ANNALI DI GEOFISICA, VOL. XXXVIII, N. 2, May 1995

The Southeastern Sicily GPS network

Vladimiro Achilli ([1]), **Marco Anzidei** ([2]), **Paolo Baldi** ([3]), **Franco Broccio** ([4]) **and Rosanna Velardita** ([5])
([1]) *Dipartimento di Ingegneria Civile Edile, Università di Bologna, Italy*
([2]) *Istituto Nazionale di Geofisica, Roma, Italy*
([3]) *Dipartimento di Fisica, Università di Bologna, Italy*
([4]) *Istituto Geofisico e Geodetico, Università di Messina, Italy*
([5]) *Istituto Internazionale di Vulcanologia, Catania, Italy*

Abstract
The area located between Catania and Syracuse (Southeastern Sicily), characterized by the presence of the Simeto-Scordia-Lentini graben, was affected in the past by a strong seismicity as proved by the occurrence of seismic events strong enough to reach the XI degree of the MCS scale. In particular the January 11th, 1693 (I = XI MCS) earthquake with a magnitude over 7.5 (estimated), caused huge damage and a great loss of human lives. Following the last seismic event which occurred on December 13th, 1990 ($M_l = 5.4$) which caused heavy damage and many victims in the Catania-Syracuse area, a geodetic Global Positioning System network (GPS) was set up with the aim of monitoring ground movements in one of the Italian areas subjected to high seismic risk. This space geodesy technique supplies high precision measurements and represents a powerful new tool for investigating both regional stress fields and the evolution of local tectonic areas. The GPS network will allow the detection of ground movements with a centimetric accuracy through repeated surveys in time. The results obtained in two surveys carried out in 1991 and 1993, are described in this paper.

Key words *Global Positioning System – crustal deformations*

1. Introduction

In historical times Southeastern Sicily was striken by some of the most disastrous seismic events of the whole Mediterranean basin. The maximum intensity isoseismal maps of the strongest events which occurred in the area (Barbano and Cosentino, 1981; PFG, 1985) in 1169 and 1693 (I = XI Mercalli scale) virtually coincide and suggest a common origin in the extensional structure known as the Simeto-Scordia-Lentini graben (fig. 1). After the last destructive event (estimated M = 7.5) of January 11th, 1693, only a few moderate earthquakes occurred in the area. Although seismic activity ceased almost completely from the beginning of the XIX century (Purcaru and Berckhemer, 1982; Mulargia *et al.*, 1991), the vertical component of the crustal deformations in this area have been measured since 1970, when a first order levelling survey was performed along a levelling route of the National Altimetric Network of the Istituto Geografico Militare Italiano (IGMI); the measurements were repeated during 1983 and again in 1989 (Mulargia *et al.*, 1985, 1991). The levelling data revealed a continuous subsidence of the order of 3 mm/yr, allowing a crustal strain of 10^{-6}-10^{-7} to be estimated (Mulargia *et al.*, 1985, 1991).

In order to confirm and explain the presence of active crustal dynamics, it appears necessary to monitor also the horizontal component of ground deformation by means of terrestrial and space techniques such as GPS. In fact the mean deformation seems to be so large that the GPS observations will also contribute, after repeated

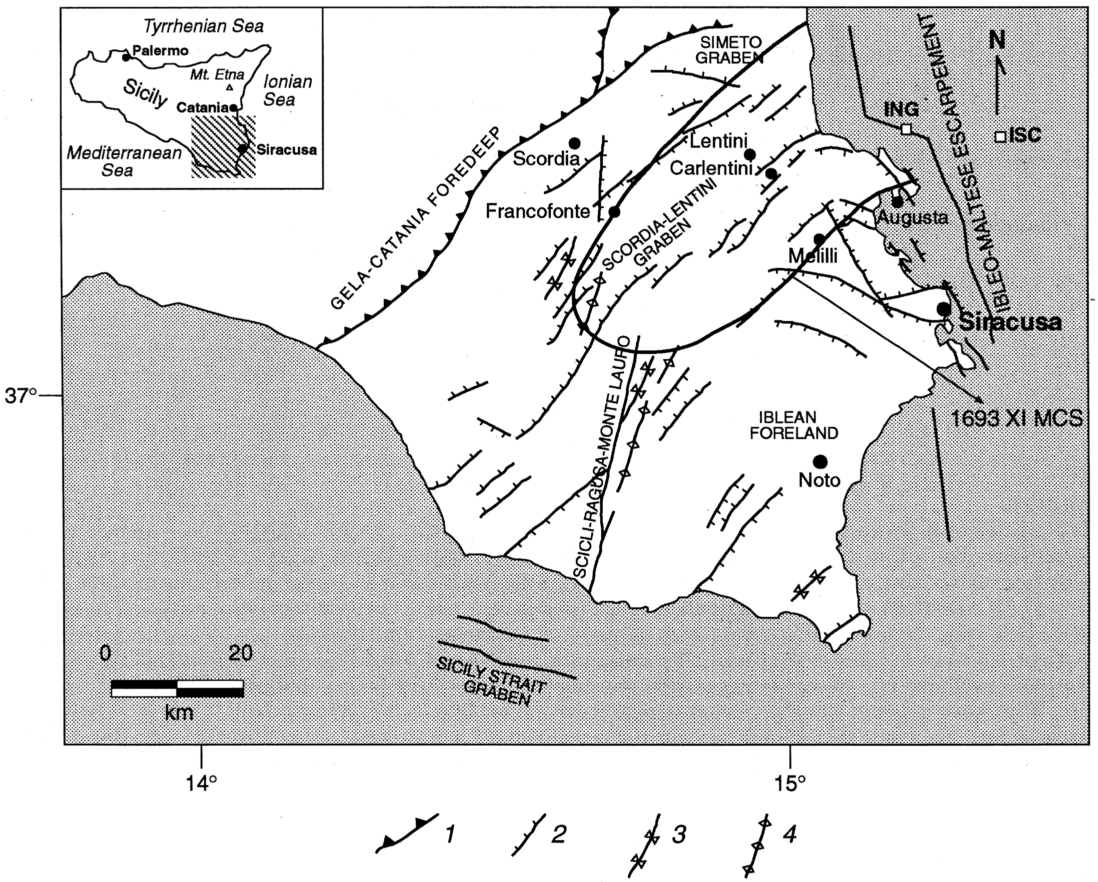

Fig. 1. Main tectonic structures of Southeastern Sicily: 1) main thrust faults; 2) normal faults; 3) syncline axes; 4) anticline axes. The mainshock epicenters from ING and ISC of December 13, 1990 (Amato *et al.*, this volume) and the XI degree intensity (MCS) isoseims of 1693 earthquake are also reported in the map.

surveys in time, to detect both the planimetric and altimetric components of the slow crustal deformations; in case of an important seismic event within the surveyed area, the coseismic displacement could be pointed out by the repetition of the geodetic measurements on the network. The geodetic network project, which at first planned the use of both terrestrial geodetic methodologies (EDM) and satellite geodetic measurements (GPS) was started at the beginning of 1991, after the occurrence of the December 13th, 1990 earthquake.

2. Seismotectonic setting

The geological-structural setting of the investigated area must be considered in the frame of the complex tectonic features of the Mediterranean basin, which is dominated by the compressive dynamics between the African and the Euroasiatic continental plates. The Hyblean foreland, which is considered by most authors as the northern margin of the African continental crust, was weakly deformed during alpine orogenesis and subjected until the present to moderate uplift and to overall extensional tectonics (Mascle, 1974; Di Grande and Grasso, 1977; Grasso *et al.*, 1979). The area is formed by horst with NE-SW alignment, delimited toward SE by the Ispica-Capo Passero tectonic depression and toward NW by a normal fault system oriented NE-SW, which lower the carbonatic series under the northern chain nappes of which the Gela Nappe is the outer front. This area is better known as the transition zone to the Gela-Catania foredeep. The Hyblean plateau, together with the northern chain, is one of the most important structural elements of Sicilian orogenesis. A subdivision of the area, founded on the structural characters and the tectonic-sedimentary evolution during the time period Upper Miocene-Quaternary, distinguishes a western sector where the tensional phenomena can be considered the surface manifestations of an overall compressive tectonics, and a eastern sector or Ionian sector which is characterized by extensional movements. Studies of this sector add to our the knowledge of the Ionian basin which is believed to be one of the most important kinematic factors during the period when the Africa-Europe interaction produced the greatest Tertiary and Quaternary deformations (Carbone *et al.*, 1982). According to a model proposed by Ghisetti and Vezzani (1980), two extensional structures can be identified in this area known as Simeto-Scordia-Lentini graben and Sicilian Strait graben which are thought to be linked by the Scicli-Ragusa-Monte Lauro fault system, by a NNE-SSW alignment, along which right-lateral movements are shown (fig. 1). This tectonic setting is attributed to an overall compressive phase dated up to the Middle Miocene while the normal movements, that affected all the main systems of the area, belong to a recent tectonic phase which lasted until the present (Ghisetti and Vezzani, 1982). This interpretation is the one that best fits the historical seismicity of the area which appears widely originated at the Simeto-Scordia-Lentini graben, except for a few events of moderate energy which occurred in the Syracuse area (Mulargia *et al.*, 1985). A high concentration of events can be observed also in the intersection of the NNE-SSW system with the graben. The strongest events appear again to be originated in the same structure, but much further to the East, away from the coast, at the intersection of the graben with the fault system of the Hyblean-Maltese escarpment (Mulargia *et al.*, 1985). After the IX century, the main earthquakes which occurred on February 4th 1169, December 10th 1542, October 3rd 1624 and January 11th 1693, originated intensities higher than the MCS IX degree. In particular the 1169 and 1693 events reached intensity as high as the MCS XI degree and caused the destruction of many cities in Southeastern Sicily (Baratta, 1900). The January 11th, 1693 earthquake was located in the Carlentini-Lentini-Melilli area (Simeto-Scordia-Lentini graben) and was certainly one of the strongest earthquakes to occur in Italy and in the whole Mediterranean basin (Barbano and Cosentino, 1981) The analogies in the macroseismic field distribution and the epicenter identification of the 1169 and 1693 seismic events, imply the same source mechanism (Mulargia *et al.*, 1985).

After a long period of seismic quiescence, on December 13th, 1990 the area was struck by a $M_l = 5.4$ seismic event that caused heavy damage and loss of human lives in a wide area between Syracuse and Catania. The earthquake, whose epicenter has been located offshore (fig. 1) a few km away from the coastline (ING location: 37°32′N, 15°25′E, depth = 22 km; ISC location: 37°31′N, 15°43′E, depth = 10 km fixed) and almost in coincidence with the Ibleo-Maltese escarpment, displayed a right lateral movement as shown by the focal mechanism of the main shock (Amato *et al.*, 1991; De Rubeis *et al.*, 1991; Giardini, 1991). This solution could be in accordance with the main structural and tectonic features of the area.

If such a rupture mechanism is characteristic of this area and if the deformations produced by the seismogenetic structure after an important earthquake are large enough to be measured on the topographic surface within the network, the repetition of geodetic surveys by means of the GPS technique will provide important future information on eventual coseismic displacement, the temporal evolution of the deformation and the GPS site velocities.

3. Geodynamics and Global Positioning System

The NAVSTAR-GPS, whose acronym means NAVigation Satellite Timing And Ranging-Global Positioning System, was set up by the Department of Defense of the United States of America and was designed to provide an absolute three-dimensional, real time navigation. The same system can provide relative position accuracies of two or more observers in the centimeter range. A Space segment covers the entire constellation of the NAVSTAR-GPS satellites (21 operational plus 3 spare satellites), orbiting in six orbital planes at almost circular orbital paths. A Control segment that consists of a Master station located in Colorado Springs (U.S.A.) and several monitor stations distributed around the Earth compute the satellite orbital data, control the clock's synchronism and the operational system.

The User segment is represented by the users that install the GPS receivers and antennas in the sites to be measured. The satellite signal, produced by an atomic clock at the fundamental frequency of 10.23 MHz, is modulated on two carriers L_1 (1575.42 MHz) and L_2 (1227.60 MHz) and by the codes P and C/A.

A GPS receiver generates a signal like that transmitted from each GPS satellite and identifies for each satellite the codified sequence on the carriers. The phase shift between the signal coming from the satellite and that produced by the receiver depends on the distance between the receiver and the satellite, and than on the receiver's position in a geocentric reference system. The use of a carrier phase data recorded simultaneously by two receivers yields baseline estimates with an accuracy of 1-0.1 ppm or better, using different linear combinations of the two frequencies L_1 and L_2. The utilization of different linear combinations of the L_1 and L_2 carriers reduces the effect of ionospheric refraction (L_3), provides solutions that are independent of the clocks and of the geometry of the receivers (L_4), and reduces any unmodelled systematic errors (L_5) (Rotacher *et al.*, 1990).

The combination of the main characteristics of the GPS system, such as accuracy, versatility, low cost, has given rise to a wide variety of applications in geodesy and geodynamics. Surveys can be carried out easily at observation sites not visible to each other and even located at long distances, without the limitations of the terrestrial techniques, offering the opportunity for a conspicuous saving both of economic and human resources during the setting up and survey of geodetic networks. These features improve the way of planning and setting up geodetic networks, allowing accurate measurement of relative position of observation sites, in short time intervals (Achilli *et al.*, 1988; England, 1989, 1991; Anzidei *et al.*, 1990; Ashkenazi and Foulk Jones, 1990).

Geodetic GPS measurements performed on local networks (baselines shorter than 50 km), located in seismic areas characterized by fault systems, can provide reliable, accurate and rapid determination of crustal motion at centimetric level, in particular seismically induced deformation. In fact the GPS technique is a powerful new geodetic method capable to provide valuable information, not easily available with other techniques, of the measurement of the coseismic strain field, aspects of the rupture mechanism and in general of the ground movement evolution during seismic and interseismic periods (Straub and Kahle, 1993; Kahle *et al.*, 1993; Bock *et al.*, 1993; Blewitt *et al.*, 1993; Ruegg *et al.*, 1993). GPS can also be successfully employed for the observation of other geological phenomena such as filling and emptying processes of magma chambers in volcanic areas, monitoring of sliding slopes, subsidence, etc... (Gibbons, 1990; Achilli and Baldi, 1991; Dixon, 1991). The accurate 3-D vectors provided by the GPS networks also allow constraints for the detection of block rotations, which is not possible with conventional techniques (Davis *et al.*, 1989).

4. The GPS network

The Southeastern Sicily GPS geodetic network consists of 8 observation sites (fig. 2); two of these coincide with the terrestrial geodetic network of the International Institute of Volcanology (I.I.V.) of Catania, which was

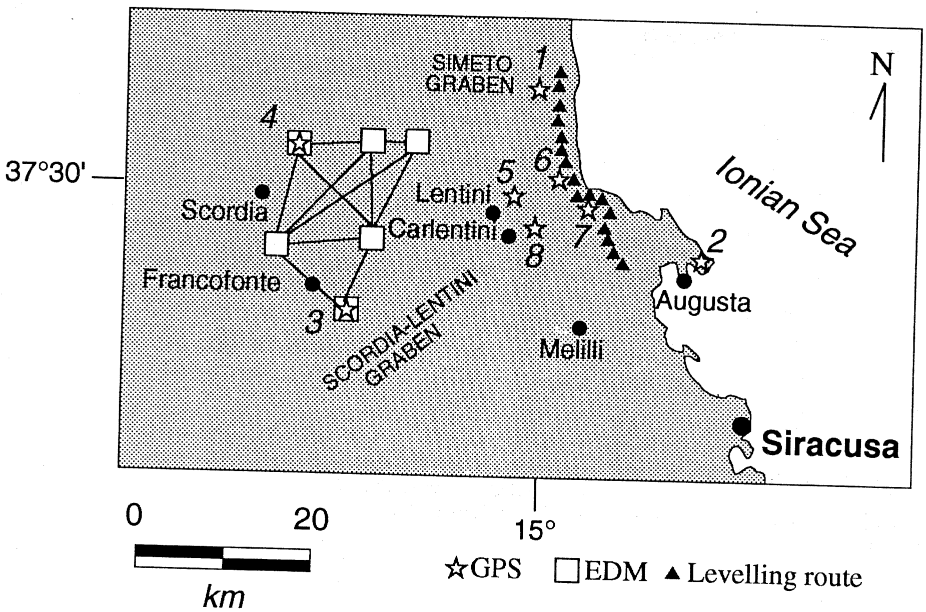

Fig. 2. The Southeastern Sicily GPS network: 1) Iazzotto; 2) S. Croce; 3) Pedagaggi; 4) Rannè; 5) S. Lio; 6) Speronello; 7) Gattone; 8) S. Giovannello. The terrestrial (EDM) geodetic network belonging to the Istituto Internazionale di Vulcanologia and part of the levelling route of the Istituto Geografico Militare Italiano are also reported in the map.

measured just after the December 13th, 1990 earthquake. The GPS site installation, carried out at the beginning of January 1991, was performed using stable reference markers made of stainless steel nails set up directly on the rock. The markers distribution was chosen both to satisfy the planned network configuration and the geophysical needs: they are located near the epicentral area of the December 13th, 1990 earthquake, across the main tectonic structures that belong to the Simeto-Scordia-Lentini graben. The first epoch GPS survey was carried out in January 1991, using four dual frequency Wild Magnavox WM102 receivers (table I). During the measurement time windows up to 4 satellites were simultaneously tracked in the three sessions. As the GPS satellite constellation improved after the first epoch campaign, a new survey was required to achieve a better determination of the network parameters. In October 1993 a second epoch survey was performed and all the sites of the network were reoccupied using four or five dual frequency WM-102 receivers during the planned five session measurements when up to 6 satellites were simultaneously tracked.

Table I. General features of the GPS surveys.

Campaign	01-1991	10-1993
Sites	8	8
Receivers (WM 102)	4	5
Session length (h)	2	4+4
Total satellites observed	6	15

5. GPS data analysis

The data analysis was carried out by means of PoPS vers. 3.42 running on a MS/DOS Personal Computer. After careful screening of the data, the baseline repeatabilities were analysed

Table II. Number, names and geographic coordinates (WGS84) of the network vertices.

No.	Site	Latitude (N)	Longitude (E)	H (m)
1	Iazzotto (IAZ)	37°22′49.185″	15°02′52.328″	86.56
2	S. Croce (CRC)	37°14′28.786″	15°15′20.300″	45.52
3	Pedagaggi (PGD)	37°11′34.360″	14°56′22.604″	416.89
4	Rannè (RNE)	37°19′46.580″	14°54′33.085″	134.36
5	S. Lio (SLI)	37°18′29.496″	15°00′53.948″	61.769
6	Speronello (SPE)	37°18′44.705″	15°03′18.239″	99.62
7	Gattone (GAT)	37°17′56.189″	15°06′16.376″	156.80
8	S. Giovannello (GIO)	37°16′17.697″	15°01′49.773″	271.88

to detect poor observations. All the ambiguities (integer number of carrier wavelengths) were determined in the computation. Low quality data were considered separately. Only observation of satellites with elevation angles greater than 15° above the horizon were considered in the analysis in order to reduce the tropospheric noise. During the computation the broadcast ephemeris received by the satellites of the NAVSTAR-GPS constellation were used. To achieve more precise results, data computation was carried out using both L_1 and L_2 frequencies and their linear combinations. This was necessary to correct the noise due to the ionosphere (L_3) and to resolve the ambiguities (L_5). A ionospheric correction was based also on a single layer ionosphere model and was computed as a function of the total electronic content estimated on the basis of the two GPS carriers, the elevation angle of the satellites and the observation time (Rotacher, 1990; Dixon, 1991). The meteorological parameters were not collected during the measurements, thus a local correction for atmospheric refraction was included in the computation using a standard atmosphere model based on mean temperatures, pressure values and humidity (Saastaimonen, 1973). Finally a solution taking into account all the data collected throughout campaign was calculated for the 1993 surveys. The daily repeatability was of about 10^{-6} 10^{-7} for the baseline vectors.

Due to a poorer satellite availability, the results related with the first campaign in some cases were not accurate enough and only a few observations provided reliable data. Tables II and III report the results of the surveys. Table II indicates the number, GPS site labels and their geographic coordinates as derived from the network computation. The comparison of some baselines between the 1991 and 1993 surveys are reported in table III (in meters). The error ellipses of the network vertices measured in 1993 are shown in fig. 3 (network adjustment performed by Geolab software). The

Table III. Comparison of some baselines between 1991 and 1993 surveys (distances in meters). Data computation was performed by PoPS software vers. 3.42.

Sites	1991 (m)	1993 (m)
CRC-GIO	20255.167	20255.145
CRC-GAT	14848.877	14848.890
RNE-GIO	12536.375	12536.357
RNE-IAZ	13514.870	13514.859
RNE-SLI	9674.105	9674.093
IAZ-SLI	8519.835	8519.849
GAT-GIO	7236.336	7236.347
PGD-SLI	14444.548	14444.563
PGD-RNE	15415.720	15415.723
PGD-IAZ	22915.245	22915.243
PGD-GAT	18783.232	18783.226
SPE-GIO	5004.100	5004.098

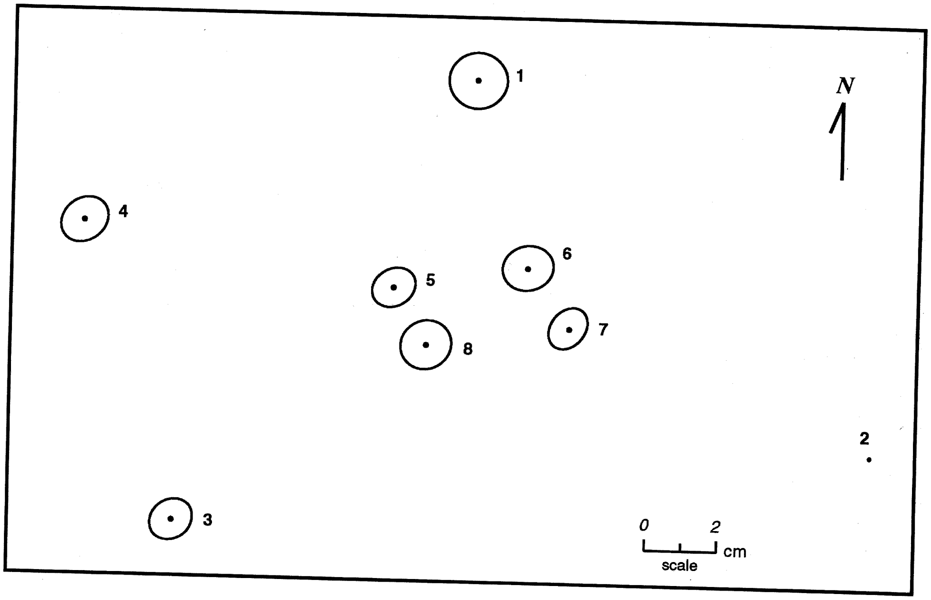

Fig. 3. Error ellipses of the computed GPS network (1993 surveys).

site CRC is considered fixed in the computation. The comparison between the two campaigns and the internal consistency the 1993 solution, confirms the reliability of the GPS measurements which provide a data base for the next surveys at centimetric accuracy level. The residual error can be imputed to the not well known electronic phase center of the receiving antennas and to troposphere refraction.

6. Conclusions

The pattern of crustal deformations may provide essential indications on the state of stress of a seismic area and on the different phase of the seismic cycle; the dislocation on the topographic surface associated with an earthquake may lead to an improvement in information on seismic source mechanisms provided by seismic data. Geodetic space techniques and in particular the GPS system, allow the strain field of small and wide areas of the earth surface to be investigated, with a precision of 10^{-6} or better.

In 1991 a GPS geodetic network was set up and measured in Southeastern Sicily, to monitor the ground deformations of an area characterized by a high seismic risk, where levelling surveys performed since 1970, had already evidenced vertical motion at a rate of 3 mm/yr. In case of an important seismic event within this area, the immediate repetition of the measurements of the network will allow the identification of the superficial dislocation. The results obtained from 1991 and 1993 surveys constitute a first data base of a time series that will provide the rate of change of relative station coordinates by repeated surveys to be performed at least every two years.

Acknowledgements

We wish to thank Prof. E. Boschi, President of the Istituto Nazionale di Geofisica (ING) and Dr. C. Gasparini, Director of the Geodynamic Department of the ING, who encouraged this project. We are thankful to Mr. G. Capone of the Servizio Sismico Nazionale for his contribution in the field during the 1993 GPS surveys.

REFERENCES

ACHILLI, V., M. ANZIDEI, P. BALDI, F. BROCCIO, V. CAGNETTI, P. MARSAN, G. SALEMI, R.M. STROLLO and S. ZERBINI (1988): Il progetto Arco Calabro. Misure geodetiche classiche e GPS, in *Atti del VII Convegno del GNGTS, Roma*, vol. II, 1015-1022.

ACHILLI, V. and P. BALDI (1991): Prospettive ed applicazioni delle tecniche geodetiche per lo studio di aree sismiche, *Aree Sismogenetiche e Rischio Sismico II* (Ed. Galileo Galilei, Roma), 369-380.

AMATO, A., R. AZZARA, A. BASILI, C. CHIARABBA, M. COCCO, M. DI BONA and G. SELVAGGI (1991): La sequenza sismica del dicembre 1990 nella Sicilia orientale: analisi dei dati sismometrici, in *Contributi allo Studio del Terremoto della Sicilia Orientale del 13 Dicembre 1990*, edited by E. BOSCHI and A. BASILI, *Pubblication* of *Istituto Nazionale di Geofisica*, Roma, n. 537, 57-84.

ANZIDEI, M., C. GASPARINI, F. RIGUZZI, V. ACHILLI, P. BALDI and P. MARSAN (1990): GPS networks in seismic and volcanic areas in Central and Southern Italy, *Centre Europeen de Geodynamique et de Seismologie*, in *Proceedings «GPS for Geodesy and Geodynamics»* (Luxenbourg) **1**, 305-316.

ASHKENAZI, V. and G. FOULK JONES (1990): Millimeters over hundred kilometers by GPS, *GPS World*, **6**, 44-47.

BARATTA, M. (1900): I terremoti d'Italia, *Soc. Geogr. Ital. Torino*, 30-33.

BARBANO, M.S. and M. COSENTINO (1981): Il terremoto siciliano dell'11 gennaio 1693, *Rend. Soc. Geol. Ital.*, **4**, 517-522.

BLEWITT, G., M.B. HEFLIN, K.J. HURST, D.C. JEFFERSON and F.H. WEBB (1993) Absolute far field displacements from the 28 June 1992 Landers earthquake sequence, *Nature*, **361**, 340-342.

BOCK, Y., D. AGNEW, P. FANG, J.F. GENRICH, B.H. HAGER, T.A. HERRING, W.K. HUDNUT, R.W. KING, S. LARSEN, J.B. MINSTER, K. STARK, S. WDOWINSKI and F.K. WYATT (1993): Detection of crustal deformation from the Landers earthquake sequence using continuous geodetic measurements, *Nature*, **361**, 337-340.

CARBONE, S., M. COSENTINO, M. GRASSO, F. LENTINI, G. LOMBARDO and G. PATANÈ (1982): Elementi per una prima valutazione dei caratteri sismotettonici dell'avampaese Ibleo (Sicilia Sud Orientale), *Mem. Soc. Geol. It.*, **24**, 507-520.

DAVIS, J.L., W.H. PRESCOTT, J.L. SVARC and K. WENDT (1989): Assessment of Global Positioning System measurements for studies of crustal deformation, *J. Geophys. Res.*, **94**, 13635-13650.

DE RUBEIS, V., C. GASPARINI, A. MARAMAI and M. ANZIDEI (1991): Il terremoto Siciliano del 13 Dicembre 1990, in *Contributi allo Studio del Terremoto della Sicilia Orientale del 13 Dicembre 1990*, edited by E. BOSCHI and A. BASILI, *Publication of Istituto Nazionale di Geofisica*, Roma, n. 537, 9-44.

DI GRANDE, A. and M. GRASSO (1977): Lineamenti geologici del margine occidentale ibleo nei dintorni di Comiso-Ragusa (Sicilia), *Boll. Soc. Geol. It.*, **96**, 209-224.

DIXON, T.H. (1991): An introduction to the Global Positioning System and some geological applications, *Rev. Geophys.*, **29**, 249-276.

ENGLAND, P. (1989): Geophysical application of GPS surveying, in *Seminar on the Global Positioning System*, University of Nottingham.

ENGLAND, P. (1991): Geophysical application of GPS surveying, in *Seminar on the Global Positioning System, Nottingham.*

GHISETTI, F. and L. VEZZANI (1980): The structural features of the Iblean plateau and of the Mount Iudica area (South Eastern Sicily). A microtectonic contribution to the deformational history of the Calabrian Arc, *Boll. Soc. Geol. It.*, **99**, 57-102.

GHISETTI, F. and L. VEZZANI (1982): The recent deformation mechanism of the Calabrian Arc, *Earth Evol. Sci.*, **3**, 197-206.

GIARDINI, D. (1991): Analisi dei dati MEDNET per il terremoto della Sicilia Orientale del 13 Dicembre 1990: Modellazione a lungo periodo, in *Contributi allo Studio del Terremoto della Sicilia Orientale del 13 Dicembre 1990*, edited by E. BOSCHI and A. BASILI, *Publication of the Istituto Nazionale di Geofisica*, Roma, n. 537, 103-114.

GIBBONS, G. (1990): GPS and the quake, *GPS World*, **1**, 34-39.

GRASSO, M., F. LENTINI, G. LOMBARDO and G. SCAMARDA (1979): Distribuzione delle facies cretaceomioceniche lungo l'allineamento Augusta-Monte Lauro (Sicilia Sud Orientale), *Boll. Soc. Geol. It.*, **98**, 175-188.

KAHLE, H.G., V.M. MULLER, S. MULLER and G. VEIS (1993): The Kephalonia transform fault and the rotation of the apulian platform: evidences from satellite geodesy, *Geophys. Res. Lett.*, **20** (8), 651-654.

ISTITUTO NAZIONALE DI GEOFISICA: *Catalogo degli Eventi Sismici Italiani.*

MASCLE, G. (1974): Le système de failles de Comiso, bordure nord occidentale du haut plateau ibléen (Sicilie), *C. R. Somm. Soc. Geol. France*, **16**, 134-136.

MULARGIA, F., F. BROCCIO, V. ACHILLI and P. BALDI (1985): Evaluation of a seismic quiescence pattern in Southeast Sicily, *Tectonophysics*, **116**, 335-364.

MULARGIA, F., V. ACHILLI, F. BROCCIO and P. BALDI (1991): Is a destructive earthquake imminent in Southeastern Sicily ? *Tectonophysics*, **188**, 399-402.

PURCARU, G. and H. BERKHEMER (1982): Regularity patterns and zones of seismic potential for future large earthquakes in the Mediterranean region, *Tectonophysics*, **85**, 1-30.

ROTHACHER, M., G. BEUTLER, W. GURTNER, T. SCHILDKNECHT and U. WILD (1990): *Bernese GPS Software Version 3.2*, University of Berne.

RUEGG, J.C., P. BRIOLE, K.L. FEIGL., A. ORSONI, C. VIGNY, M.A. ABDALLAH, O. BELLIER, J.B. DE CHABALIER, P. HUCHON, E. JACQUES, S. AL KIRBASH, A. LAIKE, N. D'OREYE and M. PREVOT (1993): First epoch geodetic GPS measurements across the Afar plate boundary zone, *Geophys. Res. Lett.*, **20** (18), 1899-1902.

SAASTAIMONEN, J. (1973): Contribution to the theory of atmospheric refraction, *Bull. Geod.*, **107**, 13.

STRAUB, K. and H.G. KAHLE (1993): Global Positioning System (GPS) estimates of crustal deformation of Marmara Sea region, Northwestern Anatolia, *Earth Planet. Sci. Lett.*, **121**, 495-502.