International Geoid Service (IGeS)

http://www.iges.polimi.it

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Overview

Over the period 2007-2011, IGeS activities have been mainly focussed on:

- a test on quasi-geoid computation methods, the Auvergne test;
- the participation to the validation of the EGM2008 global geopotential model;
- the computation of a global geopotential model based on GOCE data;
- the organization of schools on geoid computation;
- the support given in computing high definition geoid in South India and Bangladesh.

The Auvergne test on quasi-geoid estimation has been set up in co-operation with IGN and EGGP. IGN supplied the gravity, DTM and GPS/levelling data while EGGP contributed in assessing the test procedures. A first comparison between the computations performed by six different groups have been presented during the last Hotine-Marussi Symposium held in Rome (July 5th-9th, 2009). The results of this test proved the substantial equivalence of the applied computation methods.
The validation of the EGM2008 global geopotential model has been performed in the framework of the activities of the Joint Working Group (JWG) between the International Gravity Field Service (IGFS) and the Commission 2 of the International Association of Geodesy (IAG), entitled "Evaluation of Global Earth Gravity Models". IGeS participated to the test on EGM2008 comparing it with data covering two areas: the Central Mediterranean area and the South of India. The scientific papers on EGM2008 validation have been collected in a special issue of the *Newton's Bulletin* (the Bulletin n° 4) which can be downloaded at the IGeS web page (www.iges.polimi.it). This special issue of *Newton's Bulletin* consists of 25 peer-reviewed evaluation papers of EGM2008 (and partially of PGM2007A), which are grouped into four different sections according to the geographical region of the evaluation tests: Global, the Americas, Europe and Africa, and Asia, Australia and Antarctica. Their results provide a thorough external assessment of EGM2008, using a variety of geodetic data and testing methodologies.
Furthermore, IGeS has been deeply involved in estimating a global geopotential model based on GOCE data and the space-wise approach. As new data have been provided by ESA, refinements in the global geopotential model estimating procedure have been devised and applied to these data.
Also, as it is usually done since 1999, schools on geoid computation have been organized by IGeS. One school have been held in Como (Itlay), in September 15th-19th, 2008. On September 7th-11th , 2009 a second geoid school was organized at the Universidad National de la Plata, Fac. de Ciencias Astronómicas y Geofísicas, La Plata (Argentina) which was then followed by a third school held in St. Petersburg (Russia), from June 28th to July 2nd, 2010.
Finally, IGeS gave support to researchers in computing local geoids. This has been done in the last two years period in two different areas of the world, namely South India and Bangladesh.
The National Geophysical Research Institute of Hyderabad (India) contacted IGeS in order to get support in computing a gravimetric geoid in South India. This has been done mainly for

geophysical investigation in this area, even though the quality of the estimated geoid allows its use also in height conversions (e.g. from ellipsoidal to orthometric heights).
A co-operation was also established with the Survey of Bangladesh. A researcher of the Survey of Bangladesh was hosted at IGeS in Milano, in February, 2009. During this period, a refinement of the EGM2008 over Bangladesh was computed, based on GPS/levelling points which were collected by the Survey of Bangladesh. This refinement proved to be effective and led to a significant improvement of the global EGM2008 model.

Activities

1. The Auvergne test on geoid computation

This test aims at comparing different gravimetric geoid estimation methods. Data were provided by H. Duquenne (IGN) and were distributed by IGeS. IGeS and EGGP co-operated in defining the testing procedures and the general framework of this test.
The test field is the Auvergne area, located in the centre of France, covering a 4° x 6° wide area (see the blue square in the Figure 1). The IGN gravity dataset consists of 244009 values, covering most of the French territory. The used DTM is based on SRTM, with a 3''x 3'' grid spacing and the global geopotential model taken into account is EIGEN_GL04C up to degree and order 360 (this was the most recent model available when the project started). In the test field, 75 GPS/leveling points are also available to be used as control points.
Height anomalies were computed on a 1´ × 1´ grid, in the area 44°N < lat. < 48°N; 0°E < lon. < 6°E, and then interpolated on the 75 GPS/levelling control points.

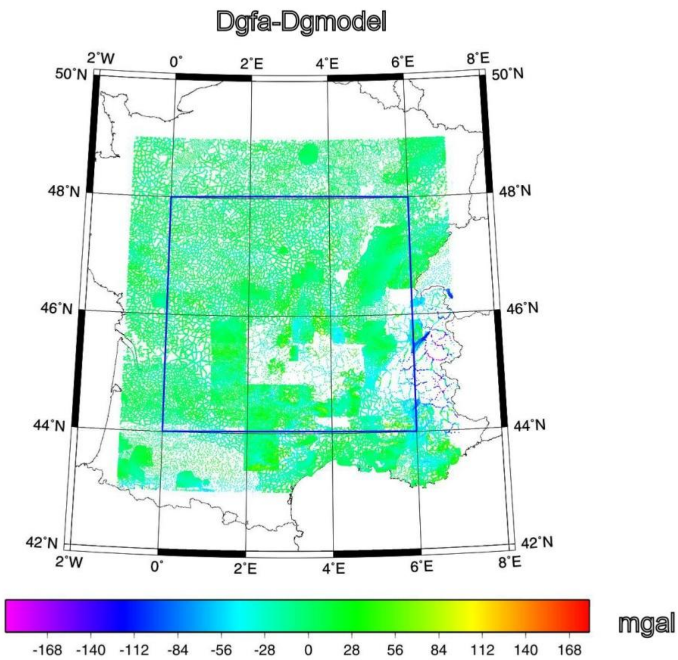

Figure 1. – The test area and the gravity database (residual gravity after geopotential model reduction)

The six participating research groups have performed the computation using, basically, remove-solve-restore procedure. The main differences refer to the residual height anomaly computation. In the following table, the six research group participating to the test and the different methods applied in this computation step are summarized.

Swedish Mapping, Cadastre and Registry Auth / Zanjan University (**Swed_Map**)	KTH (Sjoberg) method: least squares (stochastic) kernel modification; additive corrections for: topography, downward continuation, the atmosphere and the ellipsoidal shape of the Earth.
Politecnico di Milano (**PoliMi**)	Fast collocation approach.
Institut f.Erdmessung (**IFE**)	Data screening, RTM terrain reductions, spectral combination with 1D FFT.
Niels Bohr Institute (**NBI**)	Least-Squares Collocation as implemented in GEOCOL.
Department of Geodesy and Surveying, Aristotle University of Thessaloniki (**DGS_Thess**)	1D spherical FFT methods.
Laboratoire de Recherche en Géodésie, Institut Géographique National (**IGN**)	Stokes' integration.

Table 1. – The six research groups participating to the test and the used computation methods

The results obtained using the estimation methods listed above are collected in Table 2. They are the statistics of the residuals on the 75 GPS/levelling points after datum shift estimation.

	Swed_Map	**PoliMi**	**IFE**	**NBI**	**DGS_Thess**	**IGN**
Check points	75	75	75	75	75	75
Mean (m)	0.000	0.000	0.000	0.000	0.000	0.000
St. dev. (m)	0.029	0.036	0.035	0.067	0.035	0.037
Min (m)	-0.094	-0.100	-0.085	-0.196	-0.066	-0.069
Max (m)	0.053	0.078	0.079	0.161	0.092	0.093

Table 2. – The results of the Auvergne test

The results achieved by the different research groups show a reasonable agreement. Differences are only of the second order, thus assessing the substantial equivalence of the different approaches and software. In the frame of a future research it seems interesting to involve other research groups with different methodologies. Also an optimization of different groups' results will be carried out, by testing other data configurations, for instance using other DTMs, or different global models (i.e. EGM2008).

2. The participation to the EGM2008 validation test

IGeS participated to the validation of the geopotential model EGM2008 by testing its precision in two different areas, i.e. the Central Mediterranean and the South of India. Here, only a synthetic description of the main results is given. The computation details can be found in Barzaghi and Carrion (*Testing EGM2008 in the Central Mediterranean area*, *Newton's Bulletin, n° 4, 2009*) and in Carrion et al. (*Gravity and geoid estimate in South India and their comparison with EGM2008*, *Newton's Bulletin, n°4 ,2009*).

2.1 The Central Mediterranean test area

The test in the Central Mediterranean area was based on comparisons with gravity and GPS/levelling data available in this area. This was done both with respect to previous existing geopotential models (EGM96, GPM98CR and EIGEN-GL04C) and the last estimate of the Italian geoid, ITALGEO2005 (*Barzaghi et al., Bollettino di Geodesia e Scienze Affini, n° 1, 2008*).
The test area is included in the window 35°≤ lat. ≤48°, 5°≤ lon. ≤20°. In this area, 310.660 point gravity values and 977 GPS/leveling data are available. In Figure 2, the distribution of the GPS/leveling points is shown.

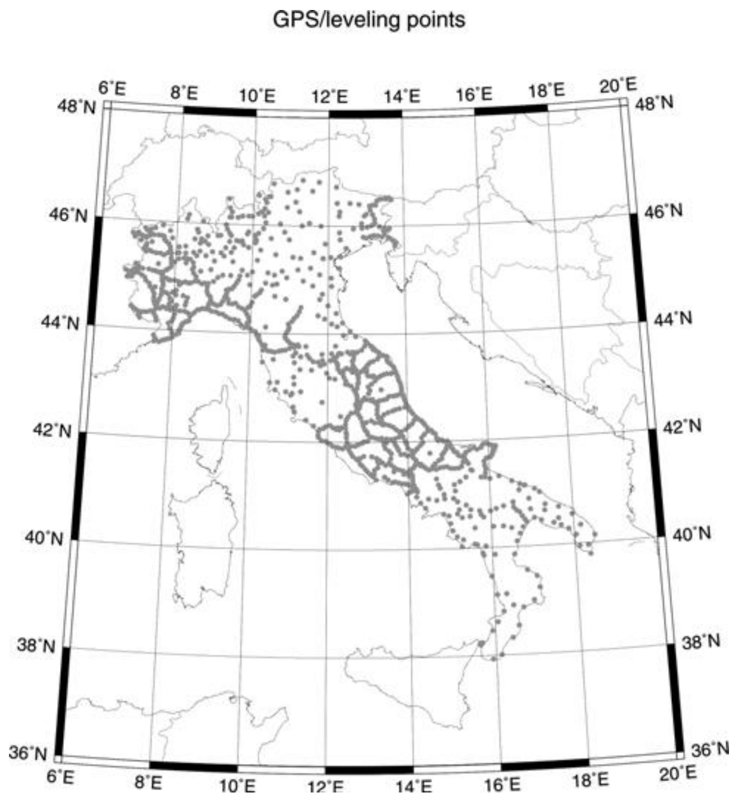

Figure 2. – The test area and the used GPS/leveling points

A first comparison has been made using the full gravity data set and the EGM2008 and GPM98CR models. The GPM98CR model has been used because it is the one giving the best results, before EGM2008.
Statistics refer to residuals after model and terrain effect reduction.

	$\Delta g_{FA} - \Delta g_{EGM2008} - \Delta g_{RTC}$	$\Delta g_{FA} - \Delta g_{GPM98CR} - \Delta g_{RTC}$
E	-0.94	-1.14
St.dev.	7.88	10.69
Min	-287.74	-274.55
Max	117.26	106.64

Table 3. – The statistics of the gravity residuals after geopotential model and terrain effect reduction (mgal)

Also, the statistics of the reduced gravity values were computed on a reduced gravity data set consisting of 142.196 values (the maximum geopotential model degree is listed too). In this case, the EGM2008 model is compared to EIGEN-GL04C and EGM96 models.

	$\Delta g_{FA} - \Delta g_{EGM08(2190)}$	$\Delta g_{FA} - \Delta g_{GL04C(360)}$	$\Delta g_{FA} - \Delta g_{EGM96(360)}$
E	-5.41	-7.33	-6.42
St.dev.	20.32	32.24	31.13
Min	-241.56	-255.89	-253.98
Max	119.49	194.81	188.23

Table 4. – The statistics of the gravity residuals after geopotential model reduction (mgal)

The comparison with GPS/levelling data are referred to EGM2008, GPM98CR and ITALGEO95 (statistics refer to residuals after datum shift estimation).

	$N_{EGM2008} - N_{GPS/lev}$	$N_{GPM98CR} - N_{GPS/lev}$	$N_{Italgeo05} - N_{GPS/lev}$
E	0.00	0.00	0.00
St.dev.	0.10	0.35	0.12
Min	-0.33	-1.30	-0.50
Max	0.34	0.64	0.32

Table 5. – The statistics of the GPS/leveling residuals after geoid model reduction (m)

2.2 The South India test area

In this test, a comparison over the Southern India region using a quite large data base collected by National Geophysical Research Institute of India is presented.
The gravity field of this area is quite regular and its structure is mainly connected to the topography**;** in fact the major variations are in the area 10°≤ lat. ≤12°, 76°≤ lon. ≤78° where

the principal relieves are concentrated. The topography varies from sea level to high mountains (about 2500 meters) and the area is surrounded by deep ocean. Land gravity is known inside the area 8°≤ lat. ≤15°, 74°≤ lon. ≤81° where 16013 gravity values were measured (see Figure 3).

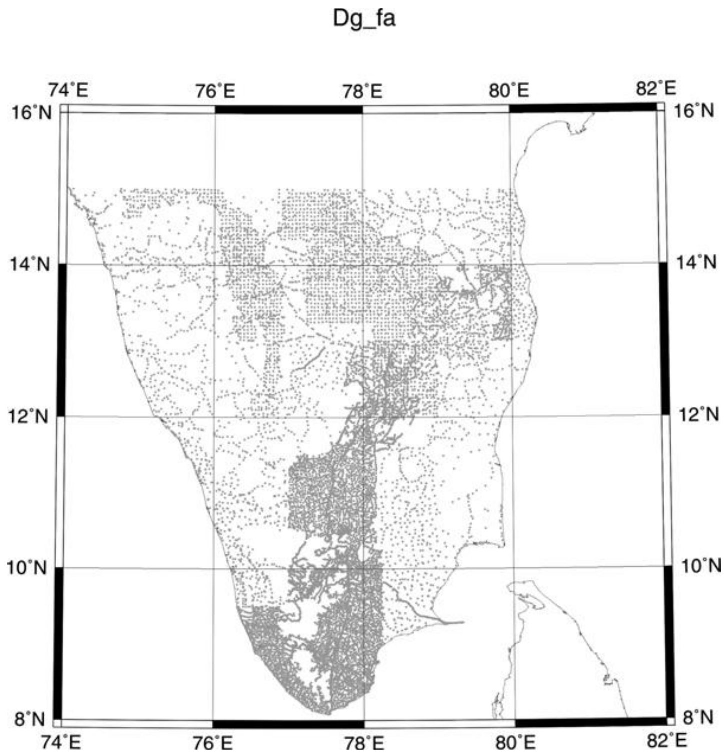

Figure 3. – The South India gravity data base

Since no GPS/levelling data were available, comparisons restrict to gravity only. In Table 6, reduced gravity statistics can be compared with those of the unreduced data

Gravity	E(mgal)	St.dev.(mgal)	Min(mgal)	Max(mgal)
Δg_{FA}	-33.93	29.13	-120.93	192.77
$\Delta g_{FA} - \Delta g_{EGM96}$	-6.45	21.85	-94.46	182.32
$\Delta g_{FA} - \Delta g_{GPM98CR}$	-7.56	22.42	-83.08	200.56
$\Delta g_{FA} - \Delta g_{GL04C}$	-6.08	21.65	-92.55	183.23
$\Delta g_{FA} - \Delta g_{EGM2008}$	-0.08	10.88	-112.54	79.40

Table 6. – The statistics of the gravity residuals after geopotential model reduction

2.3 Conclusions

The EGM2008 global geopotential model proved to be very effective in fitting gravity and GPS/leveling both in the Central Mediterranean and in the South India area. The same conclusions hold for the tests documented in the papers published in the special issue of the *Newton's Bulletin.* Hence, the tests performed by 25 research groups proved that this model is remarkably better than those previously estimated. Thus, the EGM2008 coefficients contain, even at high order, valuable information. Furthermore, its accuracy in fitting GPS/leveling data is, in most cases, equivalent to those obtained with high resolution geoid estimates based on local gravity databases (e.g. ITALGEO05). This is quite surprising since, up to now, local geoid estimates have given better results. Thus, the EGM2008 model opens new perspectives on local geoid computation that probably require the definition of new computation strategies.

3. The GOCE mission: computation method at IGeS

Since the launch of the GOCE satellite (March 17th, 2009), IGeS has been actively involved in estimating a global geopotential model based on GOCE data.
The most recent solution has been computed by applying the space-wise approach to eight months of data.
GOCE data have been divided in subsets of continuous observations with similar behavior. The subsets were then pre-processed in such a way to mark and remove outliers and fill small data gaps. Datasets with not enough valid data were disregarded.
Five subsets have been selected to produce the solution; from about 8 months of data, only 80% of them have been finally used.
The scheme adopted in computing the solution can be detailed as in the following (see also Figure 4):

- each subset is processed following the space-wise approach producing grids of potential and second order radial derivative, plus Monte Carlo (MC) sample grids describing the error;
- merged grids of the two functionals are obtained by using a moving window and weighting data on the bases of MC error covariance matrices;
- harmonic analysis is finally applied to these grids, obtaining two sets of coefficients that are merged by collocation based on the errors propagated from the MC sample grids.

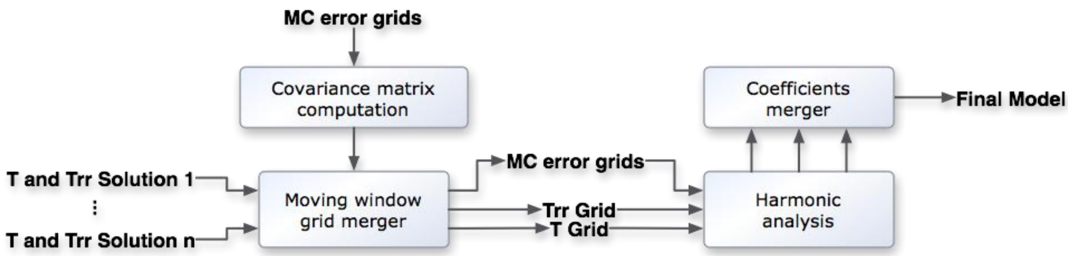

Figure 4. – The GOCE data processing scheme adopted at IGeS

The new solution has led to remarkable improvements which can be clearly seen in Figure 5 where the error degree variances of this new solution (blue line) are compared to those of a preliminary space-wise solution (black line) and to those of the time-wise solution (orange line)

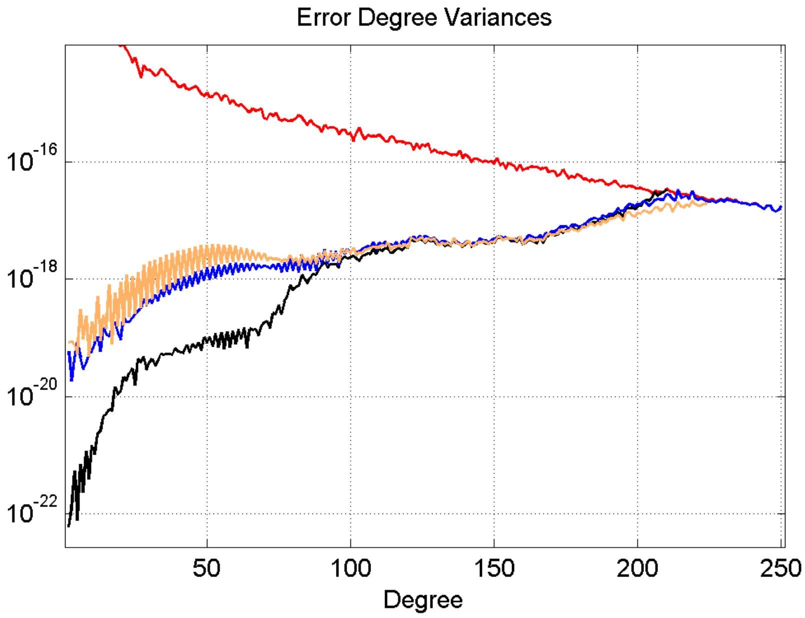

Figure 5. – Error degree variances derived from GOCE data by applying different processing strategies

Thus GOCE-only models can be estimated by using this last version of the space-wise approach; in particular a solution based on the first delivered eight months has been computed. Further improvements in the model can be achieved by properly modeling the residual signal covariance so to better control the regularization at the highest degree.
At present, the commission error up to degree 200 in the latitude interval -80 < lat. < 80 is of about 6 cm in terms of geoid undulations and 1.6 mgal in terms of gravity anomalies. The maximum degree of the model is 240.

4. The schools on geoid computation

The VIII International Geoid School on 'The Determination and Use of the Geoid' has been organized by IGeS at the Como Campus of the Politecnico di Milano, from September 15th to September 19th, 2008.
The school included both theoretical lectures and numerical exercises on local geoid computation. Lectures on theory for geoid computation, terrain effect, global geopotential models, collocation method in Geodesy and FFT for geoid estimation were respectively given by F. Sansò, R. Forsberg, N. Pavlis, C.C. Tscherning and M. Sideris. The school was attended by 23 participants coming from 12 countries. Morning theoretical lessons were given at Palazzo Natta in the historical center of Como while afternoon computer exercise sessions were held in the computer center at the Politecnico di Milano Campus in Como. The computer room is provided with 40 computers working with O.S. WinXP S.P.3, on which Fortran compilers and Phyton interface have been installed to use FORTRAN programs that usually run under Unix systems.
The IX school was organized at the Faculty of Astronomical and Geophysical Sciences of the University of La Plata in Argentina, from September 7th to September 11th , 2009.
23 participants from 5 countries attended the school. Lectures were on theory and practice on geoid computation following a structure similar to the one held in Como. Teachers were: F. Sansò, R. Forsberg, N. Pavlis, C. C. Tscherning and M. Sideris. On the first day, two seminars on *Geoid, Gravity and Sea-Level from Radar Altimetry* and *Monitoring Gravity Variations* were given by O. Andersen and S. Bonvalot respectively. On the third day, there was a seminar on *Fitting the Gravimetric Geoid to GPS Benchmarks* by G. Fotopoulos and during

the last day a seminar on *Gravity and Geoid in Argentina*. As for the Como geoid school, morning theoretical lessons were followed by practical numerical exercises that were held in a computer room equipped with 25 computers running LINUX operating system.
The last geoid school in the 2007-2010 period, the X organized by IGeS, was carried out in St. Petersburg, from June 28th to July 2nd, 2010. 15 participants attended this school from 5 countries. As for the two previous schools, lectures were given on the theory of geoid computation (R. Barzaghi), global geopotential models (N. Pavlis), marine gravity (O. Andersen), terrain effect in geoid estimation (R. Forsberg), collocation applied to geodesy (I. Tziavos), FFT methods in geodesy (M. Sideris). L. Vitushkin gave a lecture on *Absolute gravity measurements*. Numerical exercises, as usual, were performed using software related to geoid estimation.
During each school, Lecture Notes, with some upgrading as addendum, IGeS CD with software and data for exercises, the GRAVSOFT manual and a user guide explaining FFT programs were distributed to the participants. Moreover, CDs have been supplied containing all the lectures presented during the week.

5. Supporting geodetic activities in South India and Bangladesh

Contacts have been established with the National Geophysical Research Institute of Hyderabad (India) and the Survey of Bangladesh. In both cases, a support was requested for geoid computation.
In the South India area, a gravimetric quasi-geoid has been estimated in co-operation with the National Geophysical Research Institute of Hyderabad that supplied 16013 gravity data (*D. Carrion et al., Gravity and geoid estimate in South India and their comparison with EGM2008, Newton's Bulletin, n°4 ,2009*). Data over the surrounding seas were derived from altimetry (*Andersen et al., Improved High Resolution AltimetricGravity Field Mapping (KMS2002 Global Marine Gravity Field*) - *A window on the Future of Geodesy, IAG symposium, 128, 2005)*. The final global gravity data base consists of 63968 values.
The standard "remove-restore" procedure was adopted to estimate this quasi-geoid; the residual component was computed via Fast-collocation. The estimated quasi-geoid is plotted in Figure 6.

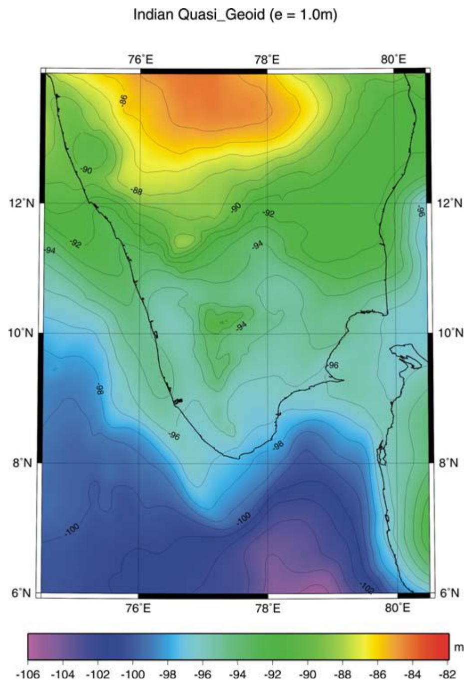

Figure 6. – The South India quasi-geoid

Unfortunately, no GPS/leveling data were available and thus no tests on its accuracy were possible. However, this can be considered a reliable estimate which will be used mainly in geophysical investigation over the South India region.

The co-operation with Survey of Bangladesh led to a geoid estimate based on GPS/levelling points used to refine the EGM2008 geopotential implied undulation. Survey of Bangladesh supplied 155 GPS/leveling points: 110 were used in the computation while the remaining 45 were considered as control points. The geoid residuals computed as

$$\Delta N_i = N_i(GPS/lev) - N_i(EGM2008)$$

were interpolated on a regular 5' grid covering Bangladesh. The final geoid estimate has been obtained by adding, on the same grid points, the geopotential model component thus obtaining:

$$\hat{N}_{grid} = N_{grid}(EGM2008) + \Delta\hat{N}_{grid}$$

$$\Delta\hat{N}_{grid} = Collo(\Delta N_i)$$

This geoid estimate improved the EGM2008 geoid estimate in this area. This has been proved by comparing the refined geoid estimate and EGM2008 on the 45 GPS/leveling control points. The statistics of this comparison are shown in Table 7.

	EGM2008	**N_{grid}**
Check points	45	45
Mean (m)	0.010	0.018
Standard dev. (m)	0.152	0.089
Minimum (m)	-0.292	-0.199
Maximum (m)	0.358	0.237

Table 7. – The statistics of the residual undulation over the 45 control points

As one can see, a remarkable improvement in st. dev. is obtained using N_{grid}. Contact with Survey of Bangladesh will continue in the future with the aim of improving the geoid estimate in this area, also including gravity data that are going to be measured.