum of 252 mm (nine fringes) of surface displacement is found (Figure 2).

3. The GPS data

Shortly after the main shocks we re-surveyed a subset of the Italian Istituto Geografico Militare, IGM95 GPS network [*Surace et al.*, 1997] located around the epicentral zone [*Anzidei et al.*, 1998]. The GPS data were processed using the Bernese software version 4.0 [*Rothacher et al.*, 1996]. We obtained 3-D coordinates with a mean accuracy of 14 mm and 25 mm in the horizontal and vertical components respectively (95% confidence). As reference coordinates we used those

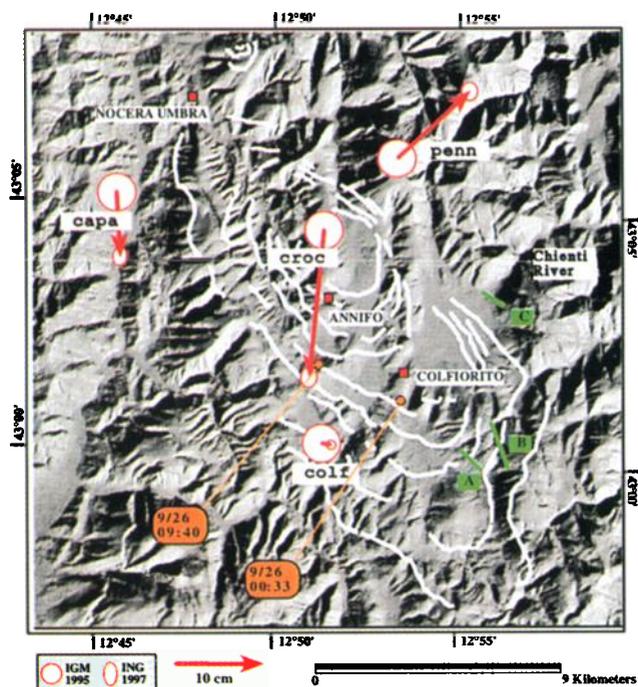


Figure 2. Geocoded displacement contours retrieved from the interferogram in figure 1. Each contour line represents a displacement increment of -28 mm in the slant range. GPS stations (in lowercase), planar displacement vectors (red arrows), and 95% confidence error ellipses for the 1995 and 1997 epochs (see Table 1), are shown. A and B are the traces of the bedrock fault plane reactivations (after *Basli et al.*, [1998]). C is the location of the scarp damming the outlet of the Colfiorito basin.

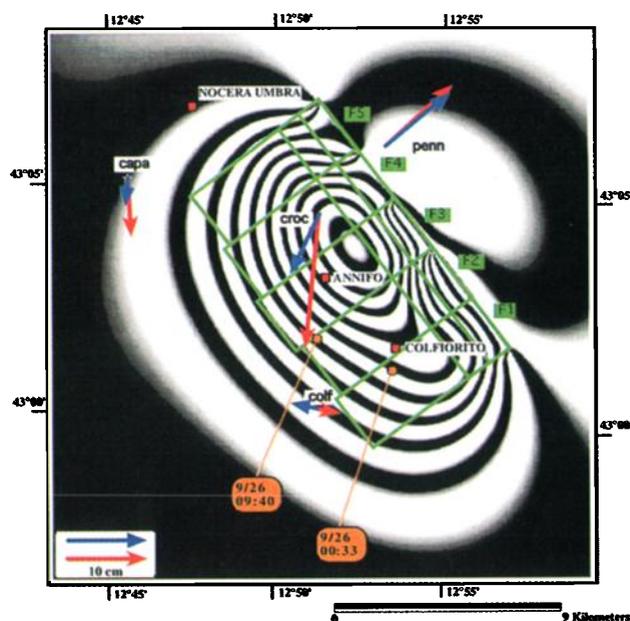


Figure 3. Synthetic interferogram and surface projection of the fault model. The parameters for the 15 fault patches are reported in Table 2. Displacement vectors and GPS stations as in figure 2. Modeled horizontal displacement vectors at the GPS stations are shown as blue arrows.

Table 1. Observed and calculated GPS displacements

| GPS point | Obs. GPS vertical | Calc. GPS slant range | Obs. SAR displacement | Obs. GPS horizontal | | Model | |
|-----------|-------------------|-----------------------|-----------------------|---------------------|------|-------|-----|
| | | | | dE | dN | dE | dN |
| COLF | -69 | -58.8 | -56 | 12 | -2 | -13 | 5 |
| PENN | -39 | -9.2 | 0 | 80 | 77 | 30 | 25 |
| CAPA | 1 | 7.9 | 0 | 10 | -57 | 0 | -10 |
| CROC | -247 | -224.7 | -252 | -19 | -139 | 2 | -30 |

All values are in mm.

computed by IGMI at the 1995 epoch, with a mean accuracy of 22 mm in the horizontal and 35 mm in the vertical components respectively (95% confidence). To compare IGMI and our 1997 coordinates we applied a 7-parameter transformation [Anzidei *et al.*, 1998]. Eventually, only Collecroce (CROC), Pennino (PENN), Colfiorito (COLF) and Capannacce (CAPA) detected a significant displacement (Figure 2).

When projected onto the SAR line of sight the GPS displacements agree well with the SAR displacements (Table 1). The large horizontal values at PENN, CROC and CAPA are nearly parallel to the ERS orbit and contribute marginally to the GPS displacement in the slant range direction.

4. Fault modeling and discussion

We modeled the data using an inversion program [Briole *et al.*, 1986] based on a least square minimization algorithm [Tarantola *et al.*, 1982] and representing the source as a rectangular fault in a uniform elastic half-space, using the Okada (1985) formulation. We used in the model 258 values of range change (one point every 0.5 km along each fringe) and the 4 GPS horizontal displacement values (Table 1), since the vertical GPS components are in good agreement with the fringe displacements. Based on the hypocentral distribution for the entire sequence [Amato *et al.*, 1998] and on the opposite directions of the rupture propagations

Table 2. Modeling results: slip for each patch and total seismic moments

| Patch layer (depth range) | Event 09:40 | | | Event 00:33 | |
|------------------------------|-----------------------------|----|----|----------------------------|----|
| | F5 | F4 | F3 | F2 | F1 |
| Upper (0-1 km) | 13 | 24 | 16 | 5 | 6 |
| Medium (1-2 km) | 12 | 29 | 29 | 5 | 19 |
| Lower (> 2 km) ^a | 41 | 72 | 69 | 30 | 47 |
| Seismic moment | | | | | |
| Model | 105.2 × 10 ¹⁶ Nm | | | 42.5 × 10 ¹⁶ Nm | |
| CMT Moment | 120 × 10 ¹⁶ Nm | | | 40 × 10 ¹⁶ Nm | |

Slip is in cm, CMT moments from Ekström *et al.*, 1998.

^aDepth of fault plane variable between 6.5 and 7 km, see fig.3

of the two mainshocks (A. Pino *et al.*, Rupture directivity of the major shocks in the 1997 Umbria-Marche sequence from regional broadband waveforms, submitted to *Geophysical Research Letters*, 1998) we assume that the two faults belong to the same tectonic structure. In order to determine the slip distribution during the earthquake, we joined the two fault planes in a single plane 12.5 km long, with dip 45°, strike 144°, rake 270° [Ekström *et al.*, 1998]. We divided the fault in 15 patches (Figure 3), allowing for slip on the fault at depths between 7 and 1 km (Table 2). The final r.m.s. residual is 16 mm, well below the value of one fringe (28 mm). It appears that, for the 09:40 event, a better fit of the horizontal GPS displacements requires considerable slip at shallow depths. In fact, giving a weight 0 to the GPS data results in a reduction of the maximum slip from 24cm (with weight=1, Table 2) to 10cm for the upper F4 patch. The total seismic moment (we used a rigidity value of $3 \times 10^{10} \text{ Nm}^{-2}$) is close to the CMT moment of Ekström *et al.* [1998] (Table 2).

For the 09:40 event, Hunstad *et al.*, (in their paper: Modeling coseismic displacements during the 1997 Umbria-Marche earthquake, submitted to *Geophysical Journal International*, 1998), performing a forward modeling of the same GPS data, found maximum slips and top-of-fault depths in agreement with our results (65cm and 0.3 km). Their estimates for the 00:33 event are slightly different (36cm and 3 km), but in their model this event is well constrained by only one GPS data, at COLF. The previously cited broadband waveform analysis by Pino *et al.*, suggests maximum slips of 52cm and 65cm for the 00:33 and 09:40 events respectively. These authors (and Olivieri *et al.*, [1998]) also suggest that the 09:40 event is composed of two subevents, about 4 s apart, the second being located about 12 km North of the hypocenter. The three small semi-circular fringes in the upper part of figure 1 are located at 12 km from the 09:40 epicentre and in principle they could be related to the second subevent, but there is no other clue to this interpretation.

As already noted by [Peltzer *et al.*, 1995] for the 1993 Eureka Valley (California) sequence, some of the fringe complexities (merging, interrupted, and/or displaced fringes) in figure 1 could represent local surface deformation due to shallow, moderate aftershocks [Amato *et al.*, 1998], not considered in our model. In the

area SE of Colfiorito, *Basili et al.* [1998] describe up to 5 cm displacement along bedrock fault planes for lengths of 1-2 km which can be seen in figure 2 (A,B). Other evidences of surface displacement mapped by *Basili et al.* [1998] and *Cinti et al.* [1998] are too local (max length 300 m, i.e. 7-8 pixels in figure 1) to be recognized in the interferogram.

Finally, we remark a certain similarity between the displacement pattern and the general topographic setting of the area, which includes the plains of Colfiorito and Annifo (Figure 2). This and other evidences, such as the tectonic scarp (C in figure 2) blocking the drainage from the Colfiorito basin towards the NE [*Cello et al.*, 1997], suggest that the presence of a topographic low in this area may be a direct consequence of repeated seismic deformation occurred during the Upper Quaternary.

4.1. Conclusions

We applied ERS SAR interferometry to the 1997 Umbria-Marche epicentral area. We retrieved the surface displacement field for the 26 September mainshocks and measured a maximum of 252 mm of range displacement in the interferogram. We applied an elastic dislocation model to the DInSAR and GPS observations, obtaining a rather good fit. The maximum depth of the faults is well constrained and stable at 6.5-7 km and the pattern of slip distribution shows that for the 09:40 event most of the energy was released from an area of 5x7 km in the southeastern part of the fault (Table 2).

The large slip values at shallow depths (0-1 km) in our model (Figure 3) for the 09:40 event do not correspond to surface faulting of comparable size, even if a high displacement gradient (Figure 1 and 3) is present close to the top of the fault. This suggests that the rupture stopped very close to the surface, as also proposed by *Cinti et al.* [1998]. The SAR and GPS observations and our modeling results are in good agreement with the independent results from geological and seismological data.

Acknowledgments. Thanks to ESA, ASI and Telespazio s.p.a. for providing the ERS images, the Italian Civil Protection for financial support and the IGMI for collaboration. Part of the research has been funded by the Italian Space Agency, contract No. RS 96-87 and Telespazio.

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(Received April 21, 1998; revised December 14, 1998; accepted January 8, 1999.)