Coseismic displacement of the 27th September 1997 Umbria - Marche (Italy) earthquakes detected by GPS: campaigns and data

Marco Anzidei (1), **Paolo Baldi** (2), **Alessandro Galvani** (3), **Arianna Pesci** (3), **Ingrid Hunstad** (3) **and Enzo Boschi** (1)
(1) *Istituto Nazionale di Geofisica, Roma, Italy*
(2) *Università di Bologna, Dipartimento di Fisica, Bologna, Italy*
(3) *ASI scholarship at Istituto Nazionale di Geofisica, Roma, Italy*

Abstract
On September 26, 1997 two earthquakes of M_w 5.7 (00.33 GMT) and M_w 6.0 (9.40 GMT), occurred in the Umbria-Marche region (Central Apennines, Italy). The epicentres were located in an area of the Apenninic chain that experienced historical earthquakes up to X degrees of the MCS scale. During the time span 1992-1996, the Italian Istituto Geografico Militare (IGM) set up a new national geodetic network measured by Global Positioning System space geodetic technique, consisting of more than 1200 vertices uniformly distributed on the Italian peninsula and islands. From October 7 to 11, 1997, a short while after the main shocks of the Umbria-Marche seismic sequence, we reoccupied thirteen stations belonging to the IGM and TYRGEONET networks to measure coseismic displacement. The determinations of the post-seismic coordinates at 13 GPS monuments detected significant coseismic displacements. The comparison between the preseismic and postseismic data sets show maximum displacements of 14 cm and 25 cm in the horizontal and vertical components respectively. In this paper, the GPS network, the field work, the data processing procedures and the computed coseismic displacements measured at the geodetic monuments are discussed with the aim to provide a data set useful to the scientific community for further geological and geophysical investigations.

Key words *Umbria-Marche earthquakes – IGM95 – GPS – coseismic displacement*

1. Introduction

The Umbria Marche region (Central Italy), that belongs to the Northern Appennine arc, formed from the progressive ENE migration of a fold-and-thrust belt-foredeep system and during the Late Miocene to Middle Pliocene was affected by extensional tectonics related to the opening of the Tyrrhenian Sea (Anderson and Jackson, 1987; Montone *et al.*, 1997). According to Cello *et al.* (1997), during the Quaternary age this area was subjected to intense tectonic activity producing N-S left lateral faults, linked by NW-SE transfer faults. In particular, the Colfiorito basin and Costa-Cesi area display faults characterized by normal to transtensive movements associated with the main N-S left lateral faults (Cello *et al.*, 1997a,b). On the basis on geological and geophysical data, the region can be considered still active and it is a matter of debate if the regional stress is dominated by crustal extension normal to the Apenninic chain (Anderson and Jackson, 1987; Frepoli and

Mailing address: Dr. Marco Anzidei, U.O. Geodinamica, Istituto Nazionale di Geofisica ,Via di Vigna Murata 605, 00143 Roma Italy; e- mail: anzidei@ing750.ingrm.it

Amato, 1997; Montone *et al.*, 1997) or whether the normal faults act as a response to different processes, such as pull-apart tectonics in a strike slip regime (Cello *et al.*, 1997).

On September 26, 1997 at 00.33 and 09.40 GMT two earthquakes of M_w 5.7 and 6.0 respectively, occurred near the Colfiorito village, causing widespread damage and few casualties. These earthquakes, which are the strongest seismic events to occur along the whole Apenninic chain since the Irpinia earthquake of November 1980, occurred in a region of the Apennines that experienced only moderate earthquakes in the instrumental era (Boschi *et al.*, 1995; Amato *et al.*, 1998). The closest and most recent seismic sequences occurred during the past twenty years around 30 km from Colfiorito area, are the 1979 Norcia-Cascia, in the southeast (M_s = 5.8; Deschamps *et al.*, 1984) and the 1984 Perugia-Gubbio in the northwest (M_s = 5.3; Haessler *et al.*, 1988). These seismic sequences were generated by normal faults, typical of the present tectonic setting of the Central Apennines.

The CMT fault plane solutions of the September 26, 1997 main shocks (Ekström *et al.*, 1998) show fault orientations and slip directions of purely normal faulting with extension perpendicular to the Apennines (NE-SW *T* axis) (fig. 1). Ruptures nucleated at shallow depth (6 ± 1 and 6 ± 2 km) with fault planes dipping SW. The aftershock distribution shows a NW-SE elongated fault zone extending for about 40 km with hypocenters located at depths ranging from 3 to 10 km (Amato *et al.*, 1998). Fault slip for the 00:33 and 09:40 GMT seismic events, show maximum amplitudes of 36 cm (uniform

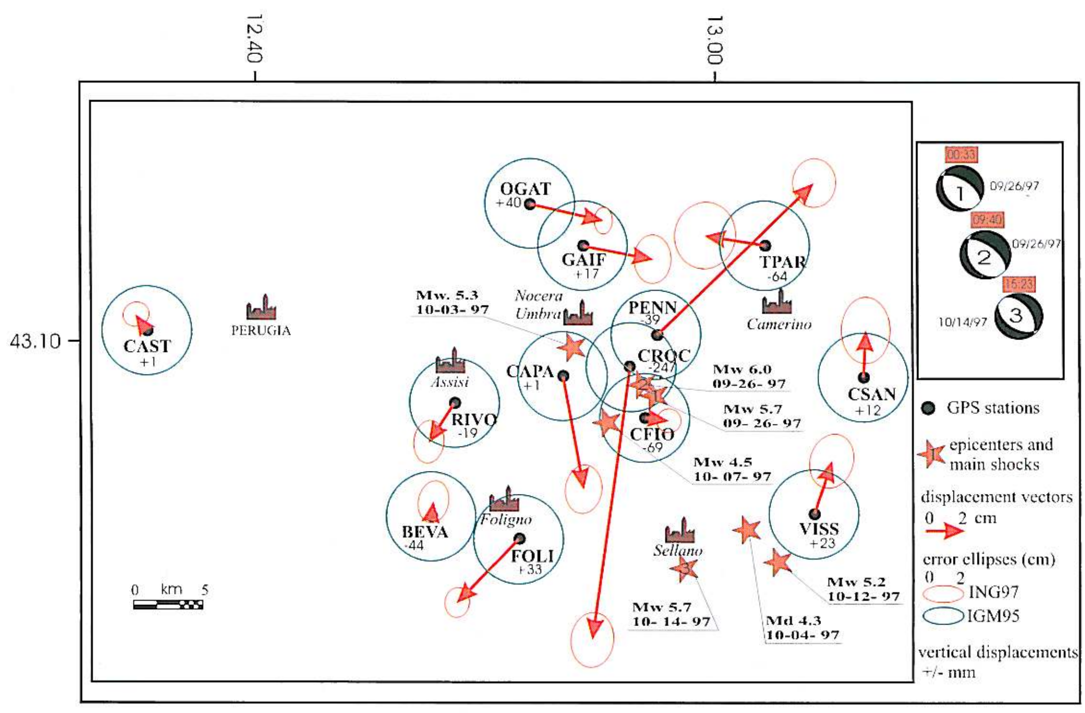

Fig. 1. The IGM95 GPS network. Coseismic displacement at the GPS stations in the epicentral area of the Umbria-Marche seismic sequence after the main shocks of September 26, 1997 are shown in the map. The figure also reports the three largest seismic events to have occurred in the area. Thick and thin error ellipses are the IGM95 and the ING97 coordinate determinations respectively (95% confidence level).

slip) and 65 cm (variable slip; average 33 cm) respectively, as reported by Hunstad *et al.* (1998) and Stramondo *et al.* (1999). Although the main shocks did not produce primary surface ruptures, the observed ground breaks (Cinti *et al.*, 1999) identified a diffuse surface deformation along a 10 km wide belt whose strike is in agreement with the seismological data (Ekström *et al.*, 1998) and the geodetic observations presented in this paper.

With the aim to measure the coseismic ground deformation of the area, we re-occupied thirteen geodetic stations belonging to the IGM95 network located around the epicentral area (fig. 1). The dense spacing of this national geodetic network in this area and its accuracy revealed significant surface displacements. GPS data were successfully used to model the sources of both seismic events by means of forward (Hunstad *et al.*, 1998) and inverse (Stramondo *et al.*, 1999) modelling.

This paper gives an accurate description of the GPS network, the field work, and the data processing strategies adopted in computing coseismic displacements measured at the geodetic monuments. This data set will be avalaible for further investigations.

2. The GPS network and the 1995-1997 surveys

During the time interval 1992-1996 the Italian Istituto Geografico Militare (IGM) set up and measured the IGM95 network, a new national geodetic network that consists of 1260 vertices planned for land surveys and designed to be measured by the GPS technique (Surace, 1993, 1997). The primary scope of this network is to provide a set of 3D coordinates based on the GPS reference system and useful for cartography and civil users. When the geodetic monuments are located in relevant tectonic areas, the geophysical community can benefit from this data, capable of providing information on ground coseismic displacements in case of moderate and large earthquakes (Anzidei *et al.*, 1998). The geodetic stations are located across important still active tectonic structures of the Central Apennines (Cello *et al.*, 1997a,b). Here the main outcropping geological units (fig. 2) are represented by the Umbria-Marche complex, characterized by sedimentary rocks of age spanning from the lower Cretaceous to the Plio-Pleistocene (Servizio Geologico d'Italia, 1970).

Thirteen stations of the IGM95 network are located around the epicentral area and were measured by IGM in March-April 1995 (fig.1, table I). The final adjustment in one block of the entire network (Surace, 1997) provided 3D coordinates with an accuracy of 35 mm and 22 mm in the vertical and horizontal components respectively (95% confidence level) (table IV). Although coordinate accuracies are not able to reveal the aseismic strain at the strain rates typical of the Apenninic chain, (0.3-3 mm/yr, Anderson and Jackson, 1987; Selvaggi, 1998), they can provide data on the coseismic ground displacement after the occurrence of moderate to large earthquakes, as in the case of the Umbria-Marche main shocks of September 26, 1997. The post-seismic GPS surveys were performed between 7 and 11 October 1997. We used six GPS TRIMBLE 4000 SSE / SSI dual frequency receivers to re-occupy thirteen monuments built by concrete pillars or markers fixed on the ground or on stable, small concrete buildings, undamaged by the co-seismic ground shaking (figs.1 and 2, table II).

The general features of the monuments, consisting of permanent markers or pillars placed on the ground, are shown in table II. The reported quality level (A = high, B = intermediate, C = low) of the single stations is based on the monument type (pillars, markers located on stable small concrete buildings or walls), geological location (mechanical properties of the outcropping units) and GPS antenna set up (IGM type base or tripod; the former reduces possible errors of the operator during GPS antenna set up). This observation can provide information for the cosesimic and long term stability of the monuments for future surveys.

Three receivers were kept fixed at Castiglione del Lago (CAST), Foligno (FOLI), and Colfiorito (COLF) stations and logged data continuously at a 30 s sampling rate. The other ten sites were measured by three roving receivers during a time window 4-6 h long each day, for at least two survey sessions.

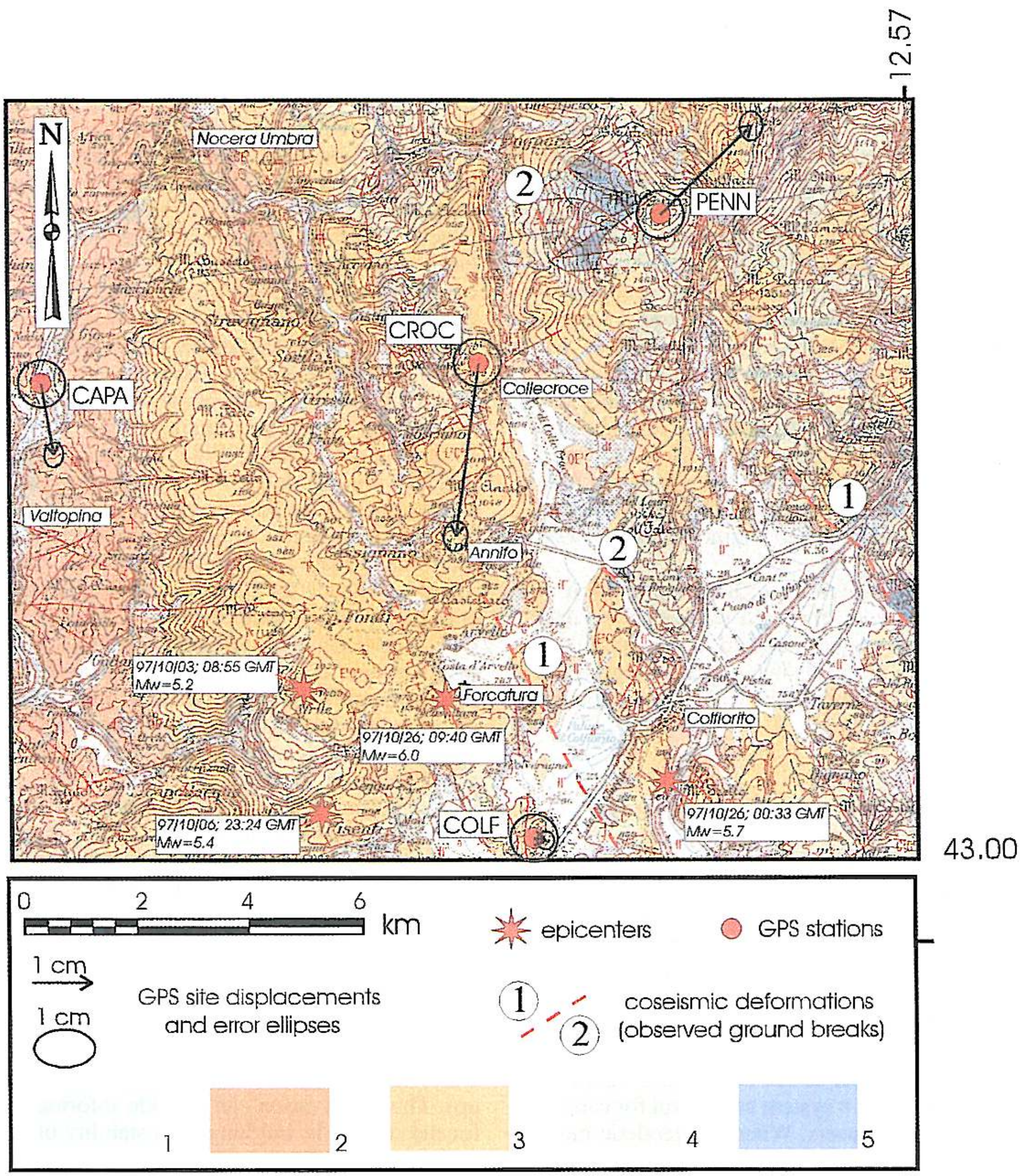

Fig. 2. Main geological units outcropping in the epicentral area: 1 = recent and present alluvium (Olocene); 2 = sandstones (*Marnoso arenacea*, Miocene); 3 = limestones (white and red *scaglia*, Middle Eocene); 4 = limestones (*calcare rupestre*, Lower Cretaceous); 5 = limestones (*corniola and calcare massiccio*, Lower Jurassic-Upper Triassic). The map also reports the GPS stations and their displacements (CAPA = Capannacce; COLF = Colfiorito; PENN = Mt. Pennino and CROC = Collecroce), the epicentres of September 26, 1997 mainshocks, and the ground fractures observed by (1) Cinti *et al.* (1999) and (2) by the authors.

Table I. General features of the ING97 campaign.

ING97 campaign: general features	
Occupied monuments	13
Receivers employed	4 Trimble 4000sse
	2 Trimble 4000ssi
Observation window	24 h fixed stations (CAST, COLF, CROC)
	4-6 h rover receivers
Sampling rate	30 s
Data reduction software	Bernese vers. 4.0
Ephemerides of the NAVSTAR GPS satellites	Precise (CODE)
Adjustment software	Netgps

Table II. Geological setting and features of the GPS monuments. The quality level, based on surface geology, monument type and antenna mount type, represents the coseismic and long term reliability on stability of the stations: A = best; B = intermediate; C = lowest.

General features of the GPS monuments						
Station	Geology	Q.	Monument type	Q.	Antenna mount type	Q.
PENN	Massive limestones	A	Iron pillar	A	IGM type base	A
CROC	Marly limestones	A	Marker on stable concrete wall	A	IGM type base	A
COLF	Marly limestones	A	Marker on stable concrete wall	A	Tripod	B
CAPA	Recent alluvium	B	Ground marker	B	Tripod	B
GAIF	Recent alluvium	B	Ground marker	B	Tripod	B
OGAT	Recent alluvium and sandstones	B	Concrete pillar	C	IGM type base	A
RIVO	Lacustrine sediments	C	Ground marker	B	Tripod	B
TPAR	Recent alluvium	B	Marker on stable concrete small building	A	IGM type base	A
CSAN	Marls and sandstones	A	Ground marker	B	IGM type base	A
FOLI	Lacustrine sediments	C	Marker on stable concrete small building	A	IGM type base	A
BEVA	Lacustrine sediments	C	Marker on bridge shoulder	C	IGM type base	A
VISS	Marls and schists	B	Ground marker	B	Tripod	B

3. Data processing and 1995-1997 coordinate comparison

The 1997 data were processed by the Bernese software (version 4.0) using the precise satellite ephemerides computed at the Centre of Orbit Determination in Europe (CODE), and adopting the standard procedures described by Rothacher *et al.* (1996), estimating the tropospheric delay and fixing the ambiguities rounding their real value to the nearest integer. The independent baseline solutions carried out for each survey session were adjusted by the NETGPS software (Crespi, 1996). The obtained 3D coordinates show a mean accuracy of < 1.0 cm in the horizontal component (mean value of the semiaxes of the error ellipses) and < 2.0 cm in the vertical one (all at 95% confidence level) (table V).

To perform the homogeneous data treatment and to obtain an independent check for some baselines that cross the epicentral area, which were measured during IGM95 and ING97 campaigns, the original IGM95 data files were partially re-processed using Bernese software (version 4.0).

The day-by-day repeatability was evaluated and the mean values of r.m.s. of the GPS baseline cartesian components are 0.9 cm, 0.5 cm and 0.8 cm along the *x*, *y* and *z* components respectively.

In particular we verified the accuracy and the reliability of the IGM95 3D coordinates and baselines obtained after network adjustment computation (IGM95c) of all the IGM95 network (Surace, 1997) and those computed only by single baselines solutions (from CROC station), not adjusted (IGM95b). The results of this check and the comparison between the IGM95c (adjusted), IGM95b (not adjusted) and the post-seimic ING97 (adjusted) baselines are reported in fig. 3.

In the second step of the processing a comparison between 1995 (we used as reference coordinates the IGM95c) and 1997 data set was performed and a seven parameters conformal transformation was applied to eliminate all systematic effects due to the different reference

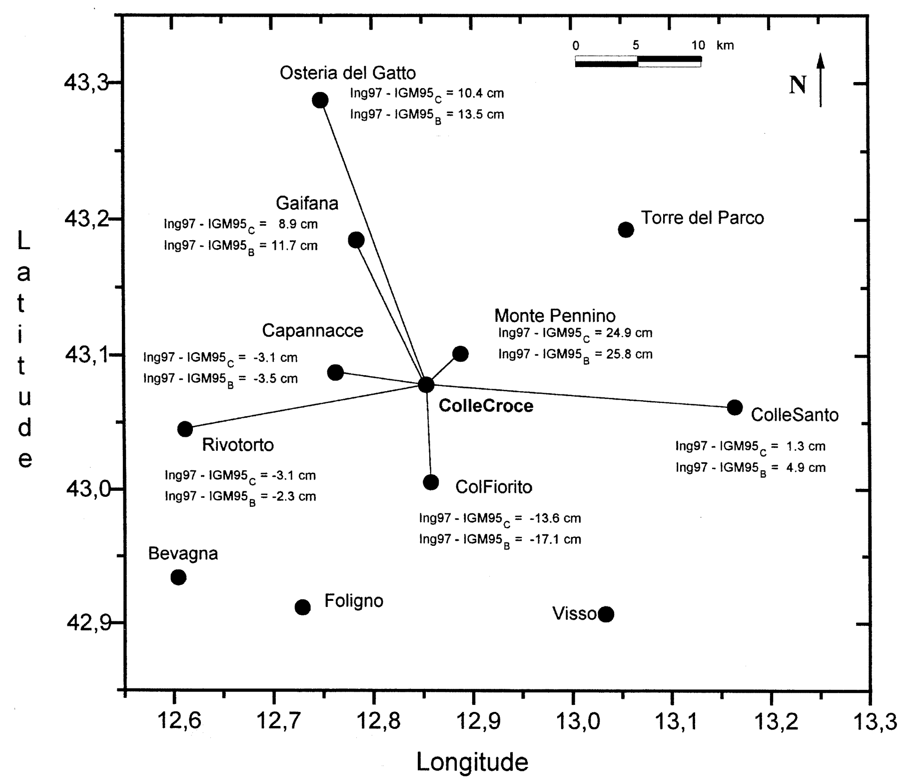

Fig. 3. Baselines and their comparison computed from Collecroce station (CROC) between IGM95 and ING97 computation. IGM95c is the IGM95 value obtained from the adjustment of the whole IGM95 Italian network (more than 1200 stations). IGM95b is the IGM95 value of the single baselines computation (not adjusted).

Table III. Result of 7 parameters Helmert trasformation between IGM95 and ING97 data set.

IGM95 – ING97 Transformation parameters	
Translation along X	0.127 ± 0.010 m
Translation along Y	0.032 ± 0.010 m
Translation along Z	0.350 ± 0.010 m
Rotation around X axis	– 0°0′0.0427″ ± 0.0817″
Rotation around Y axis	– 0°0′0.2141″ ± 0.1443″
Rotation around Z axis	– 0°0′0.0355″ ± 0.0710″
Scale factor	0.267 ± 0.344 mm/km

Table IV. Geographical coordinates and related planar error ellipses and heights (semimajor axis at 95% confidence level) of the IGM95 network (IGM computation, March-April 1995 epoch).

IGM95 network: stations surveyed in the epicentral area (coordinates at 1995 epoch)			
Station label and name	Lat N	Lon E	Ht (m)
COLF - Colfiorito	43° 00′ 20.299944″	12° 51′ 28.159492″	903.063
BEVA - Bevagna	42° 56′ 02.911034″	12° 36′ 14.903192″	253.995
CAST - Castiglione	43° 07′ 39.596258″	12° 03′ 20.293544″	379.882
CROC - Collecroce	43° 04′ 42.693004″	12° 51′ 14.209579″	965.645
CAPA - Capannacce	43° 05′ 14.806058″	12° 45′ 48.634521″	429.672
CSAN - Collesanto	43° 03′ 42.837778″	13° 09′ 52.308829″	879.154
FOL - Foligno	42° 54′ 43.208936″	12° 43′ 43.728275″	271.770
GAIF - Gaifana	43° 11′ 06.564125″	12° 47′ 05.834660″	536.862
OGAT - O. Gatto	43° 17′ 15.640230″	12° 44′ 57.906763″	462.031
PENN - Pennino	43° 06′ 04.978021″	12° 53′ 19.482631″	1619.044
RIVO - Rivotorto	43° 02′ 42.058120″	12° 36′ 43.697338″	258.313
TPAR - Torre Parco	43° 11′ 34.313939″	13° 03′ 20.536910″	369.738
VISS - Visso	42° 54′ 26.361733″	13° 01′ 59.072522″	541.508
Average accuracy (95% confidence level) S_{max} = 22 mm; S_{min} = 22 mm		Vertical Dh = 35 mm	

systems (table III). Site displacements were computed by minimising the residuals at the GPS stations located at distances greater than 15 km from the epicenters, assuming that for earthquakes of M_w = 5.7 and 6.0, coseismic ground deformation is zero at such distances, in agreement with Wells and Coppersmith's (1994) formulation. Our computations confirmed the accuracy of the IGM network (Surace, 1997) and revealed the coseismic displacements at some GPS monuments (figs.1 and 4, table VI).

Table V. Geographical coordinates and related planar error ellipses and heights of the GPS monuments after the main shocks of September 26, 1997 (October 1997 epoch, ING97 campaign).

ING97 surveys Coordinates and error ellipses							
Station label and name	Lat N	Lon E	Ht	S_{max} (mm)	S_{min} (mm)	Az. (°)	Dh (mm)
COLF - Colfiorito	43° 00′ 20.300069″	12° 51′ 28.160123″	902.994	5.4	5.4	11° 25	11.9
BEVA - Bevagna	42° 56′ 02.911185″	12° 36′ 14.903402″	253.951	9.5	6.7	1° 35	19.2
CAST - Castiglione	43° 07′ 39.596438″	12° 03′ 20.293216″	379.883	5.9	5.4	65° 19	9.9
CROC - Collecroce	43° 04′ 42.688659″	12° 51′ 14.208758″	965.398	12.2	9.5	6° 51	23.4
CAPA - Capannacce	43° 05′ 14.804241″	12° 45′ 48.634939″	429.673	10.8	8.1	7° 48	19.2
CSAN - Collesanto	43° 03′ 42.838774″	13° 09′ 52.308918″	879.166	14.8	10.8	0° 23	30.1
FOLI - Foligno	42° 54′ 43.207968″	12° 43′ 43.727474″	271.803	6.7	5.4	6° 53	13.5
GAIF - Gaifana	43° 11′ 06.563932″	12° 47′ 05.836214″	536.879	10.8	8.1	0° 56	20.3
OGAT - O. Gatto	43° 17′ 15.640156″	12° 44′ 57.908473″	462.070	5.9	4.0	1° 34	10.4
PENN - Pennino	43° 06′ 04.980608″	12° 53′ 19.486220″	1619.005	10.8	9.5	2° 19	22.3
RIVO - Rivotorto	43° 02′ 42.057546″	12° 36′ 43.696804″	258.294	9.5	6.7	7° 30	18.2
TPAR - Torre Parco	43° 11′ 34.314170″	13° 03′ 20.535370″	369.674	14.8	13.5	11° 16	30.6
VISS - Visso	42° 54′ 26.361993″	13° 01′ 59.072174″	541.531	12.2	9.5	17° 1	29.0
Average accuracy (95% confidence level)				9.94	7.89	10° 63	19.84

Table VI. Coseismic displacement vectors of the GPS stations. The north, east, total and vertical components are reported in the table.

Umbria-Marche earthquakes Horizontal and vertical displacements (mm)					
Station label and name	North component (mm)	East component (mm)	Total component (mm)	Az. (°)	Vertical displacement (mm)
COLF - Colfiorito	– 1.5	11.8	11.7	98	– 68.7
BEVA - Bevagna	2.0	0.3	2.0	8	– 43.9
CAST - Castiglione	8.4	– 5.7	7.7	326	+ 1.2
CROC - Collecroce	– 137.9	– 18.6	139.1	188	– 247.1
CAPA - Capannacce	– 57.3	10.7	58.3	170	+ 1.1
CSAN - Collesanto	24.3	0.8	24.3	3	+ 12.4
FOLI - Foligno	– 32.1	– 32.4	45.6	224	+ 33.3
GAIF - Gaifana	– 7.0	36.3	36.9	101	+ 17.1
OGAT - O. Gatto	– 8.4	37.1	38.0	103	+ 39.6
PENN - Pennino	76.4	80.4	110.9	46	– 39.0
RIVO - Rivotorto	– 19.9	– 13.2	23.9	213	– 18.8
TPAR - Torre Parco	5.5	– 31.5	31.9	279	– 63.9
VISS - Visso	27.2	8.3	28.4	18	+ 22.9

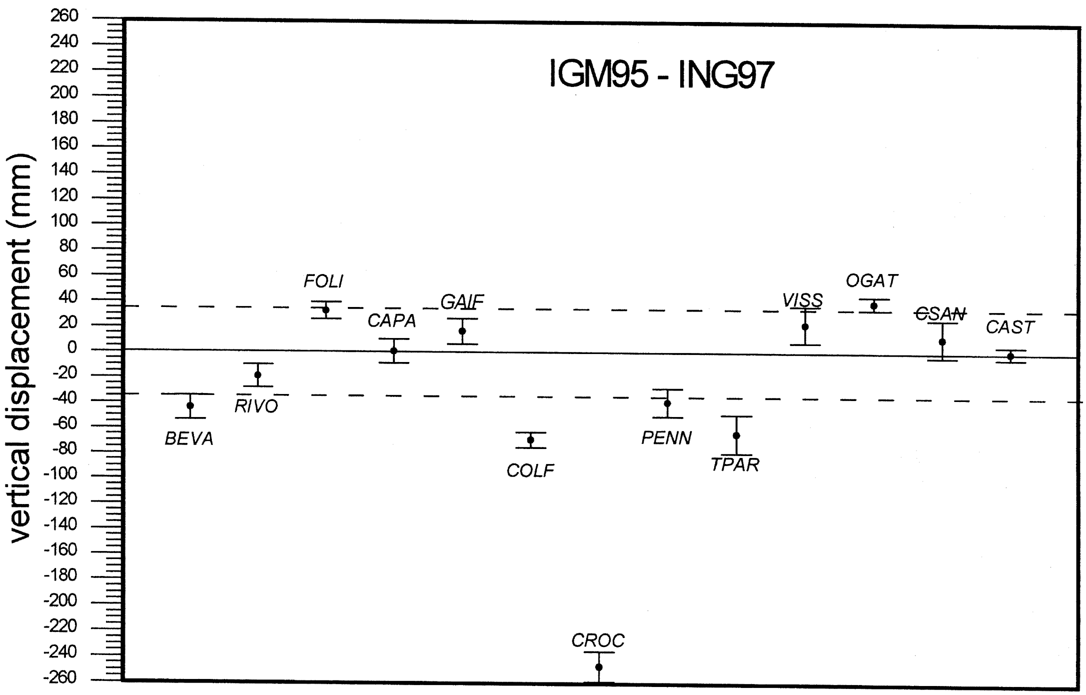

Fig. 4. Coseismic height variation at the GPS stations. Dashed lines represent the average height error field of the IGM95 data set (all at 95% confidence level).

4. Discussion

The comparison of IGM95 and ING97 data set of GPS coordinates allowed the determination at centimetric level of the displacements of 13 GPS stations located around the epicentral area, which occurred between March-April 1995 and October 1997, thus comprising the two main shocks of the Colfiorito earthquake sequence.

The largest displacements (figs.1 and 4, table VI) were measured at CROC (– 24.7 ± 3.5 cm vertical and 14 ± 3 cm planar), PENN (– 3.9 ± 3.5 cm vertical and 11.0 ± 3.0 cm planar) and CAPA (+ 0.1 ± 3.5 cm vertical and 5.8 ± 3.0 cm planar). Significant vertical displacements were measured at COLF (– 6.9 ± 3.5 cm) and BEVA (– 4.4 ± 3.5 cm), although the latter is located at one end of a small bridge and can be subjected to local instabilities. The stations of OGAT (+ 3.9 ± 3.5 cm vertical and 3.8 ± 3 cm planar), GAIF (+ 1.7 ± 3.5 cm vertical and 3.7 ± 3 cm planar) and FOLI (+ 3.3 ± 3.5 cm vertical and 4.5 ± 3.0 cm planar) display doubtful displacements being near the accuracies of the IGM95 data. Moreover they are located on recent geological units of lacustrine sediments or recent alluvium. The remaining stations of RIVO, VISS, CSAN and CAST stations do not display significant motion. The TPAR station (– 6.4 ± 3.5 cm vertical and 3.2 ± 3.0 cm planar) was measured during one single session measurement only, thus providing statistically unreliable final coordinates to be used for any tectonic interpretation.

The most relevant geodetic data were collected at the GPS monuments of PENN, CROC, COLF and CAPA, located nearest the epicentres of the mainshocks (figs.1 and 2) and can be summarized as follows:

– The PENN and CROC sites display similar but opposite horizontal displacements along the NE-SW direction. The total extension between the stations is 25 ± 2.3 cm (CROC 14 ± 1.2 cm to SW and PENN 11 ± 1.1 cm to NE);

– The CROC site displays 24.7 ± 3.5 cm of subsidence.

– The PENN site does not display significant vertical displacement (near the IGM95 accuracy).

– The COLF site displays 6.9 ± 3.5 cm subsidence but about null horizontal displacement.

– The CAPA site displays horizontal displacement of 5.8 ± 1.1 cm but about null height variation.

It must be stressed that the geodetic monuments of CROC, PENN, CAPA and COLF are in a good position with respect to the epicenters of the main shocks: the approximate surface projection of the fault plane of the 09.40 GMT (Amato *et al.*, 1998; Ekström *et al.*, 1998; Hunstad *et al.*, 1998; Stramondo *et al.*, 1999) passes between the CROC and PENN stations, about 3 km from each other.

It is relevant to note that PENN and CROC display opposite and similar magnitude of the horizontal displacement vectors (14 ± 1.2 cm at CROC and 11 ± 1.1 cm at PENN) but significant vertical variations are detected only at CROC (near the IGM95 accuracy at PENN and – 24.7 ± 3.5 cm at CROC). This can be explained by the rupture mechanism of the mainshocks, produced by purely normal faults, dipping at low angle (~ 40°) to SW and confined in the upper ~ 8 km of the crust (Amato *et al.*, 1998). The GPS data provide a robust constrain to determine that PENN is located on the footwall of the fault, while CROC (and CAPA) is on its hangingwall. It is remarkable to note that field observations revealed a ~15 cm downward SW displacement along limestone bedding at the foot of Mt. Pennino, halfway between CROC and PENN stations: this is in agreement with GPS data and fringe displacements from SAR observations (Stramondo *et al.*, 1999) that both detected the maximum gradient of vertical deformation in this area. Concerning the displacements measured at CAPA, COLF and FOLI, it must be taken into account that two moderate earthquakes occurred on October 3 at 08:55 GMT (M_w = 5.2) and October 6 at 23:24 GMT (M_w = 5.4). Their epicentral location is close to the September 26, 09:40 hypocenter, and they could have contributed to the observed surface deformation. The orientation of displacement vectors at all the GPS monuments, agrees well with the seismological observations when the depth of the upper fault edge is within 1 km and 3-4 km of depth for the 09:40 and 00:33 GMT seismic events respectively; moreover the orientation of displacement observed at CAPA and CROC require a minor left lateral strike slip component along the causative faults (Hunstad *et al.*, 1998).

Although a preseismic contribution to the measured ground deformation cannot be excluded, we believe that the observed displacements are largely coseismic because the long term tectonic deformation of the Central and Southern Apennines, recently estimated to be 0.3 mm/yr on the basis of historical and instrumental seismic data (Selvaggi, 1998), is not able to produce displacements large enough to be revealed by GPS observations during a 2 year (1995-1997) time span and can be neglected in our analysis.

The data collected during IGM95 (March-April 1995 epoch) (table IV) and ING97 campaigns (October 1997 epoch) (table V) represent a high precision geodetic 3D data set of ground displacements that are in good agreement with SAR observations (Stramondo *et al.*, 1999), seismological parameters (Ekström *et al.*, 1998; Amato *et al.*, 1998), regional stress (Montone *et al.*, 1997) and the location of the coseismic ground ruptures (Cinti *et al.*, 1999).

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