Improving the accuracy of GOCO06s global geoid model on Sardinia Island (Italy) using Ordinary Kriging interpolation in GIS

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Abstract

The geoid is the equipotential surface of the Earth's gravity field that best approximates mean sea level. In many applications of geomatics the availability of a geoid model is fundamental as it allows to transform the ellipsoidal heights provided by the GNSS (Global Navigation Satellite System) survey into orthometric heights, i.e. referred to the mean sea level. There are global-scale geoid models, while others exist on a regional scale and are more accurate than the former. Global geoids are generally obtained from measurements of the terrestrial geopotential carried out from space, appropriately integrated with data obtained in situ. This article focuses on the possibility of improving the accuracy of the global model GOCO06s (GOCO is the acronym of Gravity Observation Combination) in a local area, Sardinia Island (Italy), through two operations carried out in Geographic Information System (GIS) and based on the comparison with the local model (at national scale) ITALGEO2005: the removal of the bias found between the two (global and local) models, and the application of the Ordinary Kriging interpolator on the residuals that still remain between the two surfaces compared. The first operation determines a considerable improvement, demonstrated by the RMS value dropping from 1.000 m to 0.365 m. The second operation further increases the accuracy of the model since, with the use of 60 Ground Control Points, an RMS equal to 0.140 m is reached.

1. Introduction

The Geoid is the equipotential surface of the Earth's gravity field that is closely approximated by the mean sea level (MSL), i.e. the surface of the sea in the absence of other influences such as winds and tides and so on. The global potential surface that coincides with MSL is known also as Earth Gravitational Model (EGM) and identified by a set of geopotential coefficients used in a spherical harmonic expansion (Pavlis et al, 2007).

Geoid does not coincide with the ellipsoidal model of the Earth: geoid undulation is the vertical separation between a given ellipsoid of reference (e.g. World Geodetic System 1984, WGS84) and the Earth's equipotential surface that corresponding to mean sea level and its imagined extension over (or under) land areas (Pugh, 1987).

The availability of an accurate model of the geoid undulation allows to derive the value of the orthometric height, that is the height above the mean sea level, from the ellipsoidal height provided by the GNSS (Global Navigation Satellite System).

Different methods are available for geoid model determination. According to (Featherstone et al, 1998), at least four groups are distinguished: (1) Gravimetric, (2) Astro-geodetic, (3) Geometric and (4) Hybrid approaches.

Gravimetric approach for obtaining geoid model is based on gravity data of the earth surface which are collected through terrestrial field observation or through satellite gravity missions such as German CHAMP (CHAllenging Minisatellite Payload, 2000), the US/German GRACE (Gravity Recovery and Climate Experiment, 2002), the ESA GOCE (Gravity field and Ocean Circulation Explorer, 2009) and US/German GRACE-FO (Gravity Recovery and Climate Experiment Follow-on, 2018). The gravitational field of the Earth reflects Earth's surface mass redistribution and its inner structure and dynamics; satellite gravimetry techniques allow to observe the Earth's external gravitational field and its temporal variations on a global scale (Eshagh et al, 2024).

The astro-geodetic method is based on the determination of the deviation of the vertical which is the angle formed between the direction of the gravity force (plumb line) and the ellipsoidal normal (Kumar Ghosh and Nath Mishra, 2016). The components (along the meridian and along the prime vertical) of the deflection of the gravity vector are obtained from the astronomical latitude and longitude and the geodetic latitude and longitude (Eteje and Oduyebo, 2018). Classical approach as well as three alternative more modern ways to perform astro-geodetic observations with the use of high-end instrumentation and developed software, are well described in (Lambrou, 2014).

The geometric method requires that the geoid undulations in some scattered points on the territory for which the model is to be built, are calculated as differences between the heights determined by the GNSS and the respective levelled heights; the model is then built according to a grid whose values are determined by interpolation of the previously calculated differences (Erol and Çelik, 2004a).

A hybrid approach involves the integrated use of the operations that characterized at least two of the methods previously described. Obviously, the resulting procedure may present some variations. In the approach followed by (Chen and Luo, 2004), three main steps are identified: the construction of a gravimetric geoid; a fitting operation of the gravimetric model on the points where the undulation is given by the GNSS/leveling approach; further refinement of the geoid model with GNSS/leveling data and other information.

EGM2008 is an example of a global geoid model: proposed by the US National Geospatial Intelligence Agency, it was developed by a least squares combination of the ITG-GRACE03S gravitational model (including its associated error covariance matrix), with gravitational data defined on 5' x 5' grid. This grid resulted by merging terrestrial, altimetry-derived, and airborne gravity data. Additional gravitational information was derived by the topography in those regions where data availability was poor (Pavlis et al, 2012).

A global model of the geoid undulation usually does not have accuracy adequate for local application: depending on the area examined, values of the order of tens of centimetres (and higher) are found between the undulation obtained from measures in situ and that provided by the model (Falchi et al, 2018; Ferrara and Parente, 2021). The differences may be due, at least in part, to the different vertical datum to which the global model and the local model refer (Featherstone et al, 2011). In other words, the zero level of one does not coincide with that of the other so constant value of shift between the two levels in the area considered can be defined. The difference between the two datums can be already known or it can be calculated from the available data, i.e. the differences in some points between the undulation extracted from the global geoid model and that resulting from on-site measurements (e.g. GPS/leveling). In both cases, it is a bias that must be eliminated to adapt the global model to the local situation (Ihde et al, 2010; Maglione et al, 2018).

To further improve the accuracy of a global model over a specific region, interpolation algorithms can be used: the differences between the undulations provided in some points by the global model and the corresponding ones obtained locally, for example by GNSS/leveling, are interpolated according to a grid coinciding with that of the global model. The resulting model is subtracted from the global geoid whose values are, after this operation, more accurate for the geographical area considered.

A large number of studies about global geoid model accuracy evaluation and adaptation on local areas are available in literature; those mentioned below concern only some of them chosen as examples.

In Tanzania the differences between the GPS/leveling geoid heights and those from EGM08 model at 13 benchmarks range from 0.999 m to 1.392 m, with RMSE = 1.186 m (Gwaleba, 2018).

Using German Quasigeoid model GCG05 as comparison term, assessment of EGM2008 global model over Germany at the ellipsoidal height = 0 m, after bias subtraction, shows RMS errors of 3.3 cm with maximum discrepancies of about 25 cm occurring in the German Alps (Hirt, 2011).

Using 1542 GPS/leveling benchmarks on Greece, EGM2008, in its limited-resolution version 30' x 30' and after a least-squares constant bias fit, provides residuals within the range (-1.287 m, 1.476 m) and σ = ± 0.37 m (Kotsakis et al, 2009).

The experiments carried out on an area located in Northwestern Italy using 25 benchmarks demonstrate the good performance of the previously described approach based on interpolation algorithms. The differences between EGM2008 geoid undulations and the corresponding ones derived from local accurate geoid are interpolated using Ordinary Kriging; the resulting model is subtracted from the global model that finally provides residual within the range (-0.265 m, 0.251 m) with RMS = 0.112 m (Falchi et al, 2018).

The study described in this article analyses the accuracy of one of the most recent global geoid models, i.e. GOCO06s, over the Sardinia Island (Italy) comparing it with the Italian Geoid model named ITALGEO2005 (Albertella et al, 2008). To increase the accuracy of the global model on the study area, methodological approach based on bias subtraction and Ordinary Kriging interpolation is implemented in Geographic Information System (GIS).

The article is structured as follows. After a brief introduction (Section 1), study area and datasets are described in Section 2 resuming the main characteristics of the GOCO06s global geoid model and ITALGEO2005 local geoid model for Italy. The principal methodological aspects are presented in Section 3 introducing the principal operative steps and remarking how the adopted interpolation method (Ordinary Kriging) works. The results are shown and commented in Section 4. Finally, conclusions drawn from the results obtained are shown in the section 5.

2. Study area and datasets

2.1 Sardinia Island

The study area concerns Sardinia, one of the twenty regions of Italy and second in size only to Sicily among the islands of the Mediterranean Sea. It is located 200 km west of the Italian Peninsula, 12 km south of the French island of Corsica and 200 km north of the coast of Africa (Tunisia). It is situated between 38° 51' (Isola del Toro) and 41° 18' latitude north (Isola La Presa) and 8° 8' (Capo dell'Argentiera) and 9° 50' longitude east (Capo Comino). To the west of Sardinia is the Sardinia Sea and to east the Tyrrhenian Sea, both units of the Mediterranean Sea. Figure 1 shows the geolocalization of the study area in the Mediterranean Sea: the map is in equirectangular projection, also called plate carre (Snyder, 1993) and ellipsoidal coordinates referred to WGS84.

A large part of the island is covered by hills (67.9%) and mountains (13.6%). The territory presents a notable morphological variability, going from sea level to mountains with heights exceeding 1,000 meters. The highest peak is Punta La Marmora (1,834 m), included in the Gennargentu, a large massif in central-southern Sardinia. Among the highest mountain ranges there are: the Chain of Marghine and Goceano (1,259 m) which extends transversally for 40 km towards the north, the Sette Fratelli Range which includes Punta Sa Ceraxa (1,016 m) in the south-east, Monte Limbara (1,362 m) in the north-east, Monte Linas (1,236 m) in the south-west. The mountain ranges are separated by large alluvial valleys and plains, such as the Nurra to the north-west and the Campidano to the south-west, between Oristano town and Cagliari city.

The presence of mountains interspersed with valleys and the variability of the territory determine a significant range of geoid undulation values (more than 3 meters between the maximum and minimum value).

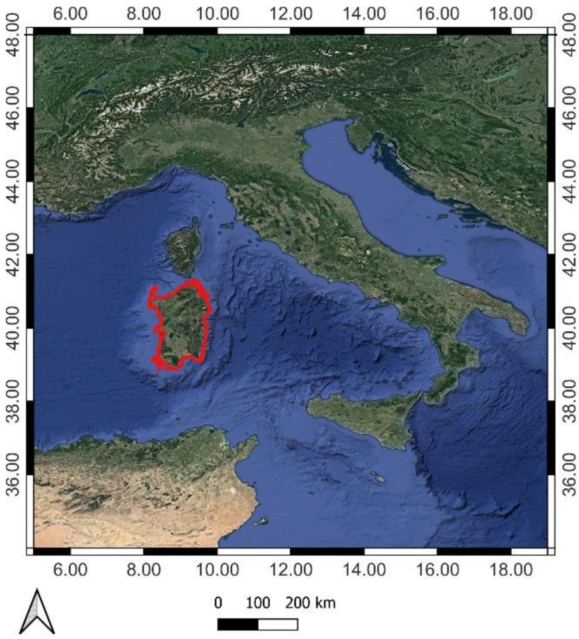

Figure 1. Geolocalization of the study area: Sardinia Island (coastlines in red) in the Mediterranean Sea (the map is in equirectangular projection and ellipsoidal coordinates referred to WGS84).

2.2 GOCO06s

Clarified that GOCO is the acronym of Gravity Observation Combination, GOCO06s is a satellite-only, global gravity field model up to degree and order 300. Produced by the GOCO Team (Technical University of Munich, University of Bonn, Graz University of Technology, Austrian Academy of Sciences, University of Bern), it is based on 1,160,000,000 observations acquired over 15 years from 19 satellites (Kvas et al, 2019). In fact, dedicated satellite gravity missions CHAMP, GRACE, and GOCE, SLR data, and kinematic orbits from different Low Earth Orbiters are considered to compute the high-accuracy and high-resolution static global gravity field model named GOCO06s.

It is the latest satellite-only global gravity field model computed by the GOCO; the motivation for the new release was the availability of reprocessed observation data for GRACE and GOCE (Kvas et al, 2020).

GOCO06s geoid model for the study area is downloaded from ICGEM (International Centre for Global Earth Models) (Ince, 2019) that provides tools for calculation of Gravity Field Functionals on Ellipsoidal Grids (selected cell size: 3' x 3'; reference system: WGS84).

2.3 ITALGEO2005

To analyse GOCO06s accuracy we use as comparison model the Italian Geoid computed by Politecnico di Milano for the area extending between the following WGS84 ellipsoidal coordinates (latitudes and longitudes): φ_1=35°N φ_2=48°N, λ_1=5°E, λ_2=20°E. The methodology implemented follows the classical remove–compute–restore approach: the long-wavelength component of the gravity field is first removed, the residual field is then computed using high-resolution local data, and finally, the complete model is reconstructed. Using grid spacing of 2' both in latitude and in longitude, the computation was based on gravimetric measurements, integrated with GPS/levelling data; the overall precision is about 3 cm over the entire Italian area (Albertella et al, 2008).

The practical use of the ITALGEO2005 geoid is carried out using the grids produced for datum transformation by the Italian Military Geographic Institute (IGMI) that is the Army's geographic supporting office and the National Cartographic Authority, according to the law n° 68/1960, for producing the official state cartography. In particular, the .gr2 and .grk grids provide the values of the geoid undulation with a 2' x 2' step. The value of the undulation at the points of interest is estimated by interpolation between the nodes of the grid; for this purpose, an interpolator is needed, which is present in some software distributed free of charge including Convergo used for the work presented in this article.

3. Methods

The methodological approach is based on the following steps:

- verification of the accuracy of GOCO06s through comparison with ITALGEO2005;
- identification of a systematic error and subtraction of the bias with generation of a new more accurate model (GOCO06s-Sardinia1);
- Application of Ordinary kriging interpolator with the use of three Ground Control Point datasets to further improve the accuracy of the models (Sardinia Geoids).

The above-mentioned steps are described in detail in the next three subsections.

All operations are performed in a GIS environment.

Geostatistical Analyst, an extension of ArcGIS 10.2 (ESRI), is used for the application of the Ordinary Kriging method. This software employs spatial interpolation techniques to generate precise and dependable estimates for grid nodes by leveraging measured values from known sample locations, (Johnston, 2001).

The other operations (comparison, analysis and integration of models, accuracy tests, organization of thematic maps) are performed using Quantum GIS (QGIS) version 3.34.8-Prizren. This software is a free, open-source, cross-platform and scalable GIS tool with plugin development in Python and C++ languages (Moyroud and Portet, 2018).

3.1 GOCO06s accuracy test

The use of 20 points (Check Point Dataset A, CPD-A), with geoid undulation taken from the ITALGEO2005 model, allows to test the accuracy of GOCE06s on the study area. Realized in vector format (shape file), Check Points are identified randomly but ensuring that they are distributed uniformly across the study area as Figure 2 shows.

The use of the Convergo software provides the geoid undulation of each CP according to the ITALGEO2005 model. QGIS tool for sampling raster values in predetermined points provides in the same CPs the corresponding values as resulting from GOCE06s. The differences between undulations derived from the two considered models are calculated and analysed to search for possible bias.

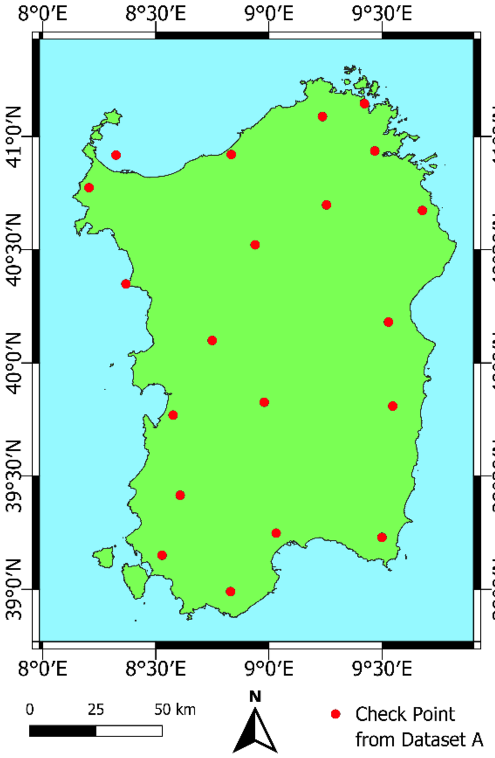

Figure 2. Check Points for testing GOCO06s accuracy on the study area (the map is in equirectangular projection and ellipsoidal coordinates referred to WGS84).

3.2 Bias identification and subtraction

The data highlight the presence of a bias: since the differences between GOCO06s geoid undulations and the corresponding ones extracted from ITALGEO2005 consistently exhibit either all positive values, it strongly suggests that the model is making systematic errors and not adequately capturing the relationship between the variables.

This pattern indicates that is subtracted from the model to improve its accuracy: this time a new Check Point Dataset (CPD-B) is used with geoid undulation derived from ITALGEO2005, too. Also in this case, CPs are identified randomly and uniformly distributed across the study area as Figure 3 shows.

3.3 Ordinary Kriging applications

Subsequently, the residuals that the new model presents on three other datasets of points are calculated, respectively with 20 (GCPD20), 40 (GCPD40) and 60 GCPs (GCPD60) respectively shown in Figures 4, 5 and 6.

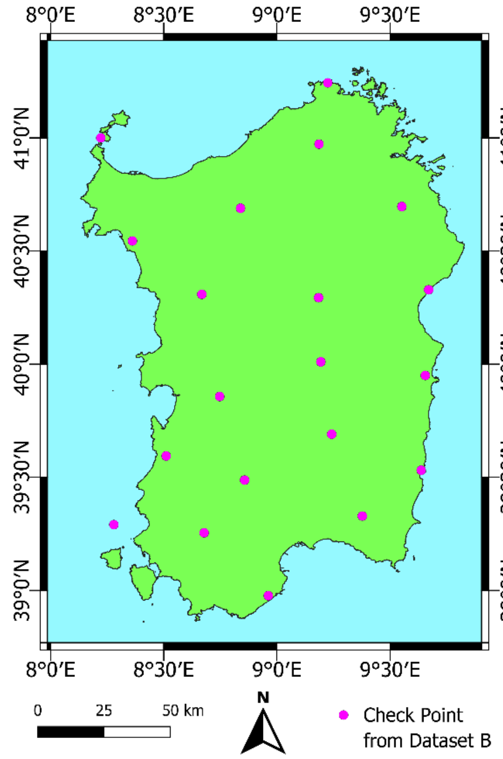

Figure 3. Check Points for testing GOCO06s adaptations on Sardinia (the map is in equirectangular projection and ellipsoidal coordinates referred to WGS84).

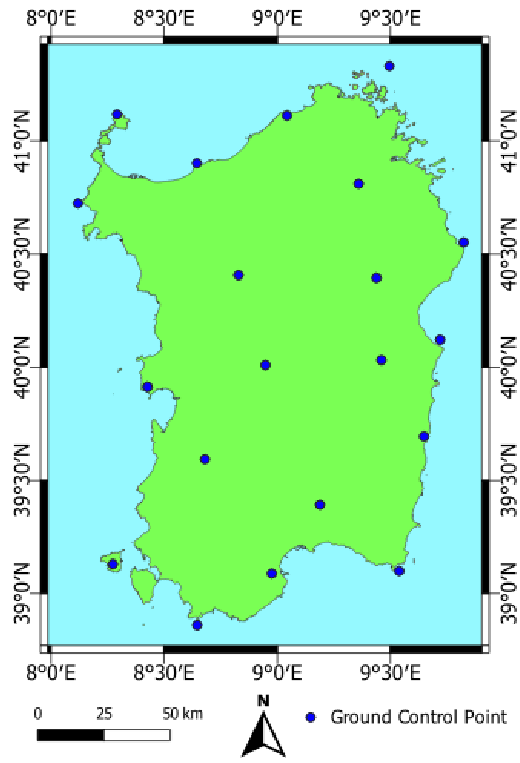

Figure 4. Ground Control Points for Kriging application: GCPD20 (the map is in equirectangular projection and ellipsoidal coordinates referred to WGS84).

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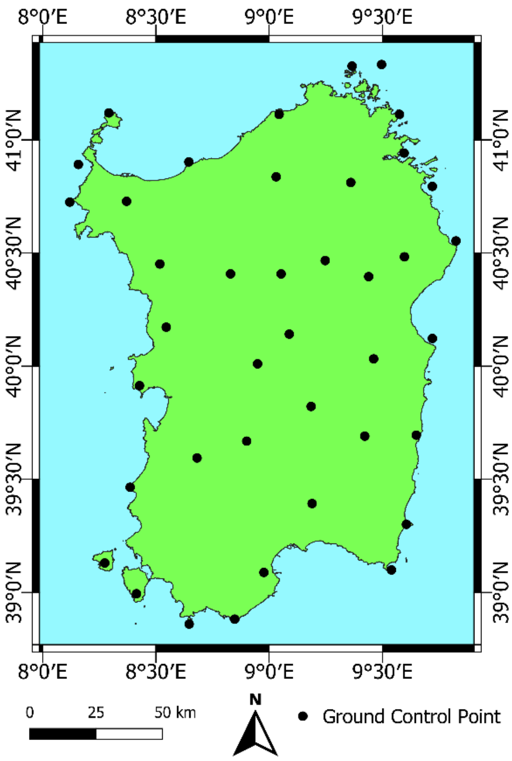

Figure 5. Ground Control Points for Kriging application: GCPD40 (the map is in equirectangular projection and ellipsoidal coordinates referred to WGS84).

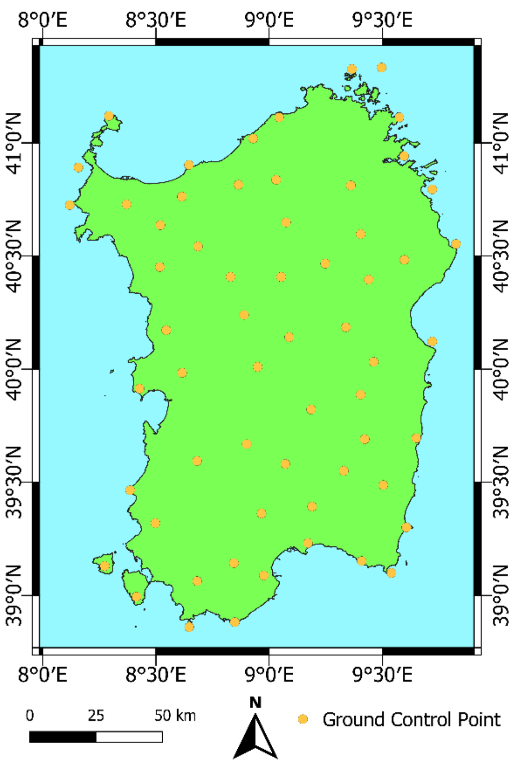

Figure 6. Ground Control Points for Kriging application: GCPD60 (the map is in equirectangular projection and ellipsoidal coordinates referred to WGS84).

The 60 GCP dataset includes the 40 GCP dataset which in turn contains the 20 GCP dataset. The respective residuals are interpolated with Ordinary Kriging (Oliver and Webster, 2014) generating three new 3D models with 3' x 3' cell.

Kriging is a regression method used in geostatistics for spatial analysis that allows a quantity to be interpolated in space, minimizing the mean square error. Knowing the value of a quantity at some points in space, it is possible to determine the value of the quantity at other points for which there are no measurements. In kriging, this spatial interpolation is based on the autocorrelation of the examined quantity: the assumption is that the quantity in question varies in space continuously, but in compliance with the fundamental principle according to which the closest things are more similar than the farthest things (Tobler's Law) (Miller, 2004).

The unknown value at a point is calculated with a weighted average of the known values. Weights are given to the known measurements based on the spatial relationship between the values measured in the vicinity of the unknown point. To calculate the weights, a semivariogram is used, a graph that relates the distance between two points and the semivariance value between the measurements taken at these two points. The semivariogram shows, both qualitatively and quantitatively, the degree of spatial dependence, which is the autocorrelation.

The semi-variance is defined by the following formula (Mert and Dag, 2017):

$$\gamma(h) = \frac{1}{2n}\sum_{i=1}^{n}\left(z(x_i) - z(x_i + h)\right)^2 \qquad (1)$$

where: γ(h) is the semi-variance value at the distance h; n is the number of paired points at distance h; z is an observed value at a particular location; x_i and x_i+h are the positions of each couple of points.

To make the process of calculating the semivariance quicker and easier, the pairs are grouped into lag intervals. In other words, the semivariance is calculated not for specific values of h but rather for pairs of points that have a distance within a range of values, for example between 10 m and 20 m, between 20 m and 30 m, and so on.

Mathematical models (e.g. Gaussian, exponential, circular, etc.) are used as a replacement for the empirical semivariogram. The user selects the standard model that best approximates the empirical one, so as to determine a law that can optimally describe the behaviour of the random variable on the territory in the area for which the measured values are available.

The use of a mathematical model instead of an empirical one allows introducing semi-variance values into the interpolation process for the lag distances that are not present in the semivariogram built on the sampled data (Armstrong, 1998).

There are several sub-types of kriging, including Ordinary Kriging, Universal Kriging, Block kriging, Cokriging. In this study Ordinary kriging, the most widely used kriging method, is applied since it is reported in literature as the most performing one for interpolating geoid undulations (Alcaras et al, 2022).

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Ordinary Kriging assumes the model (Yamamoto):

$$z(x_0) = \sum_{i=1}^{n} \lambda_i z(x_i) \tag{2}$$

where the value of the predicted point $z(x_0)$ is equal to the sum of the value of each sampled point $z(x_i)$ times that point's unique weight (λ_i). The kriging weights are computed from a normal system of equations derived by minimization of the error variance. Weight calculations for Ordinary Kriging are well described in literature (Hendrikse, 2000; Oliver and Webster, 2015).

The function $z(x_i)$ is composed of a deterministic component μ and a random function $\varepsilon(x_i)$ according to the formula:

$$z(x_i) = \mu + \varepsilon(x_i) \tag{3}$$

The deterministic component is assumed constant across the spatial field (the same value for each x_i location).

Interpolation techniques as a tool for modelling the geoid in a local area are to serve practical applications of geodesy (Erol and Çelik, 2004b); generally, GPS/leveling data are used while in this study difference values between two different geoid models registered in specific GCPs are interpolated.

Each Ordinary Kriging resulting model is algebraically added to GOCE06s already bias-cleaned. Three models are finally obtained, derived from the global geoid and adapted to the local situation through 20 (Sardinia Geoid based on 20 GCPs, SG20), 40 (SG40) and 60 GCPs (SG60) respectively. The three models are tested on the same 20 CPs (CPD-B) used previously.

4. Results and discussion

The values provided by the ITALGEO2005 model are subtracted from the respective values provided by each considered model in the 20 CPs. Statistics of the results (minimum, maximum, mean, standard deviation and root mean square error) are calculated and reported in the Table 1.

The first row concerns the accuracy of the GOCE06s model on the study area in the total absence of data processing.

The presence of the bias is evident (maximum and minimum value are both positive). This value (0.932 m) is subtracted from the model by improving the statistical values of the residuals, as highlighted in the second row of the table: RMSE decreases from 1.000 m to 0.365 m and the maximum absolute value reduces from 1.724 m to 0.775.

The next three rows concern the models obtained from the integration of GOCO06s without bias and Ordinary Kriging interpolation using 20, 40 and 60 GCPs respectively. An improvement in accuracy is noted as the number of interpolated points increases, especially with the introduction of 40 GCPs: RMSE decreases to 0.336 m for SG20, 0.162 m for SG40, 0.140 m for SG60.

Statistics					
Model	***Min (m)***	***Max (m)***	***Mean (m)***	***St. Dev. (m)***	***RMSE (m)***
GOCO06s	0.436	1.724	0.932	0.363	1.000
GOCO06s without bias	-0.771	0.775	0.027	0.364	0.365
SG20	-0.802	0.462	-0.095	0.323	0.336
SG40	-0.331	0.204	-0.042	0.156	0.162
SG60	-0.339	0.184	-0.021	0.138	0.140

Table 1. Statistical values of the residuals obtained in 20 CPs for the geoid models considered in this study.

5. Conclusion

This study demonstrates that a global geoid model can be adapted to a local area such as Sardinia Island with a series of operations totally feasible in GIS. In the specific case study considered in this article and focused on GOCO06s, the identification of the bias resulting from the comparison with an accurate local geoid model, i.e. ITALGEO2005, and its subsequent elimination already produce good results. The accuracy improves further when the residuals are interpolated, and the resulting models are algebraically summed to GOCO06s without bias.

In fact, the results highlight first that the global model GOCE06s has an accuracy not adequate for many engineering applications to be employed at a local scale for an area such as the island of Sardinia. The use of 20 check points (CP) provides an RMS that reaches 1 m, but the presence of a bias equal to 92.3 cm is also recorded. The simple removal of the bias already leads to a clear improvement: the RMS value drops to 36.5 cm, with a range of residuals between -77.1 cm and + 77.5 cm. However, the model can still be improved, trying to subtract from it the distribution of the residuals recorded in some GCPs and interpolated using Ordinary Kriging.

The experiments carried out confirm that the greater the number of GCPs used, the better the accuracy of the final model. Interpolating 40 GCPs the RMSE value drops to16.2 cm; with 60 CGPs, 14.0 cm of RMS is reached.

The study proves on one hand that a global model can be adapted to a local situation, greatly improving its accuracy when points with accurate geoid undulation are available; on the other hand, it highlights how all the operations are easily achievable using GIS software.

In this case, the reference geoid undulations are obtained from a more accurate geoid model: alternatively, points could be used for which both the ellipsoidal heights have been measured using GNSS surveying and the orthometric heights using levelling, so that the calculation of the differences between these values would provide the geoid undulations.

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