ANNALI DI GEOFISICA, VOL. XXXVII, N. 5, September 1994

The 1990.0 magnetic repeat station survey and normal reference fields for Italy

Antonio Meloni, Osvaldo Battelli, Angelo De Santis and Guido Dominici
Istituto Nazionale di Geofisica, Roma, Italy

Abstract
A survey of 116 repeat stations of the Italian Magnetic Network was carried out between 1989 and 1992. We describe the characteristics of the selected network repeat station sites, the characteristics of the measuring equipment, the data reduction procedure and the analysis in terms of normal field, data mapping and secular variation. Together with the values from our previous campaigns, we also determined, for all elements, the normal fields of secular variation. The new repeat station data are listed. Results, maps and normal fields are discussed with respect to previous work and future survey plans.

Key words *geomagnetic survey and maps – geomagnetic reference fields*

1. Introduction

The first three-component magnetic survey performed in Italy was carried out at the end of last century. That survey included measurements taken at 284 stations distributed uniformly over the Italian peninsula (Tacchini, 1892). Tacchini's is the first complete survey of all the elements, but it was preceded by several other partial surveys. In particular, surveys were performed for declination, inclination and, later, also for the horizontal component, some of which date back as far as the XVII century (see, for example Kircher, 1643).

For a complete description of the early history of measurements of the Earth's magnetic field in Italy, the reader may refer to the Italian Historical Geomagnetic Catalogue (Cafarella *et al.*, 1992a,b), recently published by the Istituto Nazionale di Geofisica (ING). The surveying activity carried out during this century is described by Meloni *et al.* (1988), in a report published on the 1985.0 magnetic survey. This paper illustrates briefly the most recent activity in this field.

Some aspects of the secular variation as observed during the present century have been described by Cafarella *et al.* (1992a,b) and by Battelli and Dominici (1991).

At present, the measuring surveys of the National Network are performed by the ING in cooperation with the Istituto Geografico Militare Italiano (IGMI). Between 1989 and 1992 the two institutes measured the declination (D), inclination (I) and the total intensity (F) of the Earth's magnetic field at 116 repeat stations distributed over the Italian territory (see fig. 1). The horizontal (H) and vertical (Z) components were computed at each site. The network is similar to that used for the 1985.0 survey but includes new stations taken on the Pontine Islands, the Egadi Islands, and the Island of Lampedusa.

The new magnetic repeat stations of this network were chosen following, as far as possible, the usual basic requirements (see Molina *et al.* 1980, 1985a,b, Newitt *et al.*, 1995):

a) absence of artificial disturbances;
b) representativeness of the surrounding area, avoiding areas characterized by large surface anomalies;
c) availability of reference marks allowing the location of the geographic north.

In all the other cases the repeat stations were simply resurveyed.

A detailed description is available for each repeat station of the network. Each description contains the information necessary for locating the bench mark, the azimuth of the reference marks, and a list of all the previous magnetic measurements.

The field equipment we used during the survey included the following magnetic and geodetic instrumentation:

1) a nuclear precession magnetometer for the total intensity *F*;
2) a fluxgate-theodolite for measurements of inclination and declination;
3) a gyroscopic theodolite for the determination of geographic north.

For each repeat station, we normally performed about ten complete measurements of *D*, *I* and *F* within a time interval of approximately 2 h, preferably early in the morning or late in the afternoon so as to avoid the most intense part of the daily variation. The values of *F, D* and *I* were used to determine the horizontal component *H* and the vertical component *Z*. The gyroscopic theodolite was used for new first occupation as a rule; at times, however, when old azimuth marks were not clearly visible it was used also at reoccupations.

2. Magnetic survey and reduction of the measurements

All the network measurements were taken between 1989 and 1992 and then reduced to 1990.0 (00.00 UT h of January 1st, 1990) using data from the main ING geomagnetic observatory in L'Aquila (42.38°N, 13.32°E). We have frequently observed that referring to a single observatory, even if located in the middle of Italy, may lead to some systematic errors that can be significant (see, for instance, Molina *et al.*, 1980) because of the variability of the time-variations of the field across the country. For the 1990.0 survey, such a choice was unavoidable because no other observatory was operating at the required same high-quality level. The Castello Tesino observatory in Northern Italy (see fig. 1) was regularly working for almost all the 1989-1992 time interval but we preferred to use only one observatory for all station reductions. It was later used to control the reduction itself, at least for Northern Italy.

If *E* is one of the elements *D*, *H*, *Z* and *F*; E_s^t is the value of the element observed, or deter-

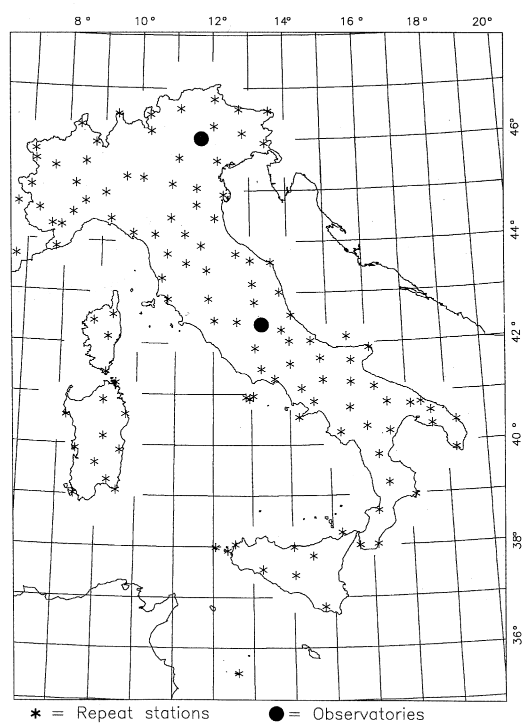

Fig. 1. Italian repeat stations network at 1990.0. Filled circles indicate observatories (L'Aquila 42.38°N, 13.32°E; C. Tesino 46.05°N, 11.65°E).

mined, at station s at the time t; E^t_{oss} is the value of E observed at the same instant t at the observatory; $E^{90.0}_{oss}$ is the value of E at 1990.0 at the observatory; then the value of E at the station s reduced to 1990.0, *i.e.* $E^{90.0}_s$, is given by:

$$E^{90.0}_s = E^{90.0}_{oss} + (E^t_s - E^t_{oss}) \qquad (2.1)$$

More precisely, $E^{90.0}_{oss}$ is the mean value of E determined between 00.00 h of July 1, 1989, and 24.00 h of June 30, 1990. This value is obtained on the basis of hourly daily means of the studied range of time; $(E^t_s - E^t_{oss})$ is the instantaneous difference between the value measured at the station and the corresponding value at the observatory (see also Meloni *et al.*, 1988). Each of the individual measurements was independently reduced to 1990.0, and then we averaged all reduced values to obtain just one value of each element at each repeat station.

Table I lists the measured element values reduced to 1990.0 and the coordinates for the repeat stations. These values can be compared with those obtained in previous campaigns to compute the secular variation of the magnetic field and to update the 1985.0 magnetic mapping for the three field elements plus total field (published in Meloni *et al.*, 1988). In the present paper these values are also used to compute the analytic expression of a second-degree polynomial in latitude and longitude, called a normal reference field (*e.g.* Bullard, 1967).

Prior to the calculation of the normal field coefficients, all the values at each repeat station were reduced to sea level (the normal field is conventionally referred to sea level). Considering only the dipolar contribution, *i.e.* neglecting degrees greater than 1 in the spherical harmonic expansion of the geomagnetic potential (*e.g.* Langel, 1987) and an ideal spherical Earth of radius $R = 6371.2$ km, any intensity element E observed at a single station at elevation, h, is smaller than the zero-elevation value by an amount:

$$\Delta E = \frac{3Eh}{R} \qquad (2.2)$$

No altitude correction was applied to angular elements (*e.g.* Tsubokawa, 1952).

3. Normal reference field

For regional studies, a reference field is an analytical expression that represents the best fit of the observational values of a given element of the Earth's magnetic field at a given site. The results of this expression mainly reflect the contribution of the main field (also called the core field, as it originates in the Earth's core) and partly of the secondary field (also called the crustal field, as it originates in the Earth's crust). The reader may refer to Langel (1987) and Harrison (1987) for a discussion on core (main) field and crustal field, respectively, and Bullard (1967) for more details on the normal field. Sophisticated analytical models of the geomagnetic field in a limited region, such as Italy, can be developed (*e.g.* De Santis *et al.*, 1990) but will not be described here. As suggested by the name itself, the normal field can be used as a reference for the detection of localized anomalies. To represent the normal field we chose a second-degree polynomial in latitude and longitude:

$$E = a_0 + a_1\phi + a_2\lambda + a_3\phi^2 + a_4\lambda^2 + a_5\phi\lambda \qquad (3.1)$$

where ϕ and λ are latitude and longitude, respectively (actually relative to a reference central site located at 42°N, 12°E), and the coefficients $a_0, ..., a_5$ are the unknowns to be determined from the observations.

Using the expression (3.1) independently for each element of the field involves certain limitations, notably a geometric inconsistency among the components H, Z and total intensity F (*i.e.*, $F^2 \neq H^2 + Z^2$) and a rotational incoherence of the field (rot $\boldsymbol{B} \neq 0$); (see for example De Santis and Meloni, 1991; De Santis and Duka, 1994). A specific procedure was applied to 1990 in order to reduce these problems as much as possible (see section 6). In table II, the reference field with the new procedure (INGRF 1990*) is indicated by an asterisk to be distinguished from the previous one (INGRF 1990).

To compute the six coefficients, $a_0, ..., a_5$, we used the values observed at the repeat stations and a least squares fitting procedure. To avoid contaminations by repeat stations located

Table I. Names, coordinates and magnetic element values of repeat stations belonging to the 1990 National Magnetic Survey. *I*, *D* and *F* are measured field values; *H* and *Z* are computed.

Station	Latitude	Greenwich Longitude	Alt. (m)	*I*	*D*	*F* (nT)	*H* (nT)	*Z* (nT)
Rasun di sotto	46°46'51''	12°03'15''	1065	62°50.6'	+0°13.6'	47108.7	21501.7	41914.5
Castel d'Ultimo	46°35'51''	11°05'53''	770	62°36.8'	+0°00.9'	47008.2	21624.3	41739.5
Cima Sappada	46°35'00''	12°43'35''	1400	62°41.3'	+0°29.2'	47117.0	21617.3	41863.2
Sella di Bartolo – Tarvisio	46°33'04''	13°32'52''	1200	62°41.4'	+0°37.8'	47151.5	21633.0	41895.2
Monte Spluga	46°29'15''	12°21'01''	1910	62°26.8'	–0°34.7'	46841.1	21667.6	41526.5
Preguzzon – Bormio	46°28'42''	10°14'52''	1950	62°27.1'	–0°14.5'	46839.9	21663.8	41528.4
Bevola – Baceno	46°16'11''	8°18'44''	800	62°20.2'	–0°38.1'	46879.1	21767.7	41519.7
Rivamonte Agordino	46°15'26''	12°01'38''	971	63°20.3'	+0°16.4'	46939.2	21788.0	41575.7
Malghe Grua	46°09'54''	10°16'23''	988	62°09.3'	–0°26.9'	46929.2	21917.4	41497.6
Tesis – Maniago	46°07'06''	12°48'38''	160	62°17.1'	+0°30.5'	46988.1	21853.4	41594.4
Castello Tesino	46°02'51''	11°39'01''	1175	62°07.0'	+0°10.4'	46864.8	21915.2	41422.3
S. Martino in Culmine	45°55'35''	8°44'38''	1087	61°51.2'	–0°46.2'	46684.5	22021.1	41162.0
Col di Medea	45°55'27''	13°25'58''	130	62°06.4'	–0°34.8'	46969.7	21971.7	41511.2
Chaffiery – La Salle	45°45'16''	7°04'42''	1390	61°38.5'	–1°07.2'	46488.4	22080.3	40909.3
Bosco Chiesanuova	45°37'42''	11°03'36''	1100	61°44.4'	+0°08.8'	46720.1	22116.5	41151.1
Scorzè	45°34'47''	12°07'03''	14	61°43.2'	+0°16.2'	46802.2	22171.9	41215.6
Pont – Rhemes Notre Dame	45°33'39''	7°06'46''	1800	61°26.2'	–1°06.1'	46403.4	22184.7	40751.6
Briona – Novara	45°32'39''	8°29'13''	194	61°36.5'	–0°40.5'	46528.7	22124.1	40931.5
Mirauda – Borgiallo	45°26'18''	7°39'09''	1330	61°21.7'	–0°51.6'	46265.9	22173.6	40604.1
Robecco	45°15'54''	9°37'27''	62	61°17.9'	–0°20.9'	46530.2	22341.2	40810.5
Campo S. Maria	45°14'49''	10°04'57''	45	61°19.9'	–0°16.6'	46554.9	22331.4	40845.0
Pontemerlano – Roncoferraro	45°07'23''	10°53'04''	25	61°16.3'	–0°06.9'	46637.7	22415.0	40894.9
San Michele	45°06'40''	8°13'59''	330	61°06.7'	–0°45.8'	46412.3	22420.1	40632.9
Balboutet	45°02'58''	7°00'50''	1550	61°03.5'	–0°37.2'	46436.1	22468.6	40635.3
Morosina – Lendinara	45°02'54''	11°33'21''	7	61°12.1'	+0°07.9'	46555.8	22424.9	40795.5
I Gessi – Retorbido	44°56'16''	9°03'44''	330	60°53.9'	–0°42.1'	46496.4	22609.5	40624.0
La Risaia – Mesola	44°55'09''	12°17'20''	4	61°05.9'	+0°27.9'	46627.4	22531.4	40818.4
Cascina Predassi 2 – Cassine	44°46'16''	8°30'55''	185	60°39.9'	–0°49.4'	46224.1	22644.7	40295.8
Malalbergo bis	44°43'16''	11°33'06''	20	60°54.9'	+0°09.0'	46539.5	22621.0	40670.7
Chiabrand	44°36'23''	7°16'27''	1280	60°36.6'	–1°02.8'	46220.1	22681.8	40269.8
Bergolo	44°33'08''	8°11'16''	646	60°43.2'	–0°39.6'	46037.9	22515.4	40155.8
Possessione – Serramazzoni	44°28'08''	10°51'32''	447	60°32.4'	+0°11.0'	46403.5	22819.6	40402.5
Villanova	44°27'46''	12°02'32''	9	60°38.9'	+0°18.2'	46462.3	22772.1	40497.8
Pian di Stuvega	44°26'33''	9°13'42''	810	60°30.9'	–0°37.9'	46158.5	22717.3	40179.0
Casa Madonnina – Peveragno	44°18'46''	7°38'28''	620	60°13.1'	–0°54.3'	46148.0	22920.1	40052.0
Roburent	44°17'45''	7°53'18''	824	60°10.0'	–0°48.3'	46201.1	22983.5	40077.7
Follo	44°10'13''	9°50'16''	320	60°14.1'	–0°20.2'	46143.8	22906.0	40054.7

Table I. (*continued*) Names, coordinates and magnetic element values of repeat stations belonging to the 1990 National Magnetic Survey. *I*, *D* and *F* are measured field values; *H* and *Z* are computed.

Station	Latitude	Greenwich Longitude	Alt. (m)	*I*	*D*	*F* (nT)	*H* (nT)	*Z* (nT)
Cà Bruciata – Bruscoli	44°08'54''	11°14'11''	835	60°14.5'	+0°03.9'	46261.4	22959.4	40160.7
Campori	44°08'32''	10°25'39''	580	60°11.6'	−0°04.3'	46238.7	22982.2	40121.0
Colle Tre Faggi – S. Godenzo	43°55'33''	11°40'22''	930	60°03.2'	+0°14.9'	46251.0	23086.5	40075.6
S. Giovanni – Ceriana	43°52'00''	7°46'30''	787	59°47.8'	−0°43.0'	45910.9	23094.4	39676.6
Cavallino di Urbino	43°45'42''	12°36'43''	420	59°56.9'	+0°33.5'	46278.9	23175.1	40057.3
Casa Turchino	43°45'38''	10°46'24''	44	59°54.9'	+0°03.3'	46078.0	23096.7	39870.8
Croce al Termine	43°37'56''	13°00'01''	248	59°49.5'	+0°54.5'	46273.5	23257.4	40000.1
Monte Venanzio	43°35'51''	13°33'04''	185	59°49.8'	+0°44.0'	46330.6	23282.7	40054.5
Monte Fili – Greve	43°34'37''	11°16'34''	548	59°37.3'	+0°19.7'	46077.8	23300.5	39751.3
La Vallina	43°26'24''	11°49'25''	267	59°27.8'	+0°11.3'	46080.4	23411.3	39688.5
Casale Marittimo	43°17'20''	10°38'33''	160	59°18.1'	−0°01.8'	45929.2	23446.7	39492.5
Casale di Mecciano – Camerino	43°10'22''	13°02'52''	433	59°20.4'	+0°38.3'	46105.3	23509.5	39659.6
Monte Castellano	43°00'56''	13°46'10''	410	59°15.9'	+0°47.5'	46107.0	23561.8	39630.5
S. Casciano dei Bagni	42°52'54''	11°52'32''	655	58°58.1'	+0°18.8'	45909.5	23666.5	39338.6
Poggio la Guardia – Follonica	42°52'17''	10°47'45''	48	58°53.3'	+0°03.0'	45778.0	23653.6	39192.9
Norcia	42°48'36''	13°05'50''	890	58°58.3'	+0°37.8'	45969.7	23693.8	39390.8
Le Pianacce	42°33'40''	14°03'39''	260	58°52.0'	+0°54.6'	46043.1	23803.6	39409.8
Poggio della Ficona	42°26'56''	12°01'59''	340	58°29.4'	+0°15.4'	45753.6	23911.9	39006.7
Configni	42°25'30''	12°37'48''	600	58°31.8'	+0°29.7'	45811.6	23916.5	39073.1
L'Aquila	42°22'56''	13°18'59''	682	58°31.2'	+0°43.4'	45840.1	23937.1	39093.3
Ponte S. Martino	42°16'04''	13°48'18''	360	58°28.3'	+0°57.0'	45926.7	24014.0	39146.0
Punta del Cimitero – Tremiti	42°07'39''	15°30'46''	72	58°24.4'	+1°09.8'	45956.9	24080.5	39141.3
Fosso Morgitella – Gissi	42°02'56''	14°34'08''	143	58°15.4'	+0°54.0'	45909.2	24152.0	39041.2
Pacentro	42°02'58''	14°00'29''	780	58°11.7'	+0°54.7'	45869.4	24175.0	38982.5
Cagnano – Subiaco	41°54'21''	13°06'26''	530	57°59.7'	+0°34.4'	45675.8	24206.1	38731.9
Lama la Vita – Vieste	41°53'46''	16°05'25''	100	58°09.8'	+1°14.7'	45938.2	24230.5	39025.3
Le Serre – Morrone nel Sannio	41°42'16''	14°48'23''	750	57°56.7'	+0°55.4'	45950.3	24387.1	38943.9
Madonna di Cristo	41°39'31''	15°36'10''	161	57°50.3'	+0°59.0'	45814.9	24386.4	38783.3
Cerasuolo Vecchio	41°35'44''	14°01'23''	810	57°41.9'	+0°51.0'	45650.5	24392.5	38584.6
Pisterzo	41°29'33''	13°16'00''	500	57°30.8'	+0°36.9'	45567.7	24475.0	38433.5
Monte Lapillo	41°18'12''	13°36'49''	800	57°20.5'	+0°41.8'	45498.0	24550.7	38303.7
Fonte di Stella	41°16'52''	14°51'55''	500	57°23.4'	+0°59.4'	45619.9	24586.0	38428.1
Masseria Boschetto	41°13'52''	15°35'14''	260	57°25.0'	+1°07.6'	45659.6	24587.4	38471.1
Cala Garibaldi – La Maddalena	41°13'09''	9°27'34''	11	57°02.0'	−0°22.8'	45292.7	24644.8	37999.2
Masseria di Messere	41°07'54''	16°11'16''	357	57°18.7'	+1°12.1'	45663.8	24664.0	38430.7
Casino Vecchio – Caserta	41°06'49''	14°18'34''	265	57°09.6'	+0°50.7'	45496.8	24672.9	38225.4
Il Varo – Isola di Zannone	40°57'54''	13°03'03''	20	56°56.9'	+0°37.8'	45420.8	24768.8	38069.5

Table I. (*continued*) Names, coordinates and magnetic element values of repeat stations belonging to the 1990 National Magnetic Survey. *I*, *D* and *F* are measured field values; *H* and *Z* are computed.

Station	Latitude	Greenwich Longitude	Alt. (m)	*I*	*D*	*F* (nT)	*H* (nT)	*Z* (nT)
Cala del Porto – Palmarola	40°56'22''	12°51'24''	10	56°55.9'	+0°28.0'	45224.4	24672.8	37897.8
Monte tre Venti – Ponza	40°54'27''	12°57'19''	150	56°57.2'	+0°34.5'	45287.2	24692.1	37959.2
Funtana de li Frati	40°52'45''	9°08'58''	520	56°41.6'	+0°03.2'	45316.8	24882.7	37872.6
Madonna della Neve	40°51'44''	14°37'25''	520	56°56.6'	+0°54.0'	45469.9	24802.4	38109.3
Altamura	40°48'59''	16°30'23''	5	56°57.8'	+1°09.3'	45560.1	24836.0	38193.0
Gravinella – Locorotondo	40°47'48''	17°22'18''	200	57°20.6'	+1°53.2'	45695.7	24655.5	38469.6
Masseria Ramundo	40°46'03''	17°06'26''	410	56°59.5'	+1°27.8'	45622.3	24832.1	38269.0
Masseria Petraccone – Bella	40°43'43''	15°32'34''	533	56°48.7'	+1°35.7'	45506.8	24907.6	38081.4
I.A.M. Brindisi	40°40'00''	19°55'00''	10	56°54.6'	+1°37.7'	45635.2	24913.9	38232.9
San Michele Salentino	40°37'22''	17°36'55''	150	56°50.4'	+1°28.0'	45670.0	24976.9	38228.8
Monte Tintiri – Siniscola	40°36'18''	9°43'42''	40	56°14.0'	–0°18.7'	45084.9	25056.9	37478.6
Punta del Giglio – Alghero	40°34'06''	8°12'14''	70	56°09.5'	–0°30.5'	44789.5	24942.6	37200.3
Osservatorio Solare – Capri	40°32'45''	14°13'43''	476	56°32.0'	+0°49.7'	45288.1	24975.6	37778.7
Masseria Lamia	40°24'44''	18°15'26''	4	56°39.1'	+1°31.7'	45625.0	25079.7	38111.8
Masseria Maserino	40°21'26''	17°38'34''	88	56°33.4'	+1°27.4'	45502.6	25075.8	37968.1
Madonna di Servigliano	40°21'09''	15°58'26''	1300	55°39.5'	+1°07.7'	45397.7	25607.4	37480.8
Santa Maria d'Anglona – Tursi	40°14'37''	16°33'11''	240	56°24.6'	+1°10.8'	45390.7	25309.3	37810.0
Vignale lo Monte bis	40°14'39''	15°17'24''	515	56°22.9'	+0°54.7'	45149.4	24997.4	37597.3
Punta Sasisorgiu – Ollolai	40°10'01''	9°10'13''	1075	55°28.2'	–0°25.3'	44777.6	25164.2	37033.7
Nuraghe Crichidoris – Cabras	39°54'45''	8°27'55''	6	55°19.9'	–0°23.9'	44669.8	25409.1	36737.2
Tescere – Ilbono	39°53'51''	9°35'44''	160	55°29.8'	–0°19.5'	44792.9	25371.3	36912.0
S. Angelo – Presicce	39°51'58''	18°13'08''	90	56°02.62'	+1°39.6'	45402.3	25358.7	37658.9
Le Vigne – Castrovillari	39°47'17''	16°14'28''	350	55°47.95'	+1°14.3'	45165.6	25385.6	37353.1
Talleri – Villamar	39°38'13''	8°58'27''	137	55°06.92'	–0°23.7'	44565.5	25487.2	36555.9
Corongiu – Cagliari	39°18'20''	9°16'50''	100	54°42.61'	–0°21.5'	44452.7	25679.9	36282.5
Lago Arvo	39°14'00''	16°28'26''	1360	55°10.00'	+1°22.1'	45019.6	25712.7	36951.6
Serra S. Caterina – Villasimius	39°06'02''	9°31'09''	70	54°33.64'	–0°18.5'	44433.4	25764.4	36203.0
Casa Seddas de Sa Murta	39°01'04''	8°26'56''	27	54°16.35'	–0°46.8'	44236.7	25829.2	35910.9
Isola di Capo Rizzuto	38°58'25''	17°07'08''	172	54°55.11'	+1°24.8'	44996.1	25860.0	36820.5
Lanzaro – bis	38°41'24''	16°10'29''	296	54°28.66'	+1°10.9'	44801.1	26028.0	36462.8
Milazzo	38°16'08''	15°13'46''	70	53°51.34'	+0°57.4'	44479.0	26231.5	35915.7
Erice I°	38°02'34''	12°33'22''	500	53°24.54'	+0°21.8'	44244.5	26373.7	35526.0
Ferruzzano	38°01'41''	16°07'05''	50	53°40.26'	+1°07.6'	44521.8	26374.3	35866.2
Portella Pantano	38°00'51''	15°39'56''	234	53°38.67'	+0°55.5'	44456.2	26351.2	35802.8
Gibilmanna	37°59'35''	14°01'26''	1000	53°27.01'	+0°37.2'	44299.3	26380.8	35587.0
Scalo Maestro – Marettimo	37°59'21''	12°03'40''	5	53°19.22'	+0°14.5'	44225.9	26411.8	35468.3
Calarossa – Isola di Favignana	37°55'14''	12°21'52''	25	53°15.81'	+0°18.5'	44209.0	26440.4	35428.2

Table I. (*continued*) Names, coordinates and magnetic element values of repeat stations belonging to the 1990 National Magnetic Survey. *I*, *D* and *F* are measured field values; *H* and *Z* are computed.

Station	Latitude	Greenwich Longitude	Alt. (m)	*I*	*D*	*F* (nT)	*H* (nT)	*Z* (nT)
Cerami	37°48'48"	14°29'52"	900	53°21.02'	+0°45.0'	44195.8	26377.2	35454.4
Sant'Anna	37°33'05"	13°14'24"	272	52°56.65'	+0°37.2'	44137.7	26596.8	35223.8
Contrada Misteci bis	37°26'19"	14°02'57"	384	52°51.37'	+0°42.0'	44126.3	26641.6	35171.6
Quartarella	36°48'36"	14°45'43"	380	52°01.46'	+1°01.6'	44244.2	27221.1	34874.7
Lampedusa – Grecale	35°31'06"	12°37'18"	49	50°06.45'	+0°19.4'	43292.1	27770.5	33216.5

Table II. Coefficients of the normal fields for the epochs 1979 to 1990 for all elements. *H* and *Z* normal fields at 1990.0 are computed as described within the text. Latitude and longitude (referred to 42°N, 12°E, respectively) are expressed in minutes.

	a_0	a_1	a_2	a_3	a_4	a_5	
D(')	18.64	+ 0.00225	+ 0.24493	– 0.00006	– 0.00005	+ 0.00008	1990.0
D(')	9.61	– 0.00539	+ 0.24929	– 0.00006	– 0.00006	+ 0.00017	1987.5
D(')	– 4.73	– 0.00087	+ 0.26177	– 0.00008	– 0.00007	+ 0.00009	1985.0
D(')	– 44.70		+ 0.289	– 0.00004	– 0.00007	+ 0.00014	1979.0
F(nT)	45641.0	+ 5.67705	+ 1.32409	– 0.00145	+ 0.00003	– 0.00037	1990.0
F(nT)	45547.7	+ 5.72967	+ 1.23966	– 0.00126	+ 0.00065	– 0.00053	1987.5
F(nT)	45506.8	+ 5.68863	+ 1.22593	– 0.00158	+ 0.00048	– 0.00014	1985.0
F(nT)	45388.4	+ 5.709	+ 1.111	– 0.00153	+ 0.00049	– 0.00068	1979.0
H(nT)	24167.1	– 9.28357	+ 0.01540	+ 0.00015	– 0.00001	– 0.00002	1990.0*
H(nT)	24163.4	– 9.19894	+ 0.03969	+ 0.00037	+ 0.00015	– 0.00004	1987.5
H(nT)	24162.0	– 9.15564	+ 0.05196	– 0.00010	+ 0.00030	+ 0.00025	1985.0
H(nT)	24104.2	– 9.043	+ 0.110	+ 0.00036	+ 0.00004	– 0.00042	1979.0
Z(nT)	38717.6	+ 12.56383	+ 1.55912	– 0.00455	+ 0.00003	– 0.00029	1990.0*
Z(nT)	38608.3	+ 12.57667	+ 1.44880	– 0.00429	+ 0.00062	– 0.00097	1987.5
Z(nT)	38564.9	+ 12.51772	+ 1.42692	– 0.00456	+ 0.00024	– 0.00083	1985.0
Z(nT)	38451.7	+ 12.467	+ 1.259	– 0.00444	+ 0.00060	– 0.00069	1979.0
I(')	3481.7193	+ 1.0999	+ 0.0619	– 0.00033		– 0.00005	1990.0

in anomalous areas, we used Chauvenet's criterion of rejection (Worthing and Jeffner, 1943): once the coefficients of the polynomial were determined using all the repeat station values, we estimated the standard uncertainty using the expression

$$\sigma = \sqrt{vv/(n-6)} \qquad (3.2)$$

where vv is the sum of the squares of the differences between observed and predicted values, n is the number of sites that participate in the inversion and 6 is the number of coefficients. The sites having residuals larger than 2σ were discarded. The procedure was iterated until σ became virtually invariant.

To reduce the influence of possible edge effects in the calculation of the normal field, we included values measured at sites and observatories outside the investigated region. In particular, we used data from Fürstenfeldbruck (Germany) and Ankara (Turkey) observatories, from four repeat stations in Corsica and two in France.

Table II lists the coefficients of the normal fields for the years 1979.0-1985.0 (Molina *et al.*, 1980; Meloni *et al.*, 1988), and the new normal field for 1990.0.

4. The secular variation

No simple definition of «secular variation of the magnetic field» is really possible.

In principle, secular variation is the first time-derivative of the main field. For our purposes we can simply say that the term secular variation refers to the changes of the field that are of internal origin and that occur over time scales of a few years to thousands of years.

Repetition of measurements at a given site allows the investigation of the secular variation at that site, hence resurveying a regional geomagnetic network allows the determination of any spatial variability of the secular variation (for the Italian area see Cafarella *et al.*, 1992b).

The exact reoccupation of each repeat station is of fundamental importance so that there is no possibility of contamination in the secular variation estimates by crustal fields. Generally the secular variation is computed, assuming that it is linear, for each element, within an interval of n years between consecutive surveys using the relation $(E_n - E_o)/n$, where E_n, E_o are the values of element, E, at the extremes of the time interval. Measuring errors and random fluctuations related to magnetic disturbances are reduced by $\sqrt{2}/n$. Once the differences had been calculated for all the repeat station values, we fitted the analytical expression of the secular variation for the Italian region. This expression was represented by a second-order polynomial in latitude and longitude after using Chauvenet's criterion, as described previously. Any value of the secular variation larger than 2σ resulted in the elimination of the two associated values of the magnetic field.

Table III. Coefficients of the secular variation normal fields for the interval 1985-1990, latitude and longitude are referred to 42°N, 12°E and are expressed in minutes.

	a_0	a_1	a_2	a_3	a_4	a_5	
D(')	37.9	− 0.003	− 0.023	+ 0.00001	+ 0.00002	+ 0.00003	1985/79
D(')	24.8	+ 0.005	− 0.016				1990/85
F(nT)	123.8	− 0.002	+ 0.044	− 0.00006	+ 0.00003	+ 0.00010	1985/79
F(nT)	136.1	− 0.012	+ 0.014	− 0.00006	− 0.00013	− 0.00012	1990/85
H(nT)	49.5	− 0.095	− 0.082	+ 0.00001	+ 0.00017	+ 0.00035	1985/79
H(nT)	1.5	− 0.086	− 0.053	+ 0.00002	− 0.00008	− 0.00003	1990/85
Z(nT)	115.3	+ 0.056	+ 0.105	− 0.00009	− 0.00011	− 0.00015	1985/79
Z(nT)	153.5	+ 0.020	+ 0.060	− 0.00010	+ 0.00005	− 0.00009	1990/85

Table III lists the coefficients of the secular variation normal field for the interval 1985.0-1990.0. Figures 2 to 5 show the contours of the spatial trend of the secular variation for *D*, *F*, *H* and *Z* respectively. The secular changes of declination across the Italian area vary from 4'/year (in the gulf of Otranto) to 6'/year (in the area of Piedmont); in this region *F* ranges between 24 and 27 nT/year, *H* ranges between –5 and 5 nT/year and *Z* ranges between 27 and 37 nT/year. These values are different from those calculated from data of the pre-1985 magnetic campaigns (Meloni *et al.*, 1988), thus confirming that the secular variation is largely unpredictable (Malin, 1985).

5. Magnetic maps of Italy

A second-order network of measurements for the elements *F*, *H*, *Z* was carried out by the Progetto Finalizzato Geodinamica (PFG). A total of 2552 measurements were taken between 1977 and 1982 (see fig. 6 for station locations). These high density measurements allowed the complete magnetic mapping of Italy, including production of the magnetic anomaly map of total intensity (Molina *et al.*, 1994). Before 1977 the data base used to compile all magnetic maps was explicitly developed by the IGMI based on subsequent updates of previous maps (see Talamo, 1975).

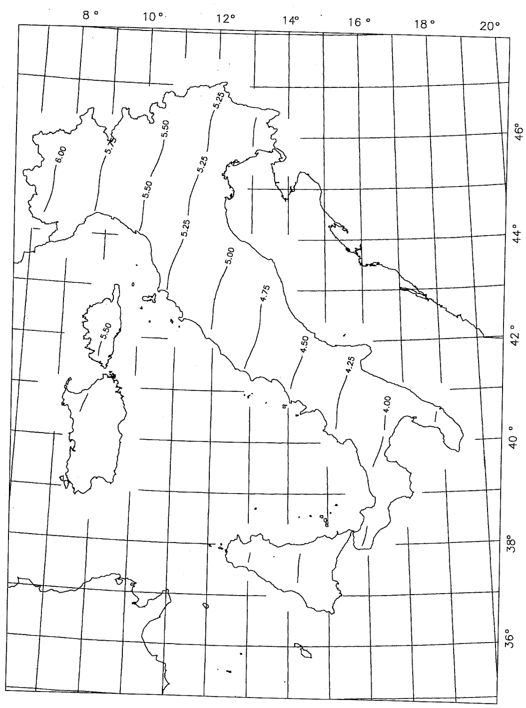

Fig. 2. Declination (*D*) yearly variation isolines computed on the basis of 1990.0 and 1985.0 surveys (in minutes/year).

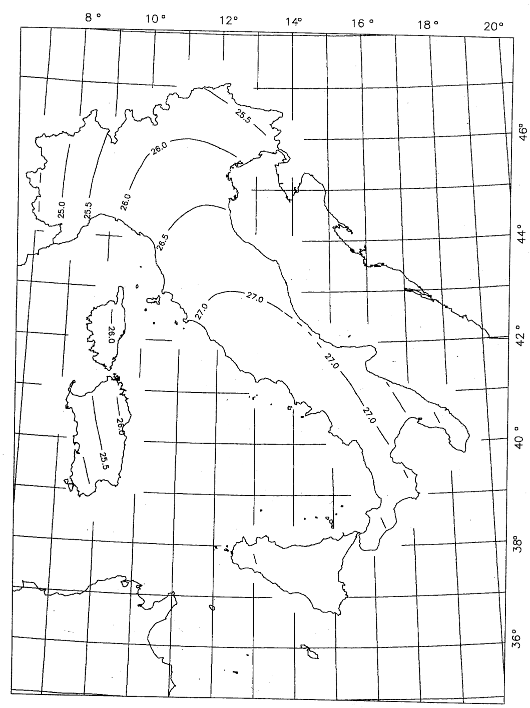

Fig. 3. Total field (*F*) yearly variation isolines computed on the basis of 1990.0 and 1985.0 surveys (in nT/year).

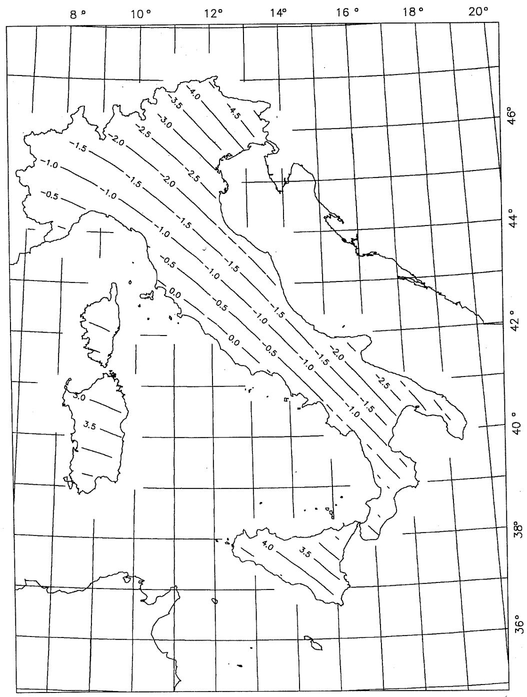

Fig. 4. Horizontal component (*H*) yearly variation isolines computed on the basis of 1990.0 and 1985.0 surveys (in nT/year).

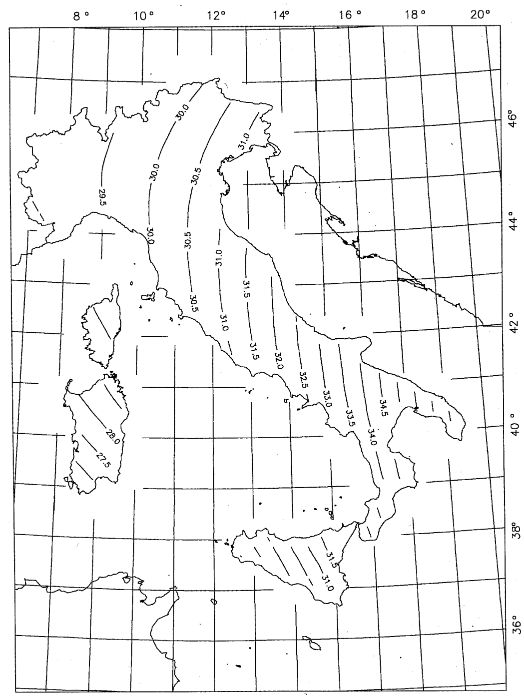

Fig. 5. Vertical component (*Z*) yearly variation isolines computed on the basis of 1990.0 and 1985.0 surveys (in nT/year).

The secular variation determined using the data of repeat stations common to the magnetic surveys (1977-1982 and 1989-1992) was used to update all the 2552 second-order data points. The second-order data set for magnetic declination consists of 1799 measurements which were also updated to 1990.0.

The new maps, for *D, F, H* and Z drawn with automatic graphic contouring programs, are shown in figs. 7 to 10.

6. Error assessment

The statistical error associated with a complex procedure, such as the one described in this paper (direct field measurements on the bench marks; reductions for both daily and secular variation), cannot be determined rigorously. Nevertheless, the effect of each step that leads to the final result can be evaluated.

First, we consider the value $E_s^{90.0}$. The error associated with this value consists of intrinsic measuring uncertainties and reduction uncertainties. Clearly, the measuring uncertainties will affect the value of E_s^t and E_{oss}^t whereas the reduction uncertainties will affect the value of $E_s^{90.0}$. A further reduction error may arise if temporal variations observed at the station are different from those recorded at the observatory. For example a detailed study of a strong magnetic storm (Bianchi *et al.*, 1992) has shown that this effect can be seen all over the Italian territory for all components, but is more relevant for the vertical component. For all these reasons the statistical error cannot be rig-

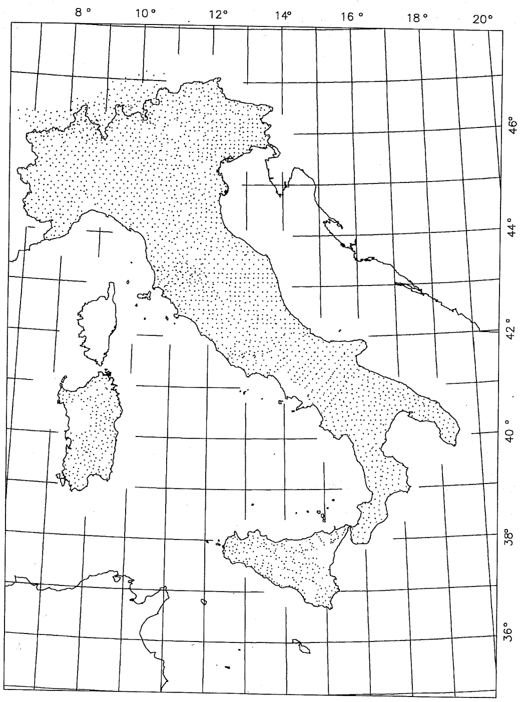

Fig. 6. Second order Italian network of measurements for *F*, *H* and *Z*.

orously assessed and only an estimate of the maximum error associated with the final value, $E_s^{90.0}$, can be given. The maximum value (which in the case of the declination includes the uncertainty in the determination of geographic north) is approximately ± 6 nT for *F* and ± 1' for *D* and *I*. For *H* and *Z* the maximum expected error is ± 8-9 nT. These errors are comparable with those typical of modern magnetic surveys (*e.g.* Newitt *et al.*, 1995).

The normal field values calculated for *F* from the polynomial expression (table II) do not coincide with those calculated from the normal polynomials of *Z* and *H*. The difference (a few nT) results from the fact that the two expressions were calculated independently. Similar considerations apply to *H* and *D*. Since *F, D* and *I* were actually measured (and not *H* and *Z*) we minimized the problem by first computing the normal fields directly for *F, D* and *I* and then deriving *H* and *Z* normal fields from a regular 0.5° × 0.5° grid of *H* and *Z* values derived from *F* and *I* normal fields. This was really made only for a question of continuity in the tradition to give *H* and *Z* normal fields (of course no geometric incoherence is found if values of *H* and *Z* are computed directly from *F, I* normal fields). The use of inclination has also the advantage that this angular element is almost insensitive to altitude variation (*e.g.* Tsubokawa, 1952). Table IV shows the actual distribution of this geometric difference ($F^2 - H^2 - Z^2$) at a few grid points across Italy. Moreover we found that this procedure also reduces the rotational incoherence of the magnetic field, as shown by table V. In practice we expect that, at least, no vertical currents occur, *i.e.* $(\text{rot}\, B)_z = 0$. Lower values in table V indicate better physical consistency. The best results were obtained for the 1979 survey because a greater number of observatories was used for reducing the data (Molina *et al.*, 1994).

Although the validity of the field is progressively reduced as the distance from the center of the region where the normal field expression coefficients were calculated increases, this edge effect can be reduced (but not eliminated) by recourse to observatories outside the investigated region.

7. Validity of the normal reference fields

The creation of maps of crustal anomalies requires that the reference magnetic field reflects only the contribution of the Earth's core (main field). Based on Bullard's rule of the equivalent degree (Bullard, 1967), the model described above is equivalent to a spherical harmonic analysis having degree N = 48 and a minimum wavelength of about 800 km (De Santis and Meloni, 1991); hence the shortest wavelength that the model can account for is about 800 km. Even though they contain a small contribution from the lower crust, the normal field polynomial models provide a good representation of the main field. These

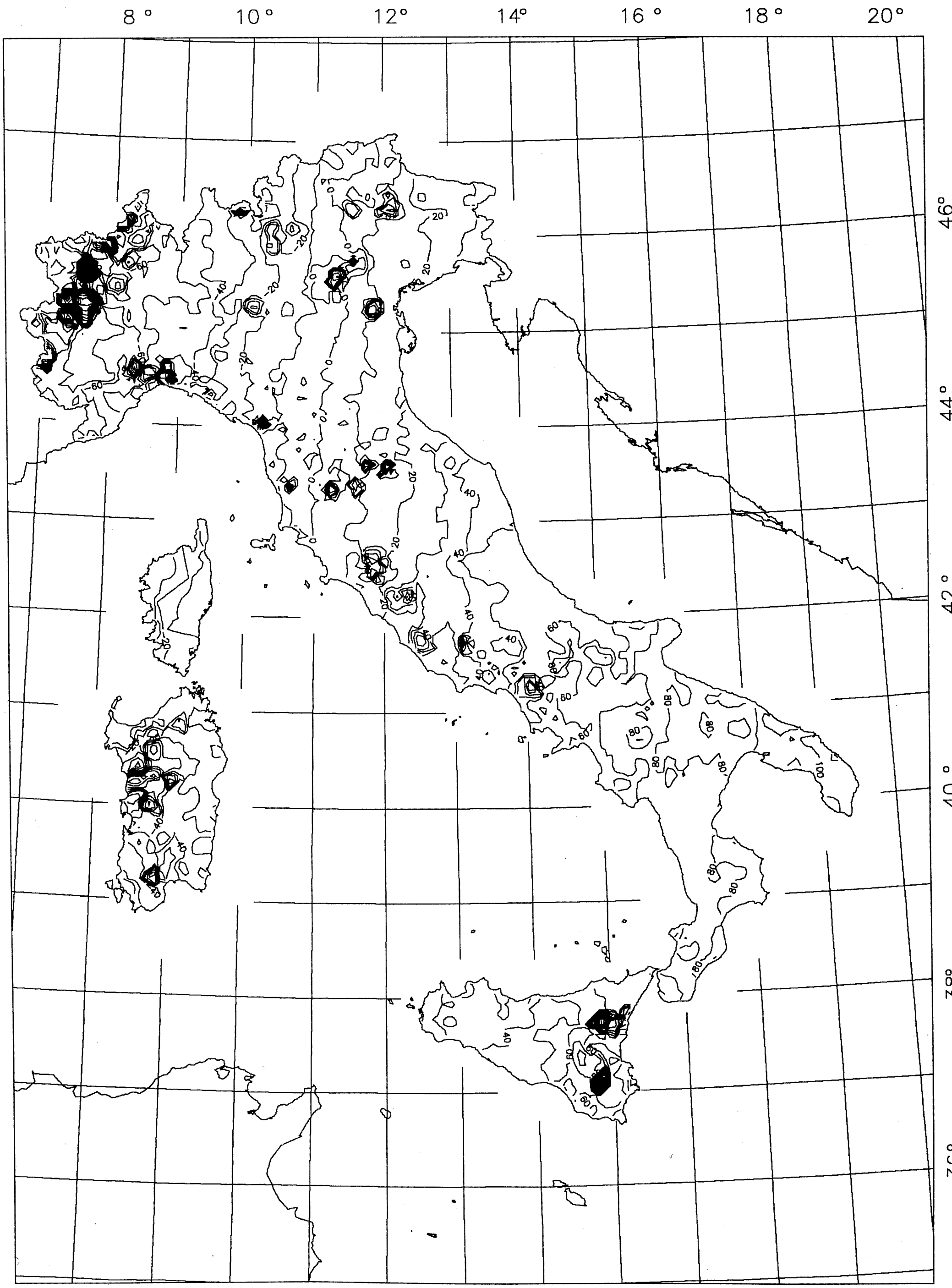

Fig. 7. Geomagnetic field map: declination (*D*). Values are in minutes.

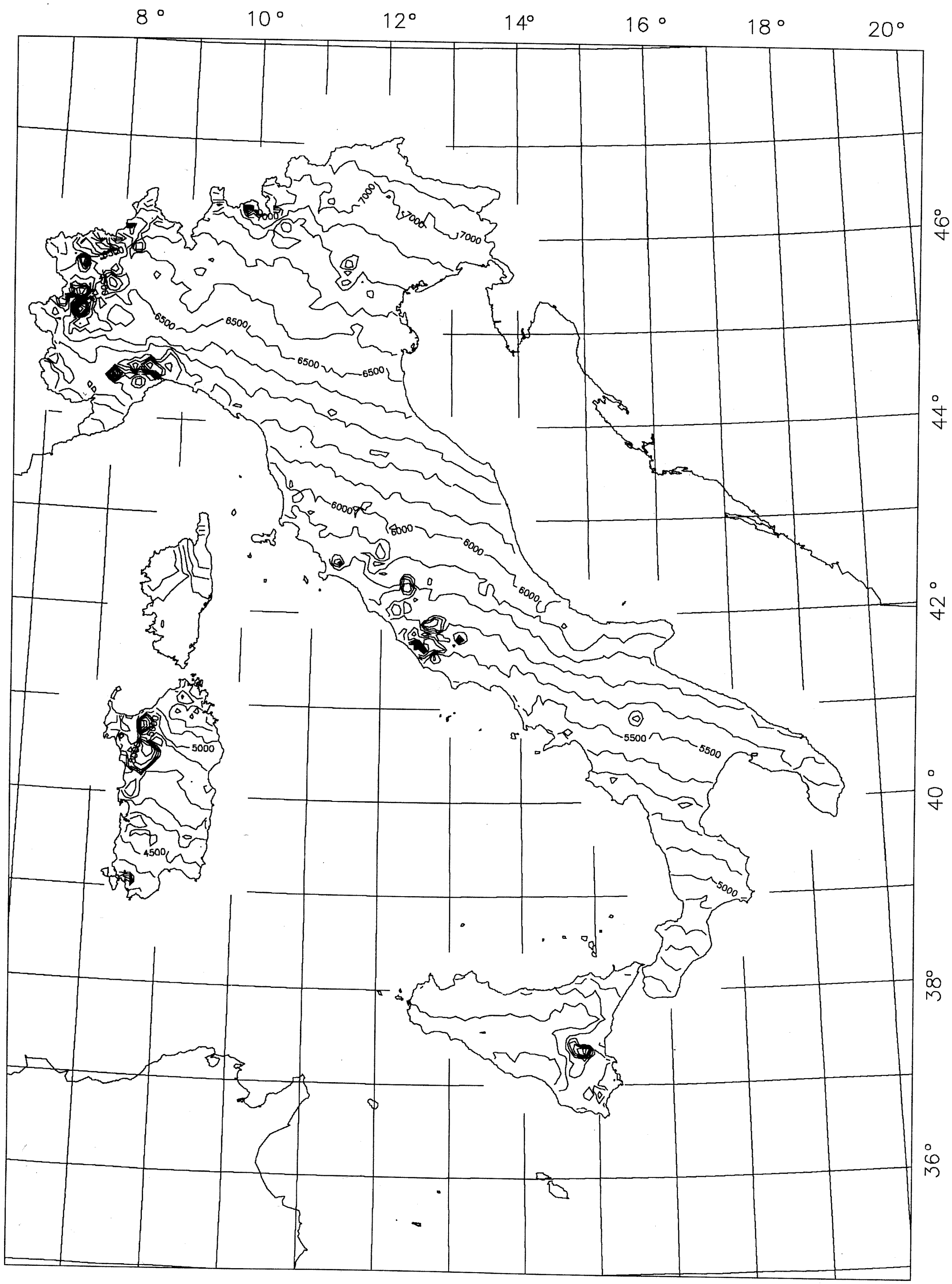

Fig. 8. Geomagnetic field map: total field (*F*). Values must be read as 40 000 + ..., in nT.

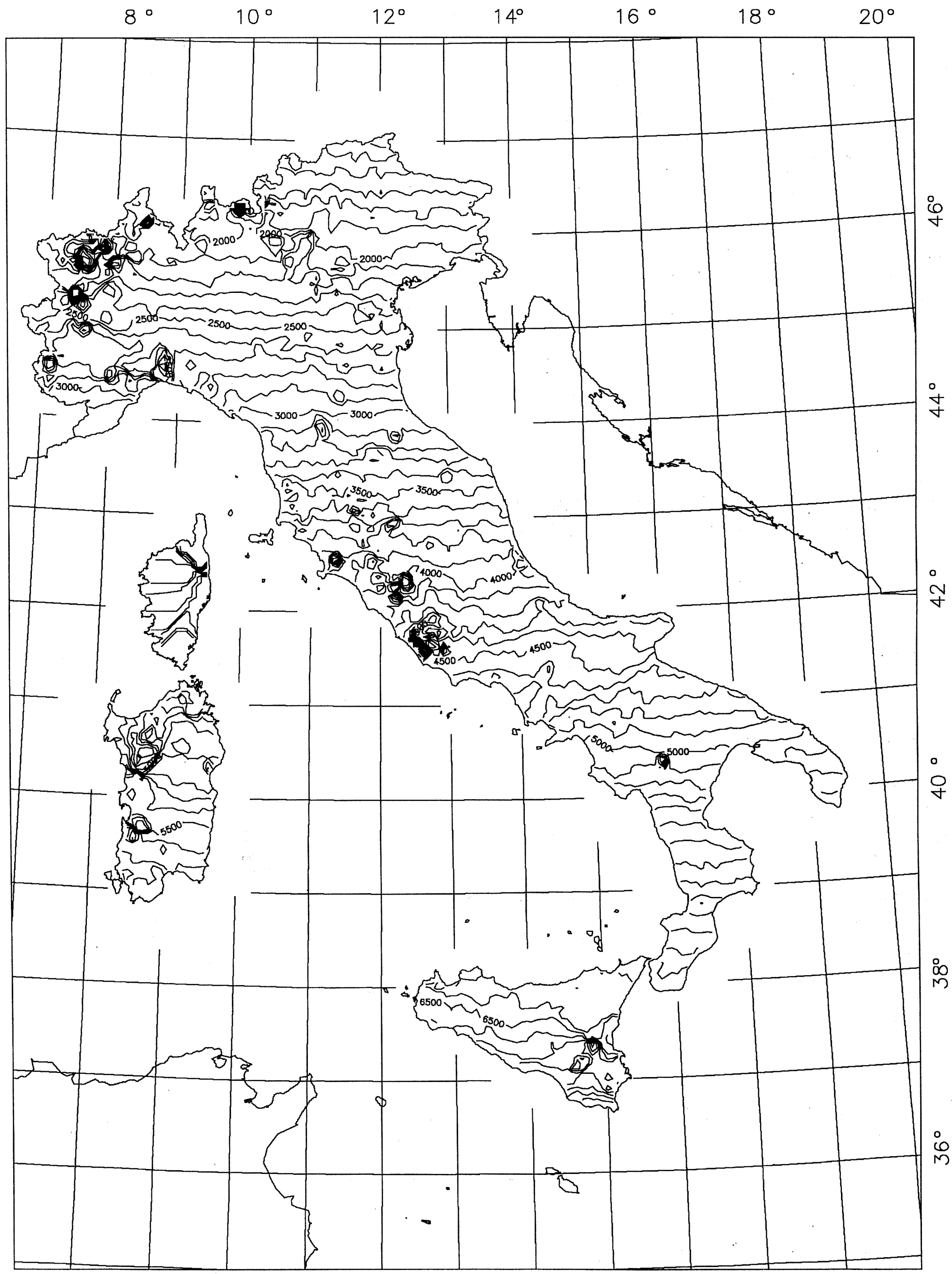

Fig. 9. Geomagnetic field map: horizontal component, (*H*) values must be read as 20 000 + ..., in nT.

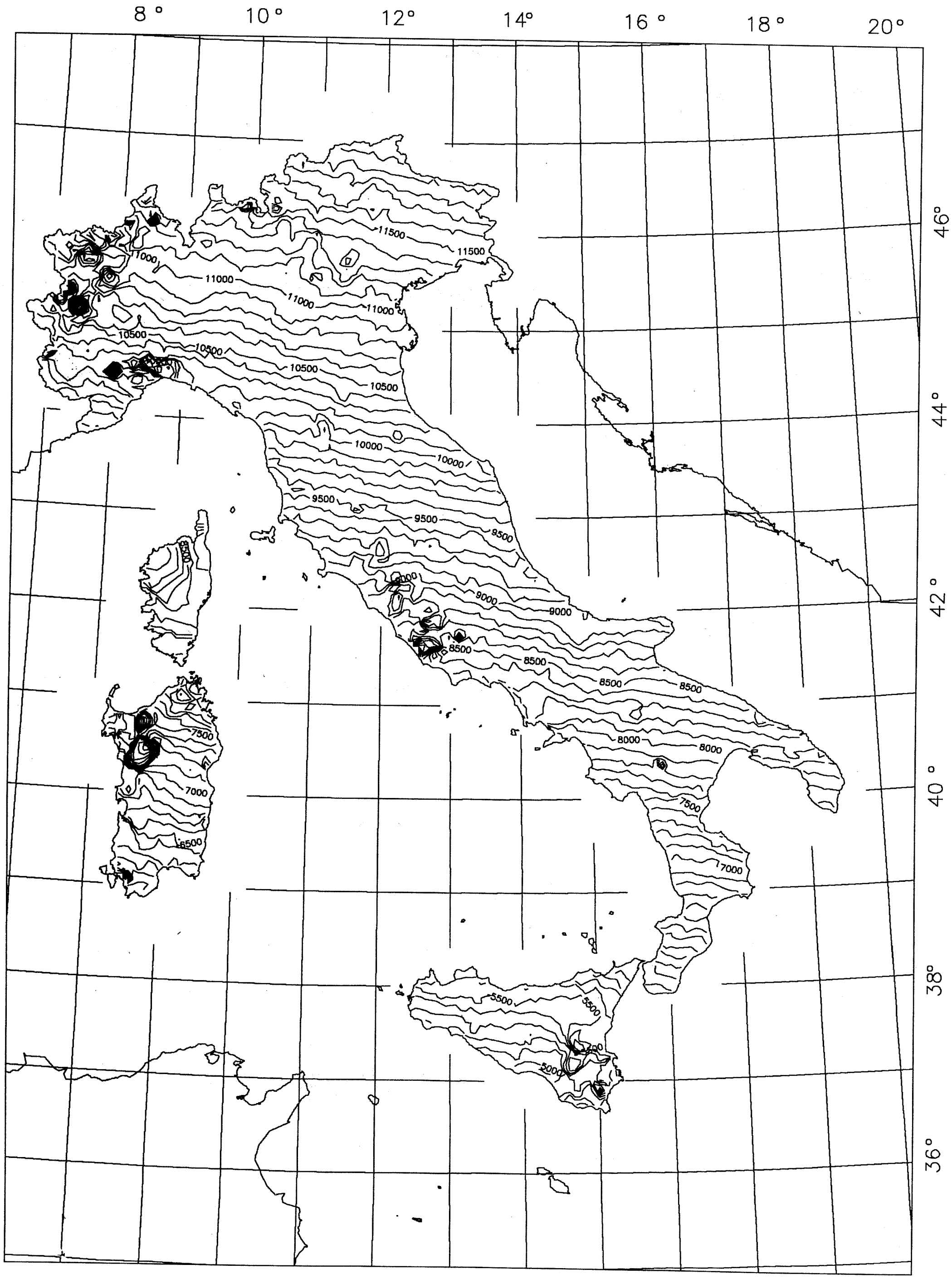

Fig. 10. Geomagnetic field map: vertical component; (*Z*) values must be read as 30 000 + ..., in nT.

Table IV. Distribution of $F^2-(H^2+Z^2)$ across Italy (geometric incoherence) at selected grid points; see text for acronyms. At the epoch 1990.0 the definitive INGRF1990* normal fields have been deduced as described in the text. Units are nT^2.

Latitude	Longitude	INGRF 1979	INGRF 1985	INGRF 1987.5	INGRF 1990	INGRF 1990*
47.0°	12.0°	0.0	− 11.0	− 3.0	− 13.6	8.9
46.0°	8.0°	2.0	5.7	7.5	10.3	− 1.3
46.0°	13.0°	5.0	− 4.3	1.8	− 6.8	− 0.6
45.0°	12.0°	3.5	5.0	5.5	1.8	− 5.3
44.0°	8.0°	− 0.5	4.0	3.6	11.6	− 4.9
44.0°	10.0°	− 0.5	7.0	4.6	7.3	− 5.5
44.0°	14.0°	4.0	2.6	3.7	− 0.7	− 6.4
42.0°	12.0°	− 6.0	2.0	− 1.4	1.0	− 0.3
40.0°	10.0°	− 7.6	− 9.0	− 6.2	− 4.9	6.3
40.0°	14.0°	− 6.0	− 1.8	− 2.6	− 7.0	5.5
39.0°	12.0°	− 1.7	− 3.9	0.0	5.2	5.3
38.0°	15.0°	9.7	3.9	9.9	− 1.2	1.2
37.0°	15.0°	28.2	13.8	25.8	9.6	− 9.2
Mean		2.3	1.1	3.8	1.0	− 0.5
SD		9.0	6.5	8.6	7.5	5.5

Table V. Distribution of $(\mathrm{rot}\ \boldsymbol{B})_z$ across Italy (rotational incoherence) at selected grid points; see text for acronyms. Units are nT/°. Lower values indicate closer consistency with the assumption that there are no electrical currents flowing in the area and therefore rot $B = 0$. Partial coherence is checked by considering $(\mathrm{rot}\ B)_z$, (no vertical currents).

Latitude	Longitude	INGRF79	INGRF85	INGRF87.5	INGRF90
47.0°	12.0°	− 2.0	18.5	12.8	9.4
46.0°	8.0°	− 5.4	1.8	7.0	3.0
46.0°	13.0°	− 0.5	19.5	13.0	9.4
45.0°	12.0°	− 1.0	13.3	10.8	7.0
44.0°	8.0°	− 3.8	− 3.4	5.8	0.9
44.0°	10.0°	− 2.2	3.5	7.7	3.4
44.0°	14.0°	0.7	16.7	11.0	8.0
42.0°	12.0°	− 0.6	3.2	6.0	3.0
40.0°	10.0°	− 1.5	− 11.2	1.4	− 1.8
40.0°	14.0°	− 0.8	− 1.8	1.8	1.6
39.0°	12.0°	− 1.6	− 9.9	− 0.9	− 1.7
38.0°	15.0°	− 2.8	7.0	− 4.8	− 1.7
37.0°	15.0°	− 4.2	− 12.7	− 8.5	− 3.8
Mean		− 2.0	3.4	4.8	2.8
SD		2.6	11.3	8.1	5.2

reference fields, which we have named INGRF (ING Reference Field) should be similar to the global reference field IGRF (International Geomagnetic Reference Field; see Barraclough, 1987; Langel, 1992), which represent only the main field.

The normal fields, so determined, are valid only at specific epochs (most recent, 1990.0); an attempt to conciliate the advantages of global models like IGRF and those of polynomial normal fields has been given by Molina and De Santis (1987).

A thorough comparison of reference models was performed prior to constructing maps of anomalies of the total field (updated to 1979.0, Molina *et al.*, 1994). At that time Molina *et al.* (1985a) suggested that a normal field be used in place of a global model, thus confirming, for the Italian area, the suggestion made by Regan and Cain (1975). Figure 11 shows a comparison between the reference field INGRF79 (which was constructed in the framework of the PFG), and the DGRF for 1979.0 for the total intensity *F*. This comparison shows that the maximum differences over Italy are ± 25 nT. This is not very significant considering that the crustal anomaly averaged over the whole planet is about 200 nT. A similar comparison was made for the reference fields generated for 1985 and 1990 (figs. 12 and 13).

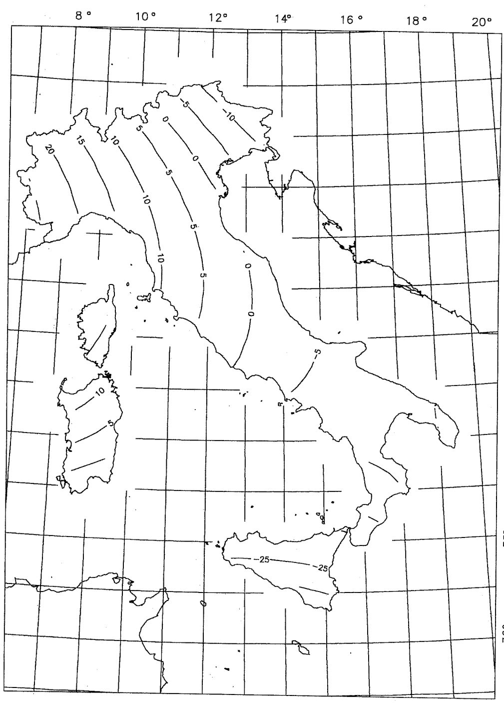

Fig. 11. Difference between reference fields INGRF79 and DGRF79 for total intensity *F* expressed in nT.

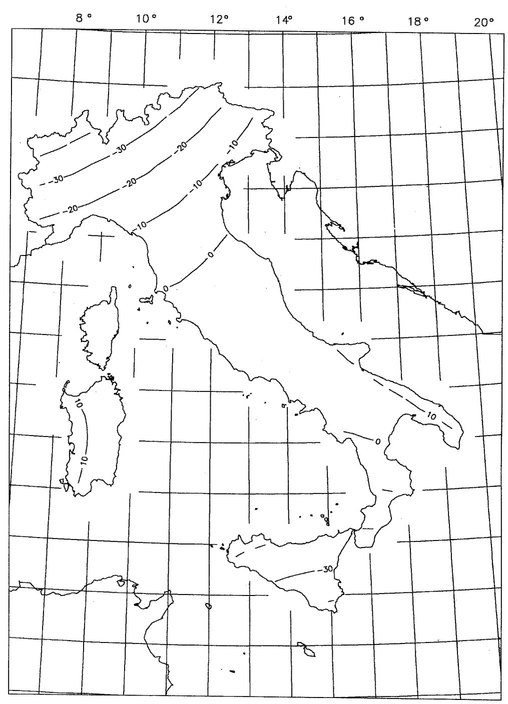

Fig. 12. Difference between reference fields INGRF85 and DGRF85 for total intenstity *F* expressed in nT.

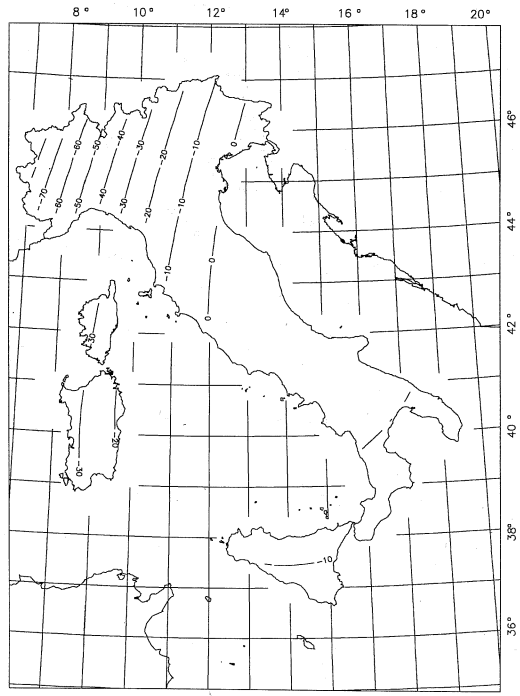

Fig. 13. Difference between reference fields INGRF90 and DGRF90 for total intensity F expressed in nT.

8. Conclusions and recommendations

The importance of national magnetic surveys is widely recognized. It is important to have a snapshot of the magnetic field and of the secular variation at a fixed epoch. It is also important for updating old previous maps. The main advantage of using normal fields instead of global models, like the IGRF, is that the former are more recent and correct than the latter. As an example, the IGRF is still considered preliminary at 1990 so our normal fields are definitely closer to reality than the IGRF for the Italian area. Another advantage is the simplicity and compactness of the expressions for the normal fields allowing their use also during field work for anomaly studies. Of course, survey data will contribute in any case, together with observatory data, to the generation of global models.

A preliminary analysis of the results of the comparison between INGRF90 and DGRF90 shows substantial discrepancies between the two models in the northwest part of the country. A possible explanation is that while six reference observatories used for data reductions in 1979, only the L'Aquila Observatory was used for the 1990 survey. Indeed, one cannot assume that the time variations of the Earth's magnetic field at each station are the same as those observed at the reference observatory, particularly for the most remote stations. For the next repetition of the national magnetic survey we plan to use portable variometers for determining the diurnal corrections to be applied. A reduction of the number of bench marks forming the network is also planned as it is clearly more important to improve the accuracy of results from individual stations than to obtain less accurate data from a large number of stations.

Acknowledgements

Field work operations were partly done in cooperation with the Istituto Geografico Militare Italiano (IGMI): we thank, in particular, Dr. L. Surace for this cooperation. Dr. C.E. Barton and an anonymous referee, are thanked for their valuable suggestions and comments on this paper.

REFERENCES

Barraclough, D. R. (1987): International Geomagnetic Reference Field: the fourth generation, *Phys. Earth Planet. Inter.*, **48**, 279-292.

Battelli, O., G. Dominici (1991): La rete magnetica italiana e la variazione secolare dal 1935 in poi, *Ist. Naz. Geofis.*, **6**, 351-366.

Bianchi, C., A. De Santis, A. Meloni and B. Zolesi (1992): Magnetic and ionospheric effects of the strong magnetospheric storm of March 13th, 1989 over Italy, *Nuovo Cimento C*, **15**, 45-56.

Bullard, E.C. (1967): The removal of trend from magnetic surveys, *Earth Planet. Sci. Lett.*, **2**, 293-300.

Cafarella, L., A. De Santis and A. Meloni (1992a): Il catalogo geomagnetico storico Italiano, *Ist. Naz. Geofis.*, **7**, 160.

CAFARELLA, L., A. DE SANTIS and A. MELONI (1992b): Secular variation from historical geomagnetic field measurements, *Phys. Earth Planet. Inter.*, **73**, 206-221.

DE SANTIS, A., O. BATTELLI and D.J. KERRIDGE (1990): Spherical cap harmonic analysis applied to regional field modelling for Italy, *J. Geomagn. Geoelectr.*, **42**, 1019-1036.

DE SANTIS, A. and A. MELONI (1991): Sulla scelta del campo geomagnetico di riferimento in Italia, *Ist. Naz. Geofis.*, **6**, 283-300.

DE SANTIS, A. and B. DUKA (1994): Improving physical and geometrical consistency of scalar and vector reference fields produced with regional magnetic surveys, *Annali di Geofisica* (submitted).

HARRISON, C.G.A. (1987): The crustal field, in *Geomagnetism*, edited by J.A. JACOBS, **1**, 512-623.

KIRCHER, A. (1643): Magnes sive de Arte Magnetica, *Coloniae Agrippinae*, 453 (2nd ed.).

LANGEL, R.A. (1987): The main field, in *Geomagnetism*, edited by J.A. JACOBS, **1**, 249-512.

LANGEL, R.A. (1992): International Geomagnetic Reference Field, the sixth generation, *J. Geomag. Geoelectr.*, **44**, 679-707.

MALIN, S.R.C. (1985): On the unpredictability of geomagnetic secular variation, *Phys. Earth Planet. Inter.*, **39**, 293-296.

MELONI, A., O. BATTELLI, G. DOMINICI, S. ARCA and A. MARCHETTA (1988): Italian Magnetic Network at 1985.0, *Bollettino Geodesia e Scienze Affini*, **4**, 339-350.

MOLINA, F., E. ARMANDO, R. BALIA, O. BATTELLI, E. BOZZO, N. DE FLORENTIIS, V. ILICETO, R. LANZA, M. LODDO, E. PINNA and R. ZAMBRANO (1980): Rete magnetica fondamentale in Italia, *Pubbl. n. 365 CNR*, pp. 24.

MOLINA, F., A. MELONI, O. BATTELLI and A. DE SANTIS (1985a): Comparison of geomagnetic planetary reference fields over Italy, *Phys. Earth Planet. Int.*, **37**, 35-45.

MOLINA, F., E. ARMANDO, R. BALIA, O. BATTELLI, E. BOZZO, G. BUDETTA, G. CANEVA, M. CIMINALE, N. DE FLORENTIIS, A. DE SANTIS, G. DOMINICI, M. DONNALOIA, A. ELENA, V. ILICETO, R. LANZA, M. LODDO, A. MELONI, E. PINNA, G. SANTARATO and R. ZAMBRANO, (1985b): Geomagnetic survey of Italy. Repeat station network and magnetic maps: a short report, *Annal. Geophys.*, **3** (3), 365.

MOLINA, F. and A. DE SANTIS (1987): Considerations and proposal for a best utilization of IGRF over areas including a geomagnetic observatory, *Phys. Earth Planet. Inter.*, **48**, 379-385.

MOLINA, F., E. ARMANDO, R. BALIA, O. BATTELLI, E. BOZZO, G. BUDETTA, G. CANEVA, M. CIMINALE, N. DE FLORENTIIS, A. DE SANTIS, G. DOMINICI, M. DONNALOIA, A. ELENA, V. ILICETO, R. LANZA, M. LODDO, A. MELONI, E. PINNA, G. SANTARATO and R. ZAMBRANO (1994): Geomagnetic survey of Italy at 1979.0. Repeat station network and magnetic maps, *Ist. Naz. Geof.*, **554**, 32.

NEWITT, L.R., C.E. BARTON and J. BITTERLY (1995): Guide for magnetic repeat station surveys, *IAGA Working Group V-B* (in press).

REGAN, D.R. and C.J. CAIN (1975): The use of geomagnetic field models in magnetic surveys, *Geophys.*, **40**, 621-629.

TACCHINI, P. (1892): Carte magnetiche d'Italia eseguite da Chistoni e Palazzo, *Annali Ufficio Centrale Meteorologia Geodinamica*, **14**, 26.

TALAMO, R. (1975): Le carte magnetiche d'Italia delle isodinamiche nella *H* e delle isogone, dell'Istituto Geografico Militare, e loro aggiornamento al 1973.0, *Bollettino Geodesia e Scienze Affini*, **34** (1).

TSUBOKAWA, I. (1952): Reduction of the results obtained by the magnetic survey of Japan, (1948-51) to the epoch 1950.0 and reduction of the empirical formulae expressing the magnetic elements, *Bull. Geogr. Surv. Inst.*, **3**, 1-29.

WORTHING, A.G. and J. JEFFNER (1943): *Treatment of experimental data* (John Wiley, New York).

(received March 23, 1994;
accepted August 28, 1994)