International Service for the Geoid (ISG)

http://www.isgeoid.polimi.it/

President: Mirko Reguzzoni (Italy)
Director: Daniela Carrion (Italy)

Structure

The Service is currently provided by two centers, one at the Politecnico di Milano (Italy) and the other at NGA (USA).

In addition to the president and the director, the ISG staff is composed by other scientists (F. Sansò, R. Barzaghi, G. Sona, A. Albertella, C.I. De Gaetani and L. Rossi) as well as a secretary (C. Vajani).

The ISG advisory board is composed by the following scientists with expertise in the field of geoid determination:

- N. Pavlis (USA)
- M. Sideris (Canada)
- J. Huang (Canada)
- R. Forsberg (Denmark)
- U. Marti (Switzerland)
- H. Denker (Germany)
- L. Sánchez (Germany)
- I. Tziavos (Greece)
- W. Kearsley (Australia)
- D. Blitzkow (Brazil)

In the period 2015-2019, ISG has been involved in the Joint Working Groups JWG 2.2.1 of Sub-commission 2.2 “Integration and validation of local geoid estimates”.

Overview

The service governance was changed on 13th April, 2018, nominating Daniela Carrion as director of the service. The service rendered by Giovanna Sona as previous director is warmly thanked.
In the period 2015-2019, the main scientific activities of ISG have been related to the following research lines:

- local/regional geoid estimation;
- merging of local geoid estimates, defining a unified height datum;
- school organization and scientific support to researchers on geoid estimation;
- ISG geoid repository and website update.

As for the geoid estimation, the main effort has been devoted to the GEOMED-II project. The goal of this project is the computation of a high-accuracy and high-resolution geoid model for the Mediterranean Sea employing land and marine gravity data and GOCE/GRACE based global models. Moreover, the Italian geoid model has been recomputed, after validating the existing gravity database. Finally ISG took part in the so-called Colorado experiment organized by NOAA’s National Geodetic Survey.

As for the local geoid merging, this activity has been performed in the framework of the JWG2.2.1 "Integration and validation of local geoid estimates" of IAG Commission 2. The output will represent a new product of ISG and aims to be a contribution in the frame of GGOS for the establishment of an International Height Reference System (IHRS).
According to tradition, during this four-year period ISG organized an international school on geoid determination and height datum definition. The school was held at the Geodesy Department of Mongolian University of Science and Technology (MUST), Ulaanbaatar, Mongolia, from 6th to 10th June, 2016. The total number of participants was 30, half of them coming from abroad.
Last but not least, to maintain the main ISG purpose of collecting, analysing and redistributing local and regional models, the ISG geoid repository has been continuously updated and the ISG website has been modified accordingly. In particular, the webpage of each model has been "standardized" in the sense of providing the same type of information. Moreover, all public models are redistributed with a unique ASCII format.

Local/regional geoid estimation

In the last four years, the activities on local/regional geoid estimation have been focused on the GEOMED-II project and the ITALGEO model update, as well as the participation to the Colorado experiment. The former is dedicated to the computation of a geoid model for the Mediterranean Sea. It is sponsored by the European Space Agency (ESA) and by all the participating Institutions. Apart from the IGFS, BGI and ISG services, the project partners are:
- Politecnico di Milano (Italy),
- GET, SHOM and OCA/Geoazur (France),
- Aristotle University of Thessaloniki (Greece),
- DTU Space (Denmark),
- General Command of Mapping (Turkey),
- University of Zagreb (Croatia),
- University of Jaén (Spain).

The processing methodology is based on the well-known remove-compute-restore approach using both stochastic and spectral methods for the determination of the geoid and the rigorous combination of heterogeneous data.
The input data come from the BGI database and from the project partners, in particular classified gravimetric data from Italy, Greece, Croatia and Turkey were used. All the available gravity observations for the wider Mediterranean basin have been homogenized in terms of their horizontal system and are being validated and homogenized in terms of gravity system. An outlier rejection has been performed and some biases have been identified. These biases have a negative impact on the covariance function estimation and, of course, on the geoid estimation. In particular, a track by track de-biasing with respect to EIGEN-6C4 has improved the results, in terms of the stochastic behaviour of the gravity residuals.
The geoid grids have been computed by the collocation method using the GRAVSOFT software. Stokes and FFT-based geoid models have been also determined and compared with the collocation-based ones. The accuracy of the estimated geoids has been assessed through comparisons to GPS/levelling and altimeter data.
At first, preliminary computations have been performed to test the processing chain. In particular, a test of the collocation method and a test of the FFT-based method have been performed. The test consisted in first estimating the EGM2008 undulation residuals starting from EGM2008 gravity anomalies residuals ($\Delta g|_{2190}$-$\Delta g|_{1100}$) and then comparing the estimates to the actual EGM2008 undulation residuals ($N|_{2190}$-$N|_{1100}$, see Figure 1). This allowed to check the procedure and to choose the best FFT kernel modification for the GEOMED-II computation.

A lot of effort has been dedicated to investigate and properly determine topographic effects over both land and marine areas to efficiently reduce land and marine gravity data towards geoid determination. In fact, over land areas, the latest SRTM-based DTMs offer high-accuracy and high-resolution information on the topographic variations, in the sense that they properly model the high-frequency contributions of the topographic masses. Over marine regions, the situation is quite different, since the resolution of the available DBMs is not always capable to remove the high frequencies that are present in shipborne marine gravity data. On the other hand, marine gravity data do not often have the necessary spatial resolution to rigorously model the high frequencies depicted in the DBM. Aliasing effects on the estimated topographic effects will be also investigated and the corresponding errors introduced in gravity anomalies and geoid heights will be taken into account.

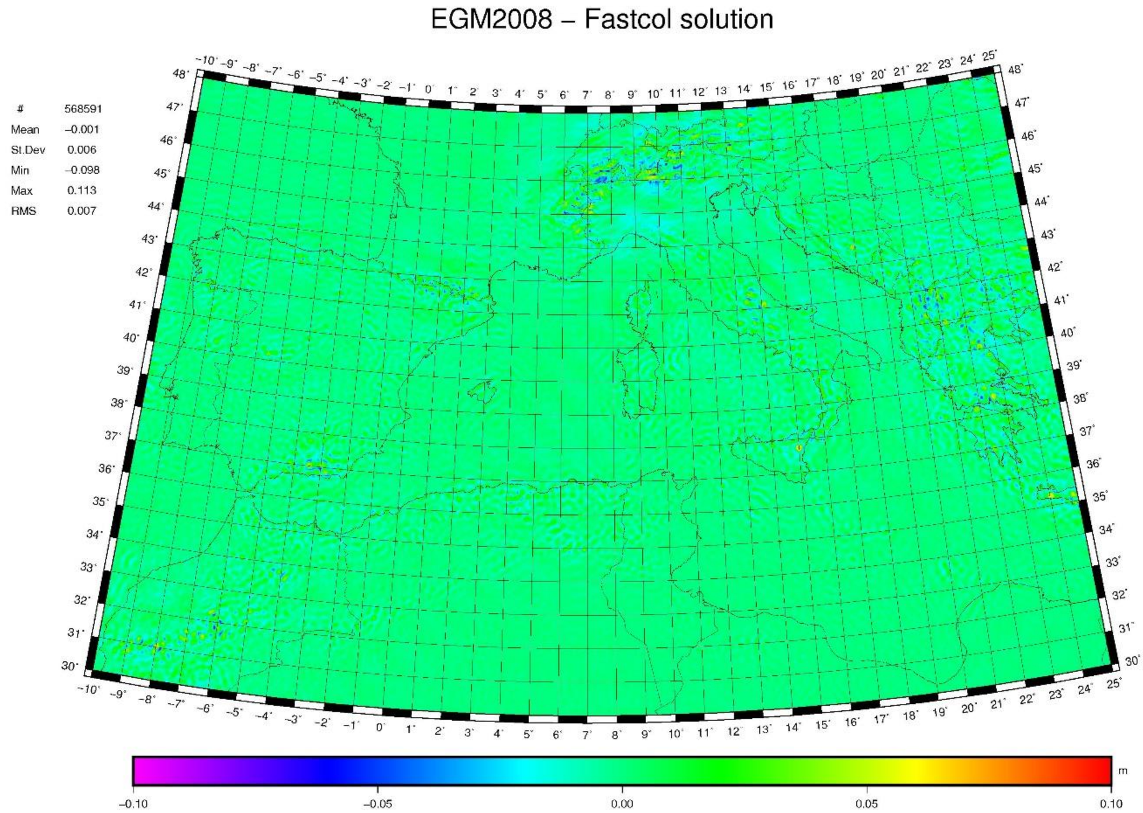

Fig. 1: Differences between EGM2008 undulation residuals ($N|_{2190}$-$N|_{1100}$) and collocation estimates starting from EGM2008 gravity anomalies residuals ($\Delta g|_{2190}$-$\Delta g|_{1100}$).

Improvements in the performance of the data reduction over sea have been obtained using the Hirt & Kuhn approach. In addition, to fill gaps in land gravity data or to avoid the propagation over sea of the effect of unreliable land gravity data, in selected critical areas, the gravity residuals have been substituted using simulated data reflecting the global stochastic behaviour of the gravity residuals. In Figure 2, the gridded gravity residuals obtained with Hirt & Kuhn approach for RTM reduction and after having substituted portions of land with simulated data are shown.

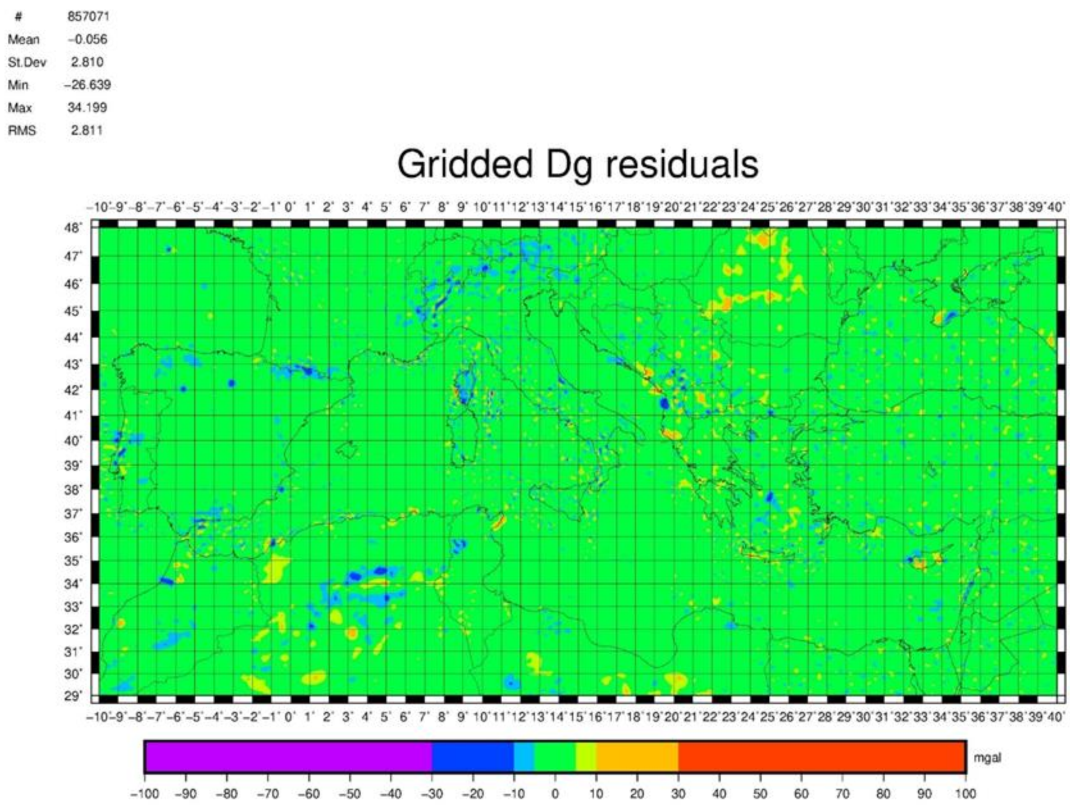

Fig. 2: Gridded gravity residuals for the remove-restore computation of the geoid of the Mediterranean Sea.

Geoid solutions of the Mediterranean Sea have already been computed and are being assessed. In particular:

- One solution has been produced at Politecnico di Milano with Fast-collocation algorithm.
- One solution has been produced at Aristotle University of Thessaloniki with a tapered version of the Wong-Gore modification of Stokes' kernel function (truncated at degree 1000), through the SPFOUR software of the GRAVSOFT package.
- One solution has been produced at the General Command of Mapping (Ankara, Turkey) with KTH method based on the least-squares modification of Stokes' formula.
- One solution has been produced at University of Zagreb with RCR approach with Stokes integration, using Heck & Grűninger kernel, with modification degree 300. Two additional corrections on geoid undulations were applied: tide free to mean tide geoid undulation and topographic bias.

The computed solutions have been compared with GPS/levelling data over Italy and Greece, see Tables 1 and 2 respectively, showing a substantial agreement. At present, solutions inter-comparisons are being performed as well as inter-comparisons with respect to altimetry models such as DTU15 (Figure 3).

	Collocation (POLIMI)	Stokes-WG (AUTH)	KTH (GCM)	KTH (UZG)
#	977	977	977	977
Mean [m]	0.000	0.000	0.000	0.000
St. Dev. [m]	0.090	0.097	0.093	0.096
Min [m]	-0.229	-0.217	-0.462	-0.409
Max [m]	0.382	0.463	0.282	0.325

Table 1: Statistics on the differences between geoid estimates and GPS/levelling over Italy (after bias and tilt removal).

	Collocation (POLIMI)	Stokes-WG (AUTH)	KTH (GCM)	KTH (UZG)
#	1542	1542	1542	1542
Mean [m]	0.057	0.068	-0.838	0.166
St. Dev. [m]	0.128	0.128	0.127	0.135
Min [m]	-0.497	-0.448	-1.286	-0.326
Max [m]	0.574	0.507	-0.365	0.560
RMS [m]	0.140	0.145	0.838	0.214

Table 2: Statistics on the differences between geoid estimates and GPS/levelling over Greece.

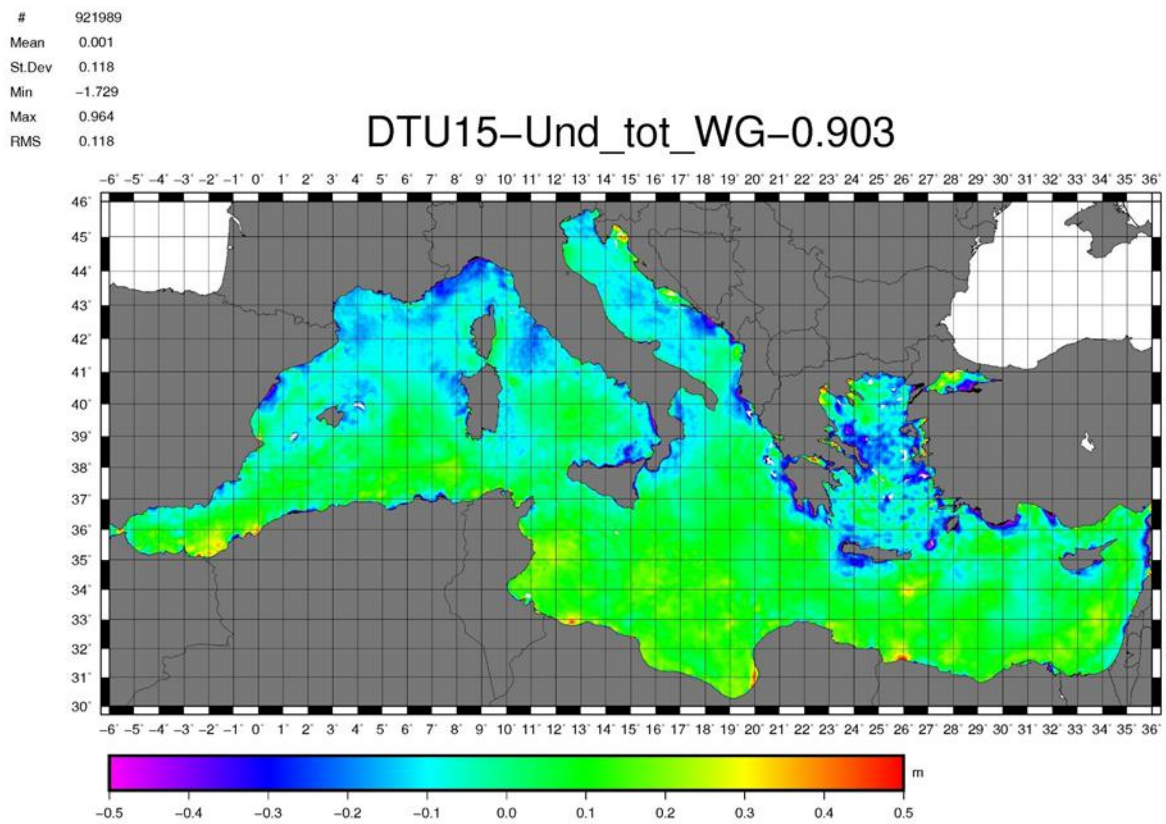

Fig. 3: Map of the differences between DTU15 and the solution obtained with the Wong-Gore modification of Stokes's kernel function (0.903 bias has been subtracted).

The new Italian gravimetric geoid (ITALGEO15) has been computed after a thorough revision of the available gravity database. The database has been homogenized in terms of horizontal and gravity reference systems and an outlier rejection has been performed mainly through local consistency checks.
This resulted in an improvement in the differences of the geoid with respect to the GPS/levelling data, after reference system adjustment, see Figure 4. The standard deviation of the differences decreases of two centimetres with respect to the previous release of the Italian geoid (ITALGEO05), see Table 3.

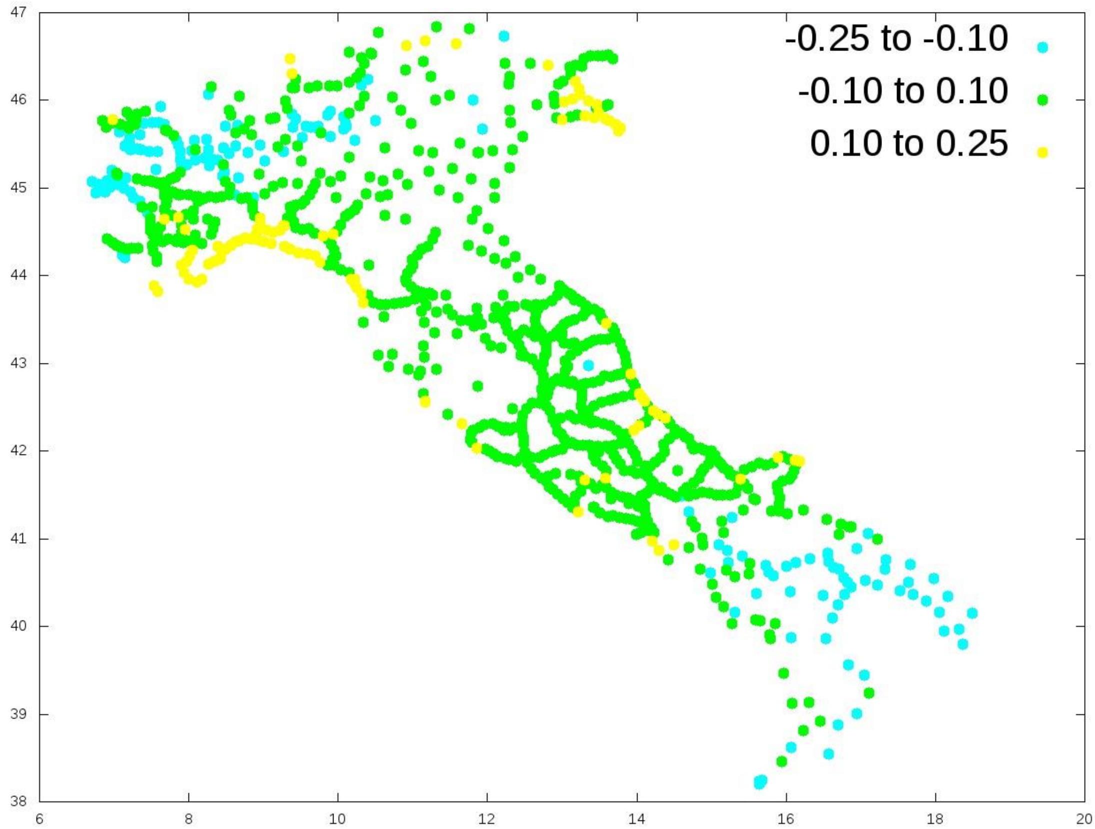

Fig. 4: Differences between GPS/levelling and ITALGEO15 gravimetric geoid after reference system adjustment (units in m).

	ITALGEO05	ITALGEO15
# Values	956	956
Mean [m]	0	0
St. Dev. [m]	0.114	0.090
Min [m]	-0.292	-0.235
Max [m]	0.294	0.235

Table 3: Statistics of the differences of ITALGEO05 and ITALGEO15 gravimetric geoids with respect to the GPS/levelling over the continental territory.

NOAA's National Geodetic Surveying is leading a geoid computation experiment over a test area in Colorado (USA). They have provided the participants with gravity data, both terrestrial and airborne, together with the DTM and GPS/levelling data. Fourteen research groups are contributing with their solutions. The performance of the computation can be assessed by every participant with respect to the GPS/levelling data and by NGS on a specific line with benchmarks which have not been distributed to the test participants.
One solution has been submitted to the test board, using the remove-restore approach, with collocation. As usual, some pre-processing has been performed to remove outliers or duplicates from the input data. For the time being, terrestrial data only have been considered.
The gravity residuals have been obtained by removing the XGM2016 model up to degree and order 1000 and the residual terrain correction (Figure 5).

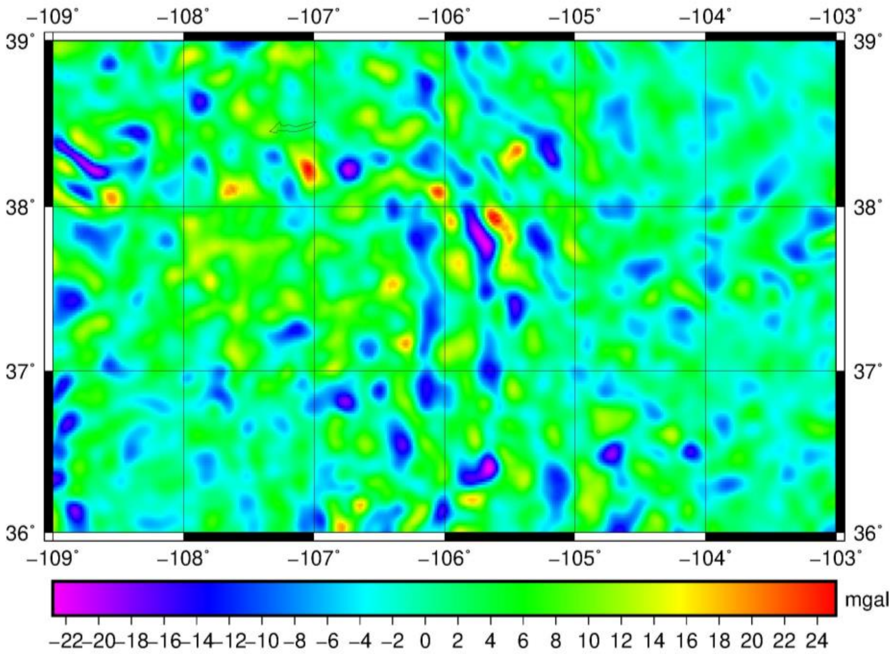

Fig. 5: Gravity residuals for NGS Colorado geoid computation experiment.

Applying collocation for geoid computation, the best performance has been obtained with a local approach, considering a moving window over the computation area and selecting only the data within a cap where the covariance function shows a significant data correlation.
Table 4 reports the statistics of the obtained geoid with respect to the GPS/levelling data which were provided to the participants. The results are consistent with the outcomes of the other participants, as well as for the benchmarks which NGS only could compute.

	Colorado
# Values	223
Mean [m]	0.187
St. Dev. [m]	0.094
Min [m]	0.004
Max [m]	0.336

Table 4: Statistics of the differences between the geoid heights computed by collocation and the ones from GPS/levelling data.

Merging of local geoid estimates

The large availability of local/regional geoid/quasigeoid models in the ISG archive fosters the study and the development of a merging strategy to produce unified models between neighbour countries. The proposed method consists of first estimating biases and systematic effects by a least-squares adjustment of the local geoid residuals with respect to a satellite-only model, and then correcting the remaining distortions along the national borders to better join the local geoid models. This investigation is performed in the framework of the JWG2.2.1 "Integration and validation of local geoid estimates" of IAG Commission 2.

A preliminary test has been implemented on a subset of European models, including the following countries (the name of the used model in brackets):

- France (QGF98)
- Corsica (QGC02)
- Italy (ITALGEO05)
- Iberian Peninsula (IBERGEO2006)
- Belgium (BG03)
- Switzerland (CHGEO2004Q)
- Greece (GreekGeoid2010).

For each model, a subset of about 1000 points on land and inside the national borders has been selected for the bias and trend estimation. The digital terrain model (DTM) for each country has been derived from SRTM.

The reference geoid has been synthesized from the GOCO-05S satellite-only global model up to spherical harmonic degree and order 280 and has been then subtracted to the local solutions. Neither the contribution of global models at higher degrees, e.g. using EGM2008, nor a residual terrain correction (RTC) has been further subtracted to the geoid residuals.

The geoid commission error of the reference model has been modelled by propagation from the block-diagonal error covariance matrix of the GOCO-05S coefficients, while the omission error above degree 280 has been modelled by using EGM2008 degree variances. A white noise with a standard deviation of 5 cm has been attributed to each local geoid model.

By using the computed geoid residuals and this stochastic modelling, a bias and a trend for each local model have been estimated by least-squares adjustment. The systematic effect *S* included into each local geoid has been modelled as follows:

$$S(\varphi,\lambda)=b_1+b_2(\varphi-\varphi_0)+b_3\cos\varphi(\lambda-\lambda_0)$$

where φ_0 and λ_0 are the mean latitude and longitude, respectively. The result of this adjustment is reported in Table 5. The estimated biases and trends are shown in Figure 6, while the residuals before and after the de-trending procedure are displayed in Figures 7 and 8.

	France	*Corsica*	*Italy*	*Iberia*	*Switzerland*	*Belgium*	*Greece*
$\hat{b}_1$	-1.067	0.344	0.246	-0.930	-0.617	-0.140	0.305
$\hat{b}_2$	1.466	21.090	-10.247	-1.826	-3.492	2.452	-0.733
$\hat{b}_3$	-4.753	-81.137	-0.873	-0.697	-2.379	-0.261	11.248
$\hat{\sigma}_{b_1}$	0.002	0.042	0.004	0.002	0.004	0.008	0.005
$\hat{\sigma}_{b_2}$	0.056	6.459	0.121	0.069	0.975	1.656	0.229
$\hat{\sigma}_{b_3}$	0.069	16.943	0.140	0.060	0.476	1.459	0.333

Table 5: Estimated biases and trends with their error standard deviations (units in m).

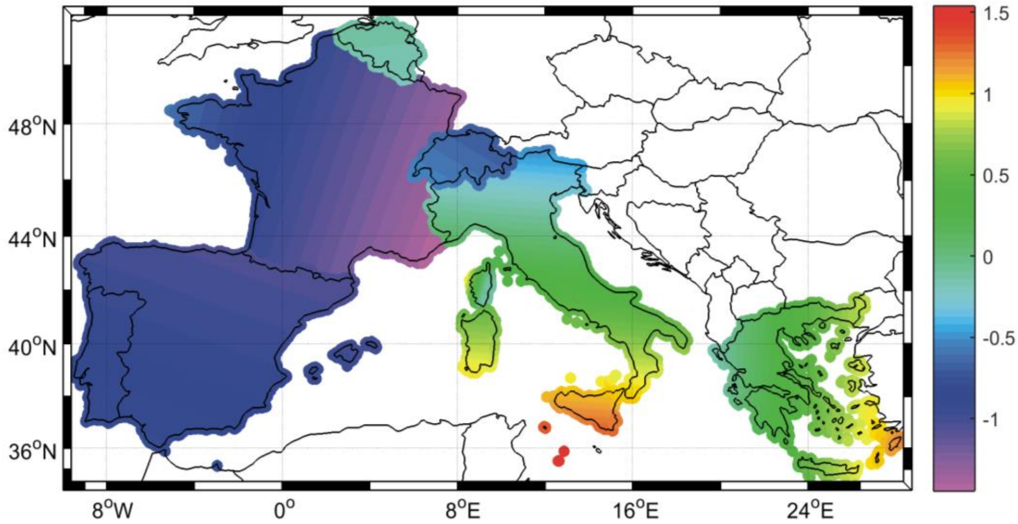

Fig. 6: Estimated biases and trends (units in m).

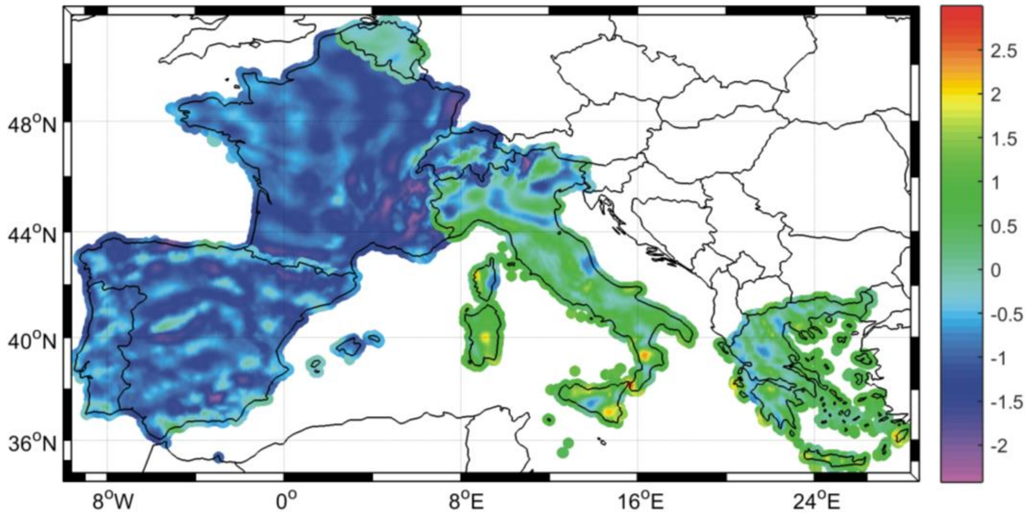

Fig. 7: Geoid residuals with respect of GOCO-05S before applying the de-trending procedure, i.e. as the models are stored in the ISG archive (units in m).

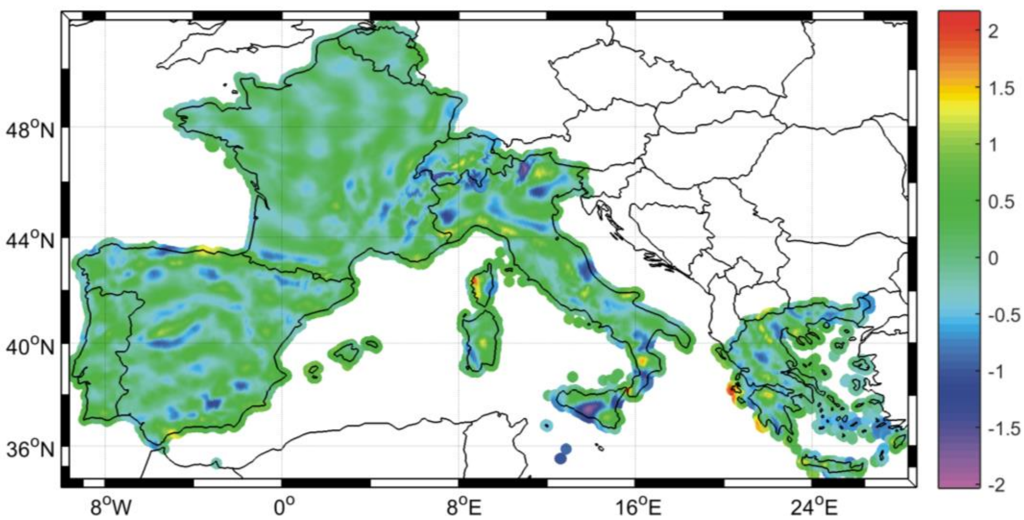

Fig. 8: Geoid residuals with respect of GOCO-05S after applying the de-trending procedure (units in m). Discontinuities at national borders are significantly reduced.

School organization and scientific support to researchers on geoid estimation

One of the main tasks of ISG consists in organizing or supporting technical schools on geoid estimation and related topics. The XII International IGS School was held in Mongolia from 6th to 10th June, 2016, at the Geodesy Department of Mongolian University of Science and Technology (MUST), Ulaanbaatar. This was the second geoid school held in Asia after the one in Johor-Baru, Malaysia, at the Department of Survey and Mapping, from 21st to 25th February, 2000.

The Local Organizing Committee (LOC) was composed by representatives from the following institutions/organizations:

- Mongolian University of Science and Technology (MUST),
- MonMap Engineering Services Co., Ltd,
- Mongolian Association of Geodesy, Photogrammetry and Cartography (MAGPC),
- Administration of Land Affairs, Geodesy and Cartography (ALAGAC),
- Ministry of Construction and Urban Development (MCUD).

A dedicated website was setup at the address: www.monmap.mn/geoidschool2016/ reaching more than 300 accesses by June. Over 100 online registration form submissions were collected, but many of willing participants from developing countries were not able to attend the school due to lack of budget and travel support. In the end, 30 participants coming from 9 different countries (Bhutan, China, India, Latvia, Mongolia, Philippines, Poland, Russia and Sri Lanka) attended the school, see Figure 9.

As usual, the program was structured to be self-contained for any participant at graduate level with basic knowledge of geodesy, including theoretical lectures and computer exercises based on the available software. The invited teachers were:

- Prof. F. Sansò, Politecnico di Milano, Italy,
- Prof. R. Barzaghi, Politecnico di Milano, Italy,
- Prof. M. Sideris, University of Calgary, Canada,
- Prof. R. Forsberg, National Space Institute, Denmark,
- Dr. S. Holmes, SGT Inc. USA.

The school program was the following:

- General theory on gravity field (6th June),
- The height datum unification (6th June),
- Terrain effect computation and remove/restore - theory and practical exercises (7th June),
- Residual geoid estimation - theory and practical exercises (8th June),
- Global geopotential models - theory and practical exercises (9th June),
- Presentations and case studies (10th June).

During the last day, a final session was given to summarize the school topics and distribute training certificates to the participants. Lecture notes of the courses were also distributed, as well as a CD-ROM containing software and data for exercises. The CD-ROM was freely distributed to the participants after a declaration of non-commercial use. An ice-breaker dinner and two sightseeing tours were organized by LOC, just before and after the school.

Apart from organizing the XII International Geoid School in Mongolia, in the last four years ISG provided educational activities and supported studies related to geoid estimation theory and in general to physical geodesy by hosting at Politecnico di Milano, Italy, the following students and researchers:

- A PhD student of the Center of Geodesy and Geodynamics of Nigeria, who is developing his thesis on the national gravity field estimation. For his studies he was hosted at Politecnico di Milano during two periods: 7-11 September 2015 and in spring 2016.

- A researcher of the Faculty of Petroleum and Renewable Energy and Earth Sciences at the University of Ouargla, Algeria. He was interested to the precise local geoid determination from the GRACE and SRTM satellite data with the aim of studying the tectonic activity in Algeria. He was hosted at Politecnico di Milano in autumn 2015.
- Two researchers of the Service of Surveying of the National Institute of Cartography of Cameroun, who came at Politecnico di Milano in November 2015 for a first training session on geoid computation. After that, they maintained frequent contacts with ISG staff, and a second training session took place again at Politecnico di Milano from 13 to 28 October 2017, this time involving three researchers. In this second session, they worked with data from Cameroun, considering all phases of geoid computation, including data pre-processing.
- A PhD student from the University of Curitiba, Brazil, who spent three months at Politecnico di Milano, from March to September 2016, developing studies on the height datum problem.
- A PhD student from the Technical University of Denmark (DTU), who spent three months at Politecnico di Milano, from October to December 2016, working together with ISG staff on radar-altimetry, gravimetry and gravity field estimation.
- Two academicians from Konya Selcuk University, Turkey, as well as a MSc student from Istanbul Technical University, Turkey, who spent one week at Politecnico di Milano in July 2018, attending a training course on geoid determination.

Usually, further contacts follow the hosting period, to strengthen the cooperation and to provide scientific support when researchers and students come back to their countries.

Fig. 9: Group photo of people organizing and attending the XII International IGS School.

ISG geoid repository and website update

In the last four years, the ISG archive of local/regional geoid models has been continuously updated. Not only the latest release of a model is stored in the archive, but also outdated versions are collected in order to keep memory of the work done in the past and to allow for comparisons. The full (or the almost full) series of official geoid models are available for some countries, like US, Canada, Europe, Italy, France, Nordic-Baltic countries, Brazil, Japan, Australia, New Zealand. Three possible policy rules are considered for the model distribution: “public” if it can be freely downloaded from the website, “on demand” in case the authors asked to be informed before distributing the model, and “private” if it is just included in the archive but it cannot be distributed to the users. Therefore, the aim of the "private" policy is to inform users that a model exists without publishing any data through the ISG service. Some models are classified as N/A if the data are not available to the service. More than 150 models are currently available in the ISG database, whose composition is reported in Tables 6, 7 and 8 (last update of the statistics was on 1st June 2019). The global coverage of the available gridded geoid models, together with their spatial resolution, is shown in Figure 10. Metadata of all models are managed through Data Citation Index by Clarivate Analytics and, therefore, the models are indexed by Web of Science.

Europe	74
North America	36
Asia	20
Africa	19
South America	14
Oceania	13
Antarctica	4
Arctic	3
Total	183

Table 6: Number of models per continent in the ISG archive.

< 1991	4
1991 – 1995	15
1996 – 2000	39
2001 – 2005	23
2006 – 2010	50
2011 – 2015	39
2016 – 2019	13
Total	183

Table 7: Number of models per year in the ISG archive.

Public	127
On-Demand	20
Private	20
N/A	16
Total	183

Table 8: Number of models per policy-rule in the ISG archive.

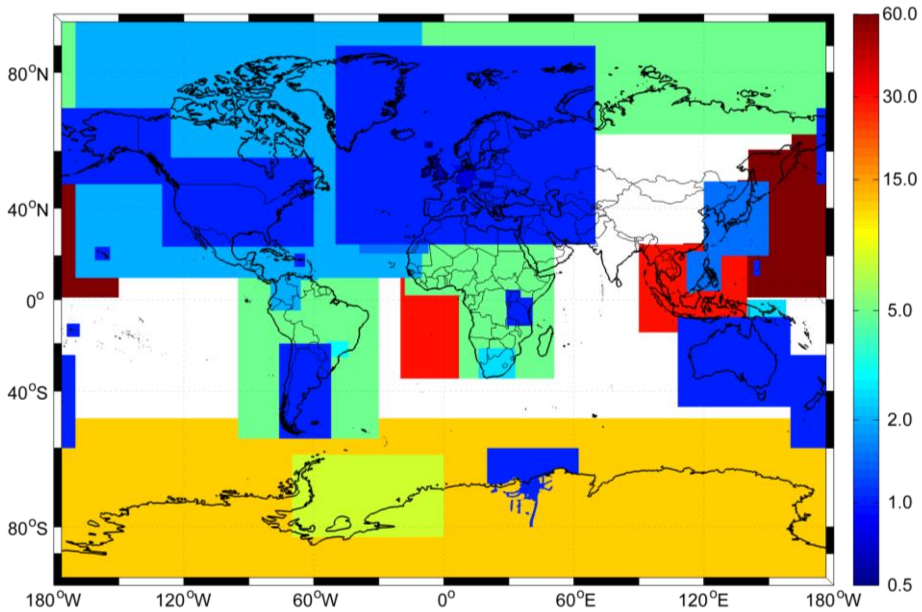

Fig. 10: Spatial coverage of the gridded geoid models available at ISG. Colourbar shows the highest spatial resolution per location (log10 scale, unit: arc-minutes).

The ISG website is updated simultaneously to the ISG archive. For each geoid model that is stored in the archive a dedicated webpage is available on the website, containing information about the model name, year, authors, contact person, type (gravimetric, geometric or hybrid, geoid or quasi-geoid) and policy rule. There is a short description of the model characteristics, at least one bibliographic reference, the Web of Science ID and a model figure.
If the model is classified as "public", the corresponding data file can be downloaded from the webpage in a unique ASCII format (.isg), whose specifications are provided in the website. After authors' authorization, the "on demand" models can be distributed to users in the same ASCII file format. The webpage of each model can be reached from a complete list of available geoids or by clicking on a geographical map.
Apart from the geoid repository, the website has been updated in the home page, in the section dedicated to the geoid schools and in the one on the on-going projects. News section has been continuously kept up-to-date. No papers have been submitted to Newton's Bulletin in the last four years. The current home page of the ISG service is shown in Figure 11. Some statistics on the website access are displayed in Figure 12. A new webpage including statistics on the model downloads has been created (some examples of these statistics are reported in Figure 13).

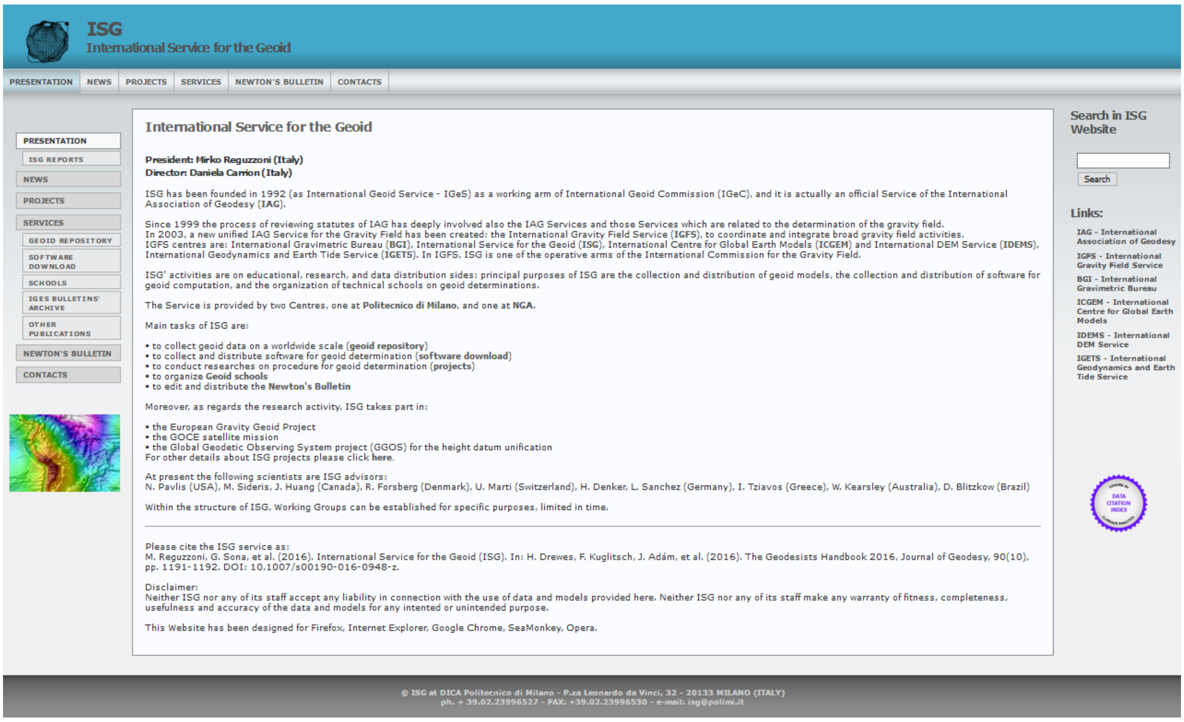

Fig. 11: Home page of the ISG website.

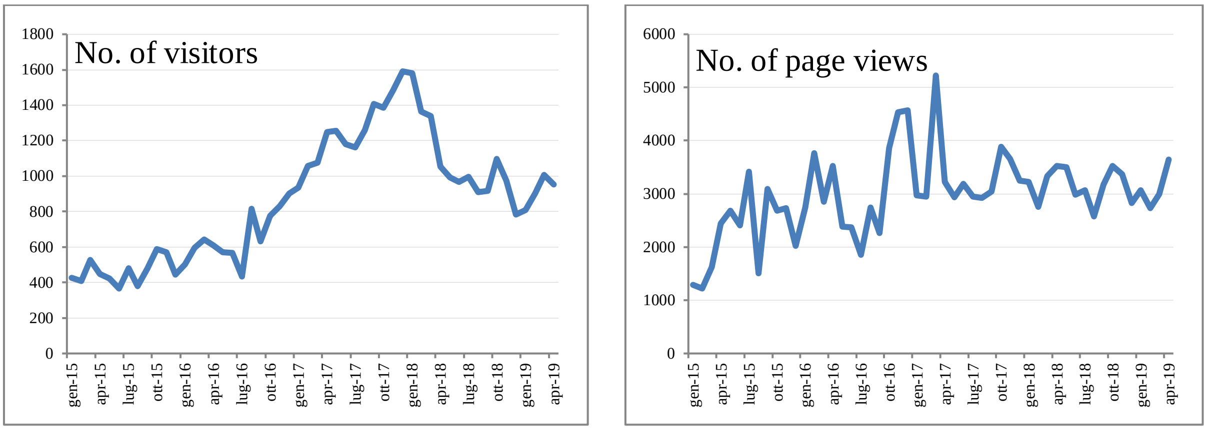

Fig. 12: Statistics on the number of visitors and page views of the ISG website.

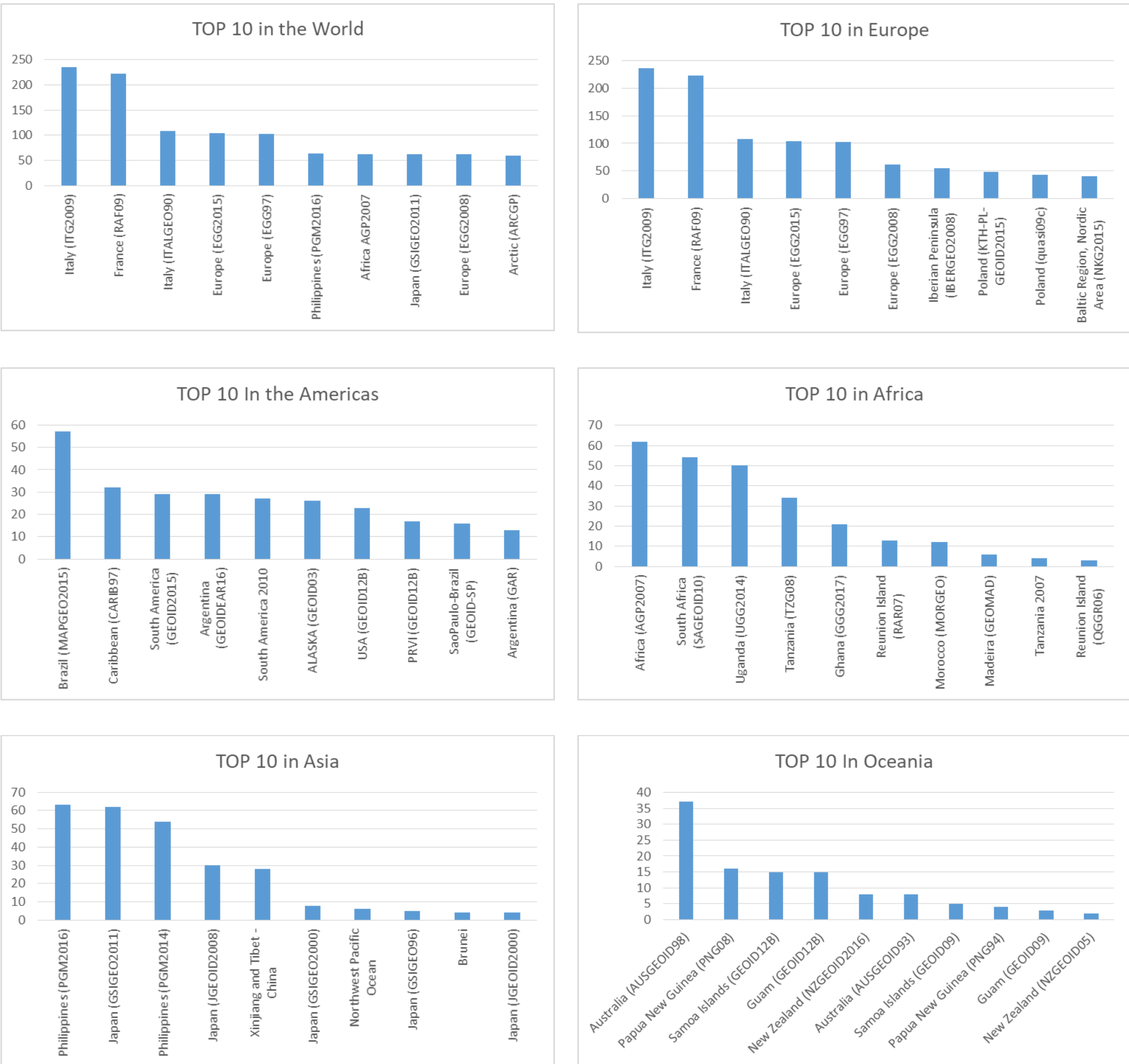

Fig. 13: Statistics on the most downloaded models from the ISG website since December 2017.

JWG 2.2.1: Integration and validation of local geoid estimates

Chair: *M. Reguzzoni (Italy)*
Vice Chair: *G. Vergos (Greece)*

Members:

- *G. Sona (Italy)*
- *R. Barzaghi (Italy)*
- *F. Barthelmes (Germany)*
- *M.F. Lalancette (France)*
- *T. Basic (Croatia)*
- *H. Yildiz (Turkey)*
- *N. Kuhtreiber (Austria)*
- *H. Abd-Elmotaal (Egypt)*
- *W. Featherstone (Australia)*
- *Jianliang Huang (Canada)*
- *Cheinway Hwang (Taiwan)*
- *Shuanggen Jin (China)*
- *G. Guimaraes (Brazil)*

Overview

A detailed description of the activities performed by this working group during the period 2015-2019 can be found in the report of the Sub-commission 2.2, also including numerical results and bibliographic references.