The new italian quasigeoid: ITALGEO95

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Summary. — The last estimate of the italian quasigeoid, ITALGEO95, has been accomplished during the first half of 1995.

This new computation has been based on a revised data set of gravity covering the area $36° \leq \varphi \leq 47°$, $6° \leq \lambda \leq 19°$ and an implemented DTM, having a grid mesh of nearly 250 m. The method used to get the estimate is the remove-restore technique (with some minor modifications) plus Fast Collocation which allows to obtain the solution over the entire area in one step only.

The final product is the estimate of ζ over a regular grid of $3' \times 3'$ in the zone $36° \leq \varphi \leq 47°$, $6° \leq \lambda \leq 19°$.

This quasigeoid has been tested with GPS/leveling measurements which showed a good agreement with it; strong improvements have been reached both with respect to the pure geopotential model (OSU91A) and the previous italian geoid (ITALGEO90).

IL NUOVO QUASI-GEOIDE ITALIANO: ITALGEO95.

Sommario. — L'ultimo calcolo del quasi-geoide italiano, ITALGEO95, è stato effettuato nella prima metà del 1995 ed è basato su un insieme controllato di dati di gravità, estendentisi sull'area compresa tra le latitudini 36° e 47° e tra le longitudini 6° e 19°, e su un modello digitale del terreno su un grigliato di passo 250 m circa.

Il metodo usato per la stima è costituito dalla tecnica «remove-restore» (leggermente modificata) insieme con la «Fast Collocation», il che permette di ottenere la soluzione sull'intera area in un solo passo.

Il prodotto finale consiste nella stima di ζ per un reticolato regolare $3' \times 3'$ nella zona individuata dai valori di latitudine e longitudine predetti.

Il presente quasi-geoide è stato sottoposto a verifica con misure GPS e di livellazione che si sono rivelate in buon accordo con esso; forti miglioramenti sono stati ottenuti sia rispetto al modello geopotenziale puro (OSU91A) che al precedente geoide italiano (ITALGEO90).

1. — INTRODUCTION

A new detailed estimate of the quasigeoid has been computed over an area covering Italy and surrounding seas. The aim of this computation is to provide an updated and reliable reference surface to be used in connection with GPS measurements, altimetric observations and for geophysical investigation in the central Mediterranean area. This quasigeoid, named ITALGEO95, has been based on a new validated gravity data set covering the area $36° \leq \varphi \leq 47°$, $6° \leq \lambda \leq 19°$ and on a DTM which is, on each side, two degrees larger than the area containing gravity. The estimation technique is the usual remove-restore method, while the computation of ζ_r, from Δg_r is based on Fast Collocation (Bottoni and Barzaghi, 1993) which allowed the estimate of ζ_r, in one step only. The result is a quasigeoid grid in $36° \leq \varphi \leq 47°$, $6° \leq \lambda \leq 19°$ with a grid mesh of $3' \times 3'$. The ITALGEO95 estimate follows a previous geoid computation on the same area which was carried out in 1989, the ITALGEO90 (Benciolini et al., 1991). Several improvements have been introduced with respect to it. Gravity and DTM data bases used in ITALGEO90 were mainly based on italian data and practically no integration with other data sources was performed. This led to an estimate which was reliable on land areas, where data were present. Another step forward has been done from the methodological point of view. ITALGEO90 was derived via remove-restore technique and collocation. Due to collocation computational limits, the N_r estimate was obtained in eleven different blocks which partially overlapped. These local solutions were then merged together to get a global regular grid of $7.5' \times 7.5'$ in the area $35.9583 \leq \varphi \leq 47.3333$, $6.4523 \leq \lambda \leq 18.9525$; the global geopotential model IFE88 was used to fill in gaps in the areas were no $\hat{N}_r$ was provided (i.e. on the seas surrounding Italy and on Corsica, since the eleven zones cover the peninsular part of Italy and its two main islands, Sicily and Sardinia).

Both merging procedure and lack of data on sea led to discontinuities in the final estimate which reflected in a quite poor agreement with GPS/leveling data, especially in the south. The procedure adopted in ITALGEO95, based on Fast Collocation together with the new implemented data base of gravity and DTM, tried to overcome exactly this fragmentation problem in order to get a homogeneous and reliable estimate both on land and on marine areas.

Finally, another relevant difference with respect to ITALGEO90 is the global geopotential model used in the remove-restore procedure. In ITALGEO95 the more recent OSU91A model was assumed as a reference field in order to remove and restore the long wavelength components of gravity and geoid.

The comparisons of ITALGEO95 with the available GPS/leveling data, distributed quite homogeneously over the entire estimation area, gave good results, which sharply improve the ITALGEO90 performances, especially where poor results were present, i.e. in the southern part of Italy.

2. — DATA ACQUISITION AND PREPARATION

Gravity data
    In the area

$$36° \leq \varphi \leq 47°; \quad 6° \leq \lambda \leq 19°;$$

all the available free air gravity anomalies were considered and merged together to ensure a proper coverage, suitable for the $3' \times 3'$ geoid computation grid. Data were collected from:
        — the italian gravity data base, the same used in ITALGEO90 (Carrozzo et al., 1982; Benciolini et al., 1991). These are mainly land data and cover quite densely the peninsular part of Italy, Sicily and Sardinia. This data base consists of 240489 gravity stations;
        — Morelli's gravity maps over the Adriatic and Tyrrhenian Seas (Morelli, 1970; Morelli et al., 1975a; Morelli et al., 1975b). These are mean gravity anomaly values on a $5' \times 5'$ grid coming from a digitalization performed by D. Arabelos. These data showed a gap in the central Tyrrhenian part which has been filled in at DIIAR digitizing Morelli's map on this area. The total number of data coming from this file is 20344;
        — BGI point gravity anomaly data mainly on land areas on the northern border of Italy plus data covering the Corsica Island. From this source 35411 gravity stations were collected.
    Since the gravity anomalies listed above refer originally to different normal gravity fields, the first step was to reduce all these data to the same normal field, i.e. to the GRS80 normal gravity. Further more, data were also reduced by selecting those closer to the center of a $1' \times 1'$ grid over to the computation area. In this way, from the original 296244 gravity observations, a smaller data base of 105695 Δg values was extracted. This has been done mainly to homogenize the distribution of gravity data which in some areas is uselessly dense. Further more a gravity data base which is nearly $1' \times 1'$ is for sure suitable for producing a $3' \times 3'$ geoid grid. It must also be remarked that on some part of the sea we have data with a $5' \times 5'$ spacing, (i.e. those coming from Morelli's map digitalization).
    This however is not so troublesome because gravity on sea is much more regular than on land, so that the interpolation procedure from $5' \times 5'$ to a $3' \times 3'$ grid (the one used in Fast Collocation) can be accomplished quite reliably.

The coverage of the reduced data set is shown in fig. 1. It can be immediately seen that a large data gap is present over the late Yugoslavia region. This deficiency could have caused problems in the north-east corner of the prediction grid and on the Adriatic sea too. However, since the correlation length of residual gravity is of the order of 15' (see fig. 2), no relevant effects are to be expected on the remaining part of the estimation grid.

DTM

In order to obtain a smoothed gravity field as input for the collocation procedure, gravity data must be reduced both for the geopotential model and terrain effect. To compute properly the terrain effect, a datailed DTM model has been prepared over the area

$$34° \leq \varphi \leq 49°, \quad 4° \leq \lambda \leq 21°.$$

As mentioned before, the area considered for DTM is two degree larger than the area containing Δg. This has to do with the terrain effect computation which must be carried out taking into account a large window of DTM data for each gravity station point. Many different DTMs were merged together to form a unique homogeneous height data base (where homogeneity refers to data spacing, not to precision). The different data sources are listed below, with their main characteristics.

— Italian DTM, covering mainly land areas. Data are on a regular geographical grid with 7.5″ × 10″ spacing (Carrozzo et al., 19882).

— Morelli bathymetry on sea; these are gridded data 5' × 7.5' (Morelli et al., 1975b).

— Austrian DTM covering whole Austria with resolution 11.25″ × 18.75″.

— French DTM in the Alps area ($42.75° \leq \varphi \leq 48°$, $5° \leq \lambda \leq 9°$) and over Corsica with resolution 9″ × 6″.

— Swiss DTM (Rimini) with grid spacing of 250 m on a regular (x, y) grid in the national Swiss map projection system.

— German DTM in the strip $47° \leq \varphi \leq 48°$, $7° \leq \lambda \leq 13°$ having resolution 30″ × 50″.

— ETOPO5U in the remaining parts of the considered area. This global data base has grid mesh of 5' both in latitude and in longitude.

Since these DTM models have different spacings the merging procedure was designed to reduce all them to a common grid mesh, namely the one of the italian DTM. This has been done by simple, bilinear interpolation without taking into account the different accuracy of the various DTM. The bilinear interpolation was applied to the various height data bases but not to the italian DTM which maintained the original values. The information stored in the final global DTM are the heights in meters coupled with a code which relates to the DTM sources used to compute those values.

This data base is stored in binary form and contains 7202 × 6122 heights (and code) on a regular geographical grid of 7.5″ × 10″.
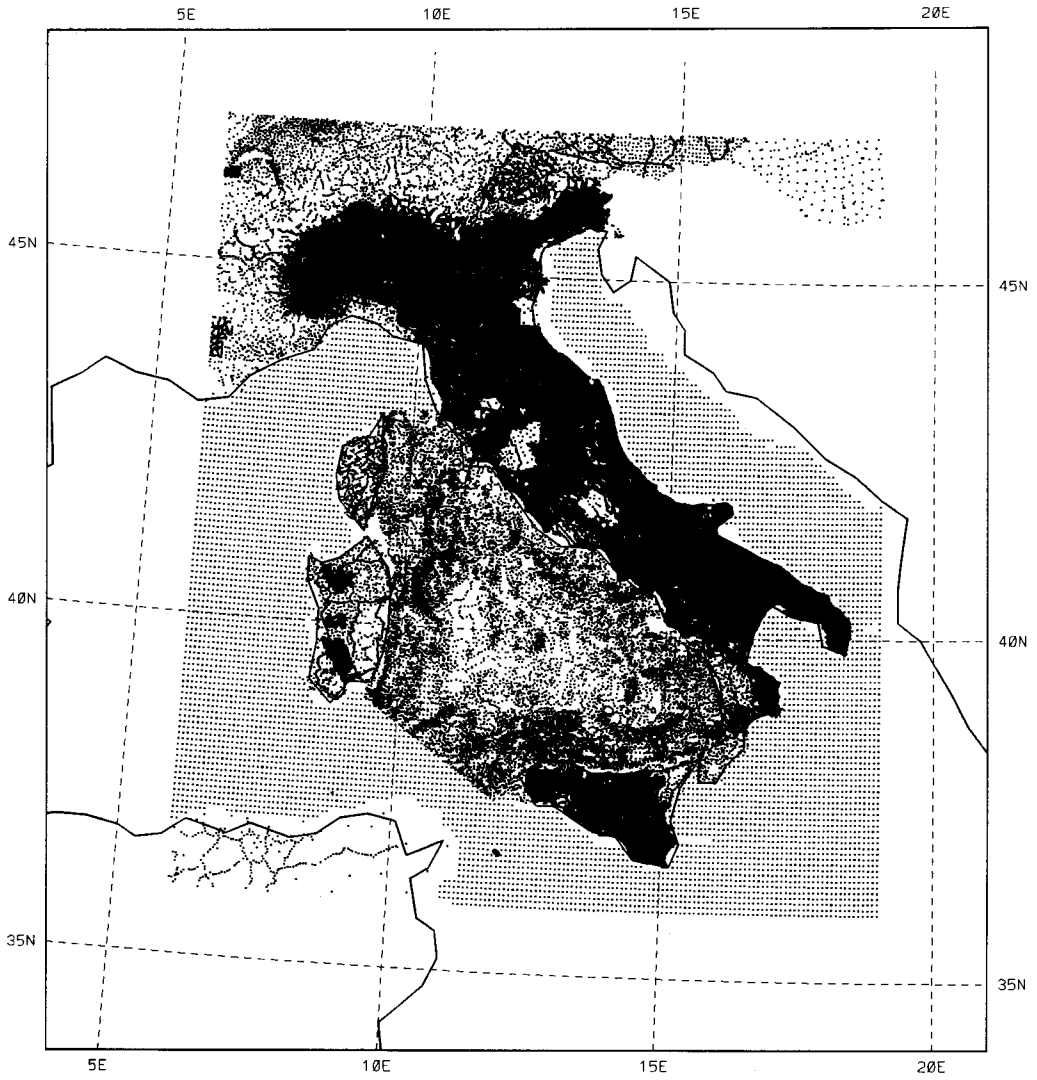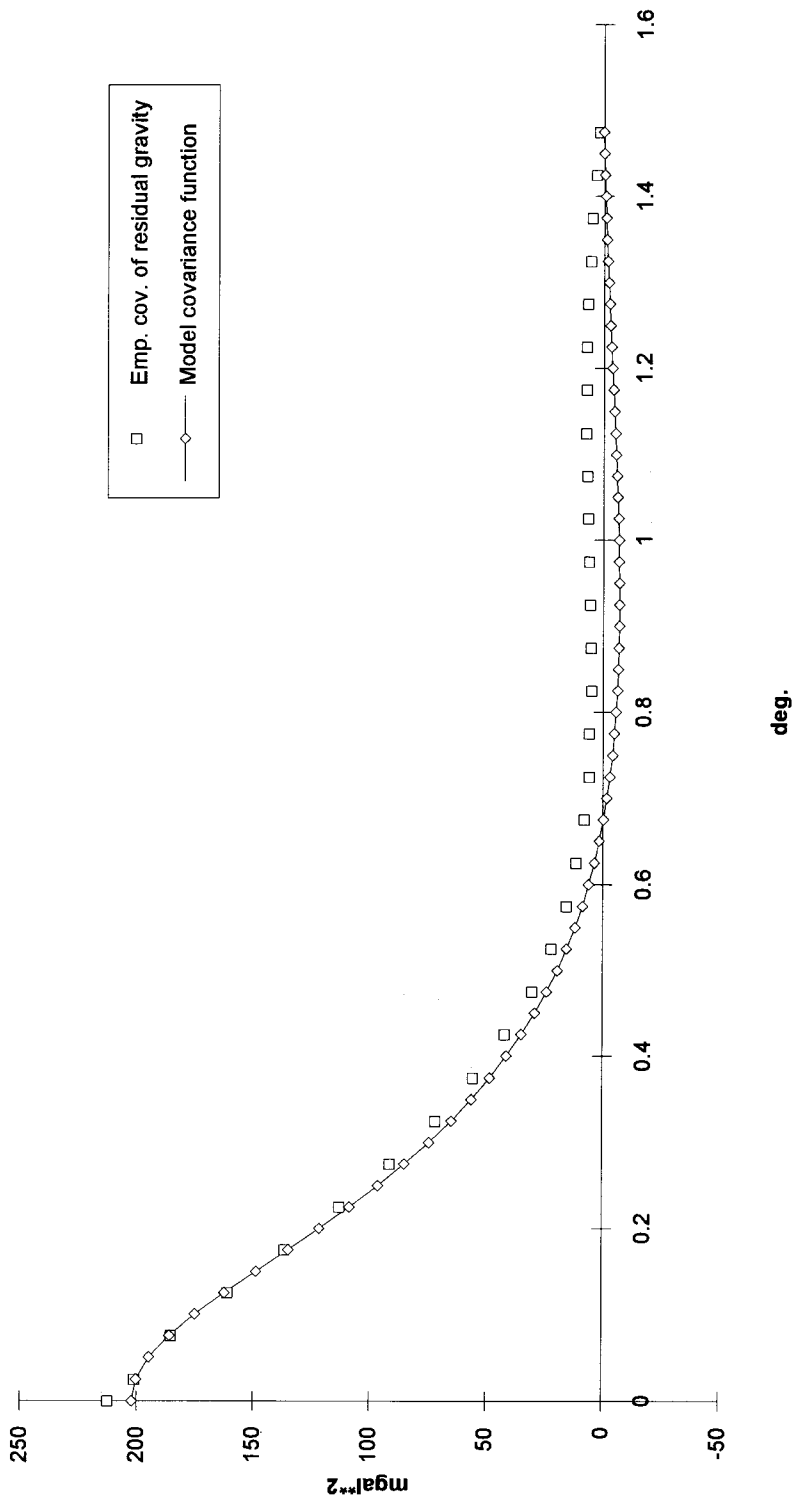
Fig. 1 — The gravity data base.

Fig. 2 — The empirical and the covariance functions of residual gravity.

3. — QUASIGEOID COMPUTATION METHOD AND RESULTS

The remove-restore procedure and Fast Collocation (Barzaghi et al., 1992) were used to get the quasigeoid estimate. Tha basic scheme of this method has been applied following these steps:

a) removal of the long wavelength component of the gravity data using the global geopotential model OSU91A in the measuring points $(\varphi_i, \lambda_i, h_i)$

$$\Delta g_0 (\varphi_i, \lambda_i, h_i) - \Delta g_M (\varphi_i, \lambda_i, h_i);$$

b) Residual Terrain Effect (RTE) computation and subtraction of such an effect to produce residual gravity values

$$\Delta g_r (\varphi_i, \lambda_i, h_i) = \Delta g_0 (\varphi_i, \lambda_i, h_i) - \Delta g_M (\varphi_i, \lambda_i, h_i) - g_{rtc} (\varphi_i, \lambda_i, h_i);$$

c) outlier rejection on $\Delta g_r (\varphi_i, \lambda_i, h_i)$;

d) gridding of $\Delta g_r (\varphi, \lambda, h)$ to produce a $3' \times 3'$ regular grid of $\Delta g_r (\varphi_j^G, \lambda_j^G)$ over the area $36° \le \varphi \le 47°$, $6° \le \lambda\ 19°$ $((\varphi_j^G, \lambda_j^G)$ latitude and longitude of grid knots);

e) Fast Collocation computation of $\Delta \hat{g}_r (\varphi_j^G, \lambda_j^G, 0)$, $\Delta \hat{g}_r (\varphi_j^G, \lambda_j^G, 1\,000\ m)$ from $\Delta g_r^G (\varphi_j^G, \lambda_j^G)$ to evaluate $\dfrac{\partial \Delta \hat{g}_r}{\partial h} (\varphi_j^G, \lambda_j^G)$;

f) computation of $\Delta g_r (\varphi_i, \lambda_i, 0)$ from $\Delta g_r (\varphi_i, \lambda_i, h_i)$ and $\dfrac{\partial \Delta \hat{g}_r}{\partial h} (\varphi_j^G, \lambda_j^G)$;

g) gridding of $\Delta g_r (\varphi_i, \lambda_i, 0)$ to produce $\Delta g_r (\varphi_j^G, \lambda_j^G, 0)$ on the $3' \times 3'$ grid;

h) estimation, via Fast Collocation, of $\hat{T}_r (\varphi_j^G, \lambda_j^G, 0)$ and $\widehat{\Delta g}_r (\varphi_j^G, \lambda_j^G, 0)$ on the $3' \times 3'$ grid;

i) evaluation of $\dfrac{\partial T_r}{\partial h} (\varphi_j^G, \lambda_j^G)$ via the fundamental equation of geodesy

$$\frac{\partial \hat{T}_r}{\partial h} (\varphi_j^G, \lambda_j^G) = - \Delta \hat{g}_r (\varphi_j^G, \lambda_j^G, 0) - 2 \frac{\hat{T}_r (\varphi_j^G, \lambda_j^G, 0)}{R}$$

$$R = \text{mean Earth radius;}$$

l) computation of $\hat{T}_r (\varphi_j^G, \lambda_j^G, h_j^G)$ using $\hat{T}_r (\varphi_j^G, \lambda_j^G, 0)$ and $\dfrac{\partial \hat{T}_r}{\partial h} (\varphi_j^G, \lambda_j^G)$;

m) restore of the model and of the residual terrain effect on the $(\varphi_j^G, \lambda_j^G, h_j^G)$ $3' \times 3'$ prediction grid, to get

$$\zeta (\varphi_j^G, \lambda_j^G, h_j^G) = \zeta_r (\varphi_j^G, \lambda_j^G, h_j^G) + \zeta_{rtc} (\varphi_j^G, \lambda_j^G, h_j^G) + \zeta_M (\varphi_j^G, \lambda_j^G, h_j^G).$$

Some comments are in order to clarify the described procedure.

The global geopotential model OSU91A gives a good description of the geopotential field in this area, apart from the Corsica Island where it appears to be completely flat, both in Δg and in ζ. This causes a mismodelling which reflects into the residual values derived at step a). To overcome this model deficiency, we decided to remove and then restore the total effect of the reference Corsican topography (the same reference heights used for RTE computation described here after) in all the points contained in the window $40 \leq \varphi \leq 44°$, $7° \leq \lambda \leq 11°$ centered on Corsica Island. In such a way the low frequency component of geopotential field of Corsica, which is not present in the OSU91A model, is assumed to be connected to the reference DTM used for RTE.

The Residual Terrain Effect was computed with respect to a reference DTM which has been related statistically to the global geopotential model previously removed.

In order to do that, we considered a subset of 8577 points, homogeneously distributed, of the gravity data base derived at step a). Then, we reduced the data of the Residual Terrain Effect computing it with various reference height fields. These different reference DTMs were obtained via moving average from the detailed DTM; the best coupling between model and residual terrain computation was reached with the smoothed DTM derived from a moving average of 20′ window size, sampled at $5′ \times 5′$. This means that using the OSU91A geopotential model and such a reference height data base, we obtained the minimum mean and the minimum variance of the residual gravity values Δg_r.

Step d) through step f) were applied to verify the interaction between gridding procedure and height information in $\Delta g_r (\varphi_i, \lambda_i, h_i)$.

The statistical analysis of $\Delta g_r (\varphi_i, \lambda_i, h_i)$ (step b)) and $\Delta g_r (\varphi_i, \lambda_i, 0)$ (step f)) showed that no significant correlation with the height is present in $\Delta g_r (\varphi_i, \lambda_i, h_i)$. In gridding the gravity data to detrmine $\Delta g_r (\varphi_j^G, \lambda_j^G, 0)$ on a regular grid, we had to face the problem due to the lack of data over late Yugoslavia. As it is quite natural, we set $\Delta g_r (\varphi_j^G, \lambda_j^G, 0) = 0$ in that region, since no information are provided there. In principle, using Fast Collocation, step h), i), and l) could be condensed in one step only, i.e. compute $\hat{T}_r$ on sparse (φ, λ, h) points from gridded data g). However, this is so CPU time consuming that the computation we did should have lasted one month: steps h) to l) are much more efficient from the computational point of view even though this is an approximate procedure (differences between the rigorous and the approximate approach on some test points amount to a maximum of few centimetres).

The computer program used for RTE (this effect has been computed using a window of 120 km around each point) and gridding computations are TC and GEOGRID of the GRAVSOFT package (Forsberg, 1994; Tscherning, 1994) while global geopotential model functionals Δg_M and ζ_M have been evaluated using F477 program by R. Rapp (1994).

We finally remark that the h_j^G of the grid l) was obtained via bilinear interpolation from the four neighbouring points of the detailed DTM. The numerical results of the estimation procedure detailed above are summarized in table 1.

TABLE 1

REMOVE-RESTORE STATISTICS

	Δg_0 [mGal]	$\Delta g_0 - \Delta g_M$ [mGal]	$\Delta g_r \div (c)$ [mGal]	$\Delta g_r \div (g)$ [mGal]	$\hat{\zeta}_r$ [m]	$\hat{\zeta}$ [m]
n	105695	105695	105308	52188	57681	57681
E	11.87	-7.57	-3.66	0.24	0.07	44.24
σ	62.86	33.47	17.91	14.57	0.59	5.02
Max	348.82	309.67	117.36	111.07	2.33	54.96
Min	-578.43	-631.00	-197.34	-118.28	-1.94	25.37

The empirical and model covariance functions used in each Fast Collocation estimation are plotted in fig. 2; the final resulting quasigeoid is shown in fig. 3.

4. — COMPARISONS WITH GPS/LEVELING DATA

Many reliable GPS campaigns have been carried out in the last years in Italy. Two geotraverses have been measured: one moving from the Brennero Pass along the Adriatic and Ionian coasts to Noto in Sicily (this is the italian part of the European geotraverse); the second starts in Rome (Monte Mario) and reaches Reggio Calabria in front of Sicily (Tyrrhenic geotraverse) (Birardi, 1993).

During the last two years, the italian Istituto Geografico Militare (I.G.M.) started a GPS measurement campaign which is planned to cover densely the italian territory (Surace, 1993). Furthermore, in the framework of the TYRGEONET project (Achilli et al., 1991), GPS measurements have been made in several part of Italy.

Finally, we took into account data over Sardinia (Asili et al., 1995), so that the estimated quasigeoid has been tested over the entire italian territory.

All these GPS stations have been connected to the italian national height system through spirit leveling so that an estimation of N in these points is possible.
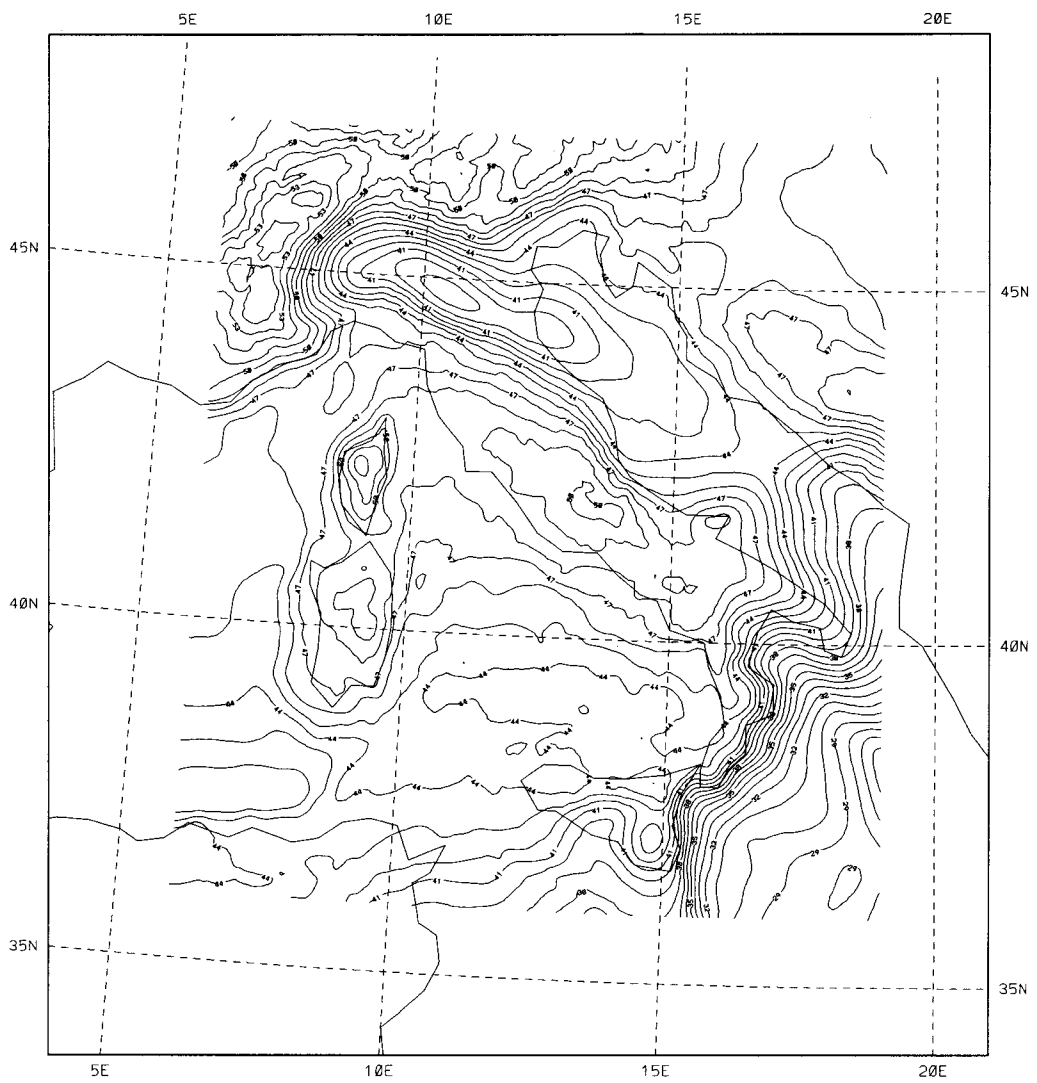
Fig. 3 — The italian quasigeoid ITALGEO95.

The statistics of the differences between N_{GPS} and ζ (ITALGEO95), N_{GPS} and N (ITALGEO90), N_{GPS} and N (OSU91A) are presented in table 2, while the distribution of GPS stations is described in fig. 4.

TABLE 2

N_{GPS} VERSUS GEOPOTENTIAL MODELS

		E [m]	σ [m]	Max [m]	Min [m]
Adriatic geotraverse $n = 56$	$N_{GPS} - \zeta$ (95)	0.76	0.54	1.81	—0.41
	$N_{GPS} - N$ (90)	0.06	0.75	0.96	—1.93
	$N_{GPS} - N$ (OSU91A)	0.45	0.63	2.43	—0.76
Tyrrhenic geotraverse $n = 28$	$N_{GPS} - \zeta$ (95)	0.16	0.11	0.51	0.01
	$N_{GPS} - N$ (90)	—0.48	0.38	0.25	—1.57
	$N_{GPS} - N$ (OSU91A)	0.03	0.37	0.90	—0.54
I.G.M. (South) $n = 29$	$N_{GPS} - \zeta$ (95)	—0.90	0.18	—0.54	—1.19
	$N_{GPS} - N$ (90)	—1.56	0.73	—0.46	—2.99
	$N_{GPS} - N$ (OSU91A)	—0.66	0.47	0.78	—1.65
I.G.M. (North) $n = 13$	$N_{GPS} - \zeta$ (95)	—0.29	0.08	—0.15	—0.41
	$N_{GPS} - N$ (90)	—0.83	0.15	—0.54	—1.14
	$N_{GPS} - N$ (OSU91A)	—0.79	0.43	—0.30	—1.63
TYRGEONET (South) $n = 12$	$N_{GPS} - \zeta$ (95)	—0.91	0.12	—0.68	—1.06
	$N_{GPS} - N$ (90)	—1.19	0.44	—0.18	—1.78
	$N_{GPS} - N$ (OSU91A)	—0.94	0.36	—0.42	—1.46
TYRGEONET (North) $n = 20$	$N_{GPS} - \zeta$ (95)	—0.36	0.20	0.08	—0.75
	$N_{GPS} - N$ (90)	—0.93	0.28	—0.30	—1.28
	$N_{GPS} - N$ (OSU91A)	—0.63	0.45	0.09	—1.48
Sardinia $n = 29$	$N_{GPS} - \zeta$ (95)	—1.13	0.18	—0.61	—1.55
	$N_{GPS} - N$ (90)	—1.25	0.37	—0.10	—1.76
	$N_{GPS} - N$ (OSU91A)	—0.74	0.30	—0.25	—1.40

The statistics show that a good fit between ITALGEO95 and GPS/leveling has been reached. The standard deviations of the differences are quite homogeneous all over Italy and improve in each case both with respect to OSU91A geoid (as expected) and ITALGEO90.

- geotraverse
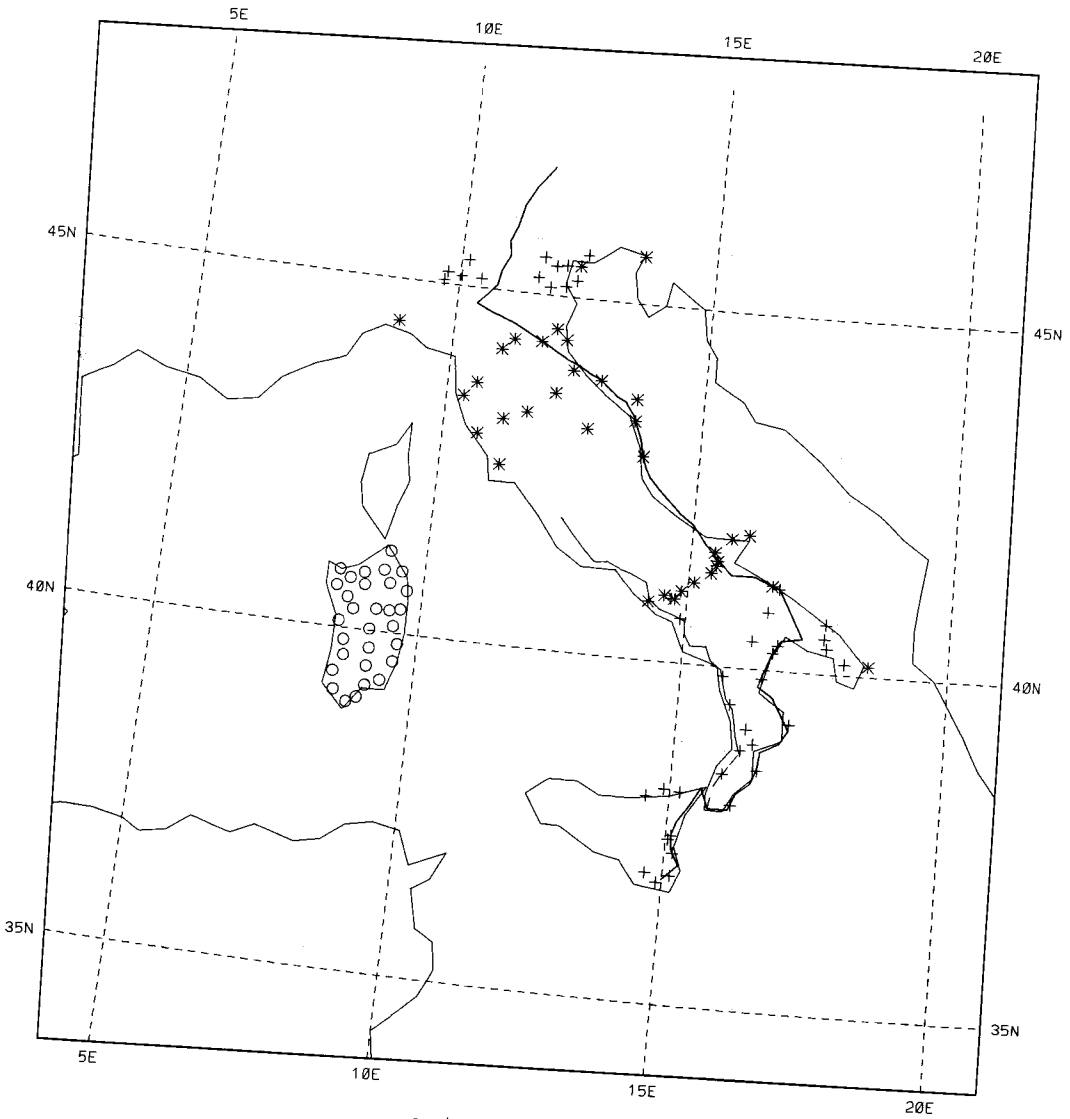* TYRGEONET
+ I.G.M.
° University of Cagliari

Fig. 4 — GPS data.

However, the result of the comparison with the Adriatic geotraverse is quite poor and this reveals the existence of some unsolved problems.

Firstly, it must be taken into account that we compared a quasigeoid and GPS/leveling data which are geoid heights. This can induce distorsions especially in areas where a relevant topography is present. Then, it must be mentioned that this is the oldest GPS campaign in Italy and that those data are not so reliable as the remaining GPS measurements. In addition to the previous comments, it is to stress that probably also the geopotential estimation procedure can give problems in areas where a rough geopotential field is present. Infact, a closer inspection of the plot of the differences along the geotraverse (see fig. 5) allows to identify two main «domains» which are homogeneous.

If we consider separately the sets of differences from point (A) to point (B) and from point (C) to the end, we have statistics which are close to the ones in tab. 2; in fact from (A) to (B) we have $\sigma = 22$ cm and from (C) to the end $\sigma = 20$ cm. We think that this behaviour can be explained taking into account the particular feature of the geopotential field along this geotraverse.

From the northernmost point to point (A) we have a strong geoid variation, which amounts to 13 m in 250 km; then the geotraverse proceeds to south nearly along an isoline of the quasigeoid to point (B). From point (B) to point (C) we again have a strong field variation, 4 m in 100 km.

Finally, in the last part of the geotraverse, we are still along a contour line of the quasigeoid and consequently we have a good fit between ITALGEO95 and GPS/leveling data.

So, the critical points along the geotraverse are connected to strong geoid variations; this probably has to do with global geopotential model distorsions occuring in such areas which the remove-restore method cannot compensate properly.

5. — CONCLUSIONS

The new italian quasigeoid, computed via remove-restore technique and Fast Collocation, provided a reliable geopotential field estimation over the area $36° \leq \varphi \leq 47°$, $6° \leq \lambda \leq 19°$. This estimate has been tested via comparison with GPS/leveling measurements which cover Italy quite homogeneously.

The mean value of the standard deviations is of 15 cm if the Adriatic geotraverse is excluded. This data set seems to indicate that mismodelling are still present; further investigations are needed to clarify the reasons of such a high discrepancy ($\sigma = 54$ cm) between the quasigeoid and these GPS/leveling measurements. Furthermore, in the near future, comparisons will be carried out with altimetry to test the effectiveness of the quasigeoid in the seas surrounding Italy.
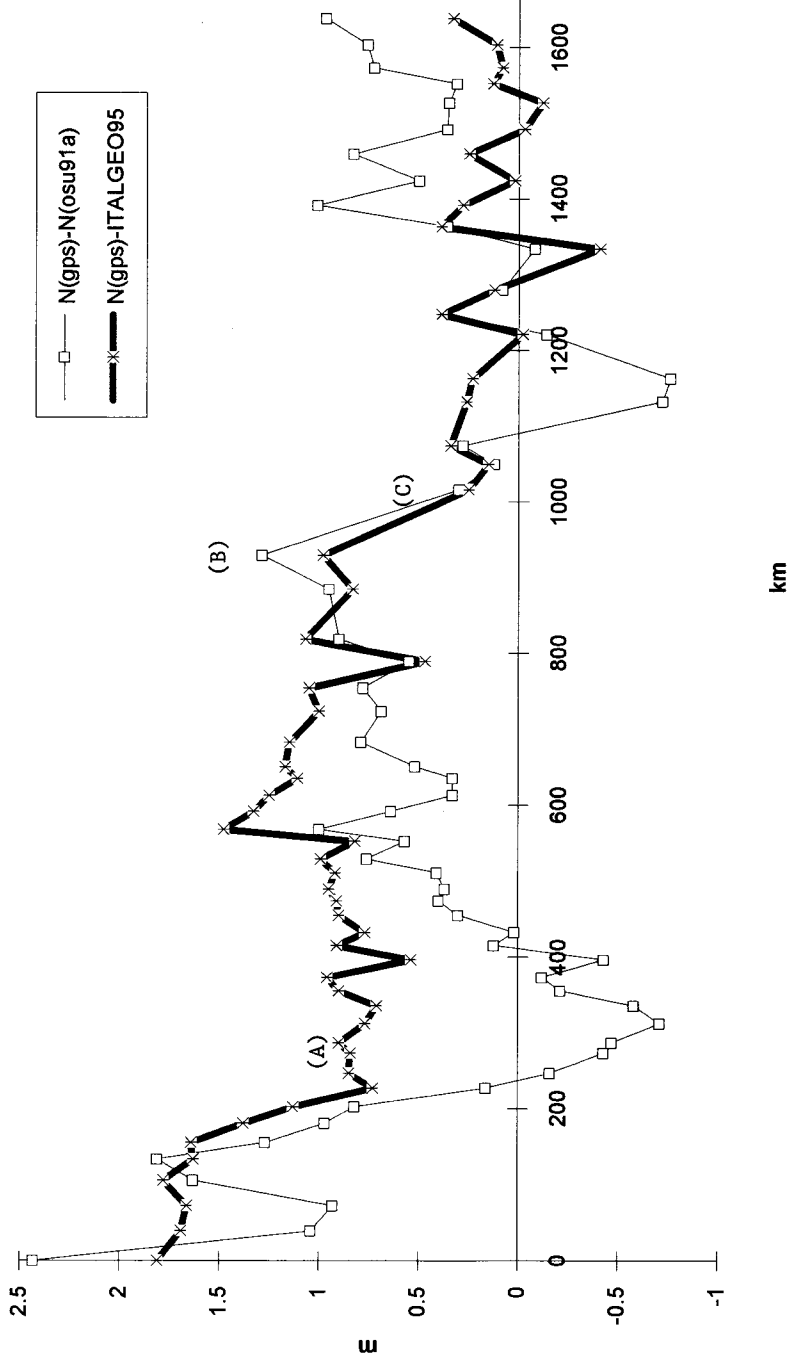
Fig. 5 — Residual along the Adriatic geotraverse.

ACKNOWLEDGMENTS

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