AFRgeo2025: The New Geoid Model for Africa Implementing Moho Information

Hussein A. Abd-Elmotaal, Norbert Kühtreiber, Kurt Seitz, Thomas Grombein, Bernhard Heck, and Hansjörg Kutterer

Abstract

Africa has a lack of gravity data, sometimes with significant gaps. This is the primary obstacle that the majority of geodetic and geophysical applications on the continent must overcome. The current study uses the Moho information in the geoid determination processes within the context of the window remove-restore technique (Abd-Elmotaal and Kühtreiber (2003) J Geod 77(1-2):77–85), to better smooth, as much as possible, the reduced anomalies aiming to minimize the interpolation errors. By integrating all available Moho data from many sources and applying the least-squares interpolation approach within the framework of the remove-interpolate-restore technique (Abd-Elmotaal et al.(2025) J Adv Eng Trends 44(2):33–38), a Moho model for Africa has been created. To serve as the height datum for Africa, the computed geoid model has been de-trended using the best satellite-only model. The paper gives a thorough discussion and comparison with earlier geoid models published by the authors.

Keywords

Africa · Geoid computation · Gravity field · Gravity interpolation · Window technique

1 Introduction

There are significant gaps in the available gravity measurements in Africa, particularly on land. In such situations, interpolating these gravity data, which does not provide new data, will result in significant interpolation errors. Accordingly, the main idea in such cases is to significantly reduce the point gravity anomalies. As widely known, this will decrease these anticipated interpolation errors.

The main objective of the current investigation is to establish and assess AFRgeo2025, an updated geoid model for Africa, for which the Moho information are used in the context of the window remove-restore approach (Abd-Elmotaal and Kühtreiber 2003) to better smooth, as much as possible, the reduced anomalies aiming to minimize the interpolation errors. The use of the Moho information in the African geoid determination is done for the first time. The developed AFRgeo2025 will be identified as the official African geoid, which is going to complete the picture towards the essentially needed International Height Reference System (IHRS).

Moho models now exist, where terrestrial and space-borne seismic, gravimetric and geometric data are combined (see, e.g., Sjöberg and Abrehdary 2022; Reguzzoni and Sampietro 2015; Reguzzoni et al. 2013; Laske et al. 2013; Čadek and Martinec 1991). By integrating these models and applying the least-squares interpolation technique within the context

H. A. Abd-Elmotaal (✉)
Civil Engineering Department, Faculty of Engineering, Minia University, Minia, Egypt

N. Kühtreiber
Institute of Geodesy, Graz University of Technology, Graz, Austria
e-mail: norbert.kuehtreiber@tugraz.at

K. Seitz · T. Grombein · B. Heck · H. Kutterer
Geodetic Institute, Karlsruhe Institute of Technology, Karlsruhe, Germany
e-mail: kurt.seitz@kit.edu; thomas.grombein@kit.edu; bernhard.heck@kit.edu; hansjoerg.kutterer@kit.edu

International Association of Geodesy Symposia,
https://doi.org/10.1007/1345_2026_395,

of the remove-interpolate-restore approach, an African Moho model has successfully been developed (Abd-Elmotaal et al. 2025). The geoid determination procedure then makes use of this Moho model.

A list of the used data sets is provided, both on land and in the ocean. The utilized height and Moho models are given. The applied window reduction approach is described. An underlying grid developed from the EIGEN-6C4 global reference model (Förste et al. 2014) has been utilized to reduce the level of freedom of the interpolation solution within the big data gaps. The underlying grid was created using the EIGEN-6C4 geopotential since it was shown to provide the most accurate representation of Africa's gravity field (Abd-Elmotaal and Kühtreiber 2026). The reduced anomalies are then interpolated on a $5' \times 5'$ grid covering the African data window ($40°S \leq \phi \leq 42°N$, $20°W \leq \lambda \leq 60°E$) using an unequal weight least-squares prediction technique. Stokes' integral with the Meissl modified kernel (Featherstone et al. 1998), for better integration of the Earth's gravity field wavelengths, has been utilized to compute the reduced geoid undulation component which accounts for the reduced gravity anomalies. The complete gravimetric geoid was finally produced via the window remove-restore technique's restore step. A descriptive flowchart of the developed geoid determination process is illustrated in Fig. 4.

In the final step, an offset and two tilt parameters are applied to de-trend the derived geoid to the DIR_R6 GOCE satellite-only model (Bruinsma et al. 2014), which emerged from the study conducted by Abd-Elmotaal and Kühtreiber (2026) as the most accurate model.

An analysis was performed comparing the geoid determined in this study with the previously established geoid models AGP2003 (Merry et al. 2005), AFRgeo_V1.0 (Abd-Elmotaal et al. 2019), and AFRgeo2019 (Abd-Elmotaal et al 2020) for the African continent.

2 Data Types and Used Data Sets

The physical data consist of point gravity values on land and sea, and altimetry derived gravity anomalies. The long- to intermediate-frequency components are represented using the EIGEN-6C4 geopotential model. The geometry-related input data comprise two regional terrain models and two models describing the Mohorovičić boundary at two different spatial resolutions.

2.1 Point Gravity Data

The point gravity observations currently used for the African Geoid Project consist of land gravity data, shipborne gravity data and altimetry derived gravity anomaly data. This data have been provided by numerous sources, which are specified in the acknowledgment, and to whom we extend our sincere gratification. In order to improve the quality of the generated geoid and the gravity database, the IAG Sub-Commission for Gravity and Geoid in Africa invites all contributions of gravity data sets from within and around the African continent.

The gravity data that was available for this project has been screened using an outlier detection method developed by Abd-Elmotaal and Kühtreiber (2025), Abd-Elmotaal et al. (2024), Abd-Elmotaal and Makhloof (2023). It provides the basis for the gravity database released as AFRGDB_V3.1 (Abd-Elmotaal et al. 2026).

In particular, these are:

Land Gravity Data

Statistical measures of the 126,202 land point data are provided in Table 1. For a detailed analysis of the data, particularly the spatial distribution and the significant data gaps mentioned, please see Abd-Elmotaal et al. (2024).

Table 1 Statistics of the free-air and window-reduced gravity anomalies for Africa using the parameter set from Table 2. Statistics of the gridded anomalies are listed in the last row of this Table

Gravity anomaly type	Region	No. of data points	Statistical parameters (mGal)			
			Min	Max	Mean	Std
Free-air	Land	126,202	−163.20	465.50	9.84	40.93
	Shipborne	184,674	−238.30	354.40	−6.21	34.90
	Altimetry	70,589	−172.23	156.60	4.09	18.23
	Total	345,465	−238.30	465.50	1.76	35.44
	Underlying	48,497	−201.09	500.30	3.45	32.81
Window-reduced	Land	126,202	−120.92	113.67	2.93	6.59
	Shipborne	184,674	−58.37	61.42	0.49	9.88
	Altimetry	70,589	−71.01	100.67	8.02	10.15
	Total	345,465	−120.92	113.67	2.92	9.31
	Underlying	48,497	−65.59	140.41	2.96	5.33
Gridded	Δg^G_{red}		−103.63	111.61	3.18	5.72

Shipborne Gravity Data

The number of the shipborne gravity data points have been reduced from 971,945 to 148,674 using the iteratively operating smart blunder detection algorithm (cf. Table 1).

Altimetry Derived Gravity Anomaly Data

Abd-Elmotaal and Makhloof (2023) provide an explanation of the source and processing of the altimetry-derived gravity anomaly data. The final set consists of 70,589 screened points (see Table 1).

2.2 Underlying Grid

A so-called "underlying grid" is generated in order to introduce some appropriate pre-information regarding the gravity anomalies within the locations of data gaps. Instead of granting the solution total freedom at such enormous data gaps, it provides valuable information to fill the existing gaps, even if only up to a specific frequency contribution. The final interpolation to the target grid is stabilized by the underlying grid, particularly in areas lacking point data. It is built up to degree and order 2190 using the EIGEN-6C4 global reference model (Förste et al. 2014). Africa's gravitational field was found to be best approximated by the EIGEN-6C4 model (Abd-Elmotaal and Kühtreiber 2026). With 48,497 nodes, the underlying grid has a resolution of $15' \times 15'$. Table 1 presents the statistical values of the corresponding free-air gravity anomalies. As expected, they are smoother than the free-air gravity anomalies on land. The information from the underlying grid is disregarded for this grid element if a grid cell of the underlying grid has at least one data point.

2.3 Digital Terrain Models

To analyze how topographic masses affect gravity in the remove-restore method, digital terrain models (DTMs) are necessary. A DTM with a higher resolution is used to simulate the near field effect, whereas a DTM with a lower resolution is utilized to describe the topography in the distant zones.

In the context of geoid determination for Africa, Abd-Elmotaal et al. (2017) created two models for this aim. The fine grid is called AFH16S30 and has a resolution of $30'' \times 30''$. The grid spacing of the related coarser height model AFH16M03 is $3' \times 3'$. The entire African window ($-42° \leq \phi \leq 44°$; $-22° \leq \lambda \leq 62°$) is covered by both models which are shown in Abd-Elmotaal et al. (2024).

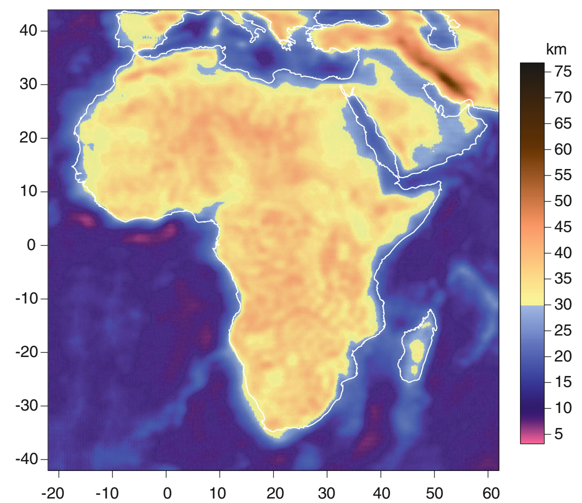

Fig. 1 The $3' \times 3'$ coarse Digital Moho Model for Africa (Abd-Elmotaal et al. 2025). Units are in [km]

2.4 Digital Moho Models

In this study, a model of the Moho is used to discretise the Moho discontinuity, rather than an isostatic concept. This is the central focus of the present investigation. The Moho models (Abd-Elmotaal et al. 2025) generated for this purpose thus serve as the lower boundary surface in the calculation of topographically isostatic effects within the Window Remove-Restore Approach.

Digital Moho models (DMMs), representing the compensating masses in the course of the gravity reduction process, are available for this study. They are derived from the available Moho models in the context of the remove-interpolate-restore technique. The details are given in Abd-Elmotaal et al. (2025).

Two DMMs are utilized within the context of the current paper; a coarse DMM with a resolution of $3' \times 3'$, and a fine DMM with a resolution of $30'' \times 30''$. They both cover the full African window. Figure 1 shows the coarse DMM for Africa. The Moho depths range between 5.55 km and 62.04 km with an average of about 23.17 km and a standard deviation of 12.04 km. Figure 1 shows general correlation with the topography.

3 Window Remove-Restore Approach

In the current research, the window remove-restore approach (WRRA) is utilized. It is described in detail in Abd-Elmotaal and Kühtreiber (2003).

The topographic-isostatic effect $\Delta g_{TI\,win}$ is calculated from the complete topographic masses, discretized by the DTM and DMM, restricted to the selected data window (cf. Sect. 1).

The long wavelengths contribution Δg_{GGM} is synthesized in the data region, using the selected global geopotential model. In the current study, the EIGEN-6C4 GGM (Förste et al. 2014) with $n_{max} = 2190$ is applied. The harmonic analysis of the topographic-isostatic masses for the data window, in terms of potential harmonic coefficients, computed by the technique developed by Abd-Elmotaal and Kühtreiber (2021) up to degree and order $n_{max} = 2190$, takes place. The result in the frequency domain is the topographic-isostatic potential harmonic coefficients for the data window, from which one computes the contribution Δg_{wincof}. Finally, the effect of the adapted GGM $\Delta g_{GGM\,Adapt}$ is computed by subtracting the effect of the topographic-isostatic potential coefficients of the data window Δg_{wincof} from the effect of the GGM

$$\Delta g_{GGM\,Adapt} = \Delta g_{GGM}\Big|_{n=2}^{n_{max}} - \Delta g_{wincof}\Big|_{n=2}^{n_{max}} . \quad (1)$$

The adapted reference field has the same maximum degree n_{max} as the reference model Δg_{GGM}.

The remove step has the goal of smoothing the free-air gravity anomaly data Δg_F as best as possible through appropriate reductions. The respective reduced gravity anomalies can be computed point-wise by:

$$\Delta g_{red} = \Delta g_F - \Delta g_{TI\,win} - \Delta g_{GGM\,Adapt}\Big|_{n=2}^{n_{max}} . \quad (2)$$

They are smoothed by applying the topographic-isostatic effects which accounts for the high frequency terms for the data window. The final expression for the reduced gravity anomalies using the window remove-restore approach is obtained by inserting Eq. (1) into Eq. (2)

$$\Delta g_{red} = \Delta g_F - \Delta g_{TI\,win} - \Delta g_{GGM}\Big|_{n=2}^{n_{max}} + \Delta g_{wincof}\Big|_{n=2}^{n_{max}} . \quad (3)$$

The free-air gravity anomalies Δg_F are calculated using the gravity data described in Sect. 2.1 in order to discretize Eq. (2). The DTMs and DMMs given in Sect. 2.3 and Sect. 2.4, respectively, are the sources of the mass-related contributions (topographic-isostatic effects).

4 Gravity Reduction

The reduced anomalies Δg_{red} are calculated from Eq. (3). The contribution of the topographic (DTMs) and isostatic (DMMs) masses $\Delta g_{TI\,win}$ are computed from the fixed data window ($42°S \leq \phi \leq 44°N$, $22°W \leq \lambda \leq 62°E$) covering the African continent. Different parameter sets have been tested to produce the minimal standard deviation of the reduced anomalies. As part of this parameter adjustment, the normal crustal thickness is set to $T_\circ = 30.0$ km, the density of the crust is $\rho_\circ = 2.4$ g/cm^3, and the density contrast between the lower crust and the upper mantle is $\Delta\rho = 0.3$ g/cm^3.

The specific term Δg_{wincof} in Eq. (3) is calculated in two steps. First, a harmonic analysis up to $n_{max} = 2190$ is performed on the DDM and DDMs from the data window. Δg_{wincof} is then synthesized from the Wincoff coefficients. This key step in WRRA technology prevents the topographical effects from being applied twice.

The statistics of the window-reduced and free-air anomalies for each data type are shown in Table 1. It demonstrates that compared to the free-air anomalies, the window-reduced anomalies are significantly smoother (centered with a smaller standard deviation). The standard deviation has decreased by roughly 74% for the entire data set (land + shipborne + altimetry) and by approximately 84% for the land data only. Additionally, Table 1 demonstrates that the statistics of the window-reduced anomalies for the underlying grid closely resemble those of the window-reduced anomalies for the entire data set, which is regarded as encouraging.

5 Point Values to Grid-Interpolation

Using the unequal weight least-squares prediction, the window-reduced gravity anomalies Δg_{red} have been gridded in a $5' \times 5'$ grid covering the African window ($-40° \leq \phi \leq 42°; -20° \leq \lambda \leq 60°$).

Hirvonen's generalized covariance model is utilized in the least-squares interpolation method which is explained in detail in Abd-Elmotaal et al. (2019). The used respective parameters are listed and compared to previous solutions in Table 2.

The relatively low value of the standard deviation for the underlying grid is assumed in order to decrease the dominant

Table 2 Used parameters in the AFRgeoYYYY versions

Parameter	2019	2025
T_o	30.0 km	30.0 km
ρ_o	2670 kg m^{-3}	2400 kg m^{-3}
$\Delta\rho$	0.4 kg m^{-3}	0.3 kg m^{-3}
σ_{land}	1 mGal	1 mGal
$\sigma_{shipborne}$	3 mGal	3 mGal
$\sigma_{altimetry}$	5 mGal	5 mGal
$\sigma_{underlyinggrid}$	20 mGal	20 mGal
p	0.364	0.305
C_o	81.30 mGal^2	79.57 mGal^2
ξ	10.38 km	9.67 km

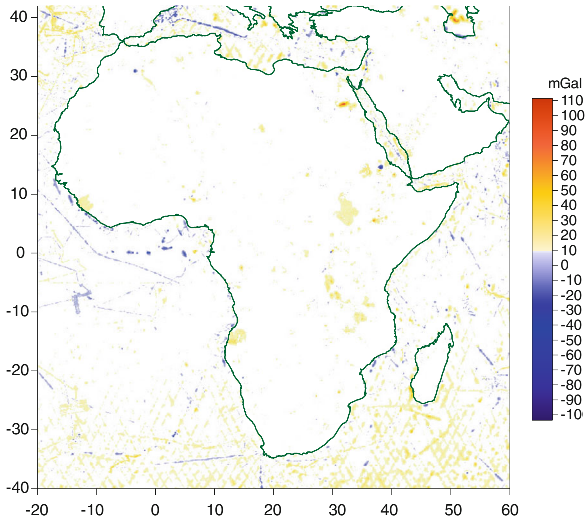

Fig. 2 The $5' \times 5'$ interpolated window-reduced gravity anomalies Δg^G_{red} for Africa. Units in [mGal]

effect of the underlaying grid, being non-observed gravity anomaly values.

The interpolated window-reduced gravity anomalies Δg^G_{red} on the $5' \times 5'$ grid for Africa, illustrated in Fig. 2, showing good reduced anomalies for Africa; which is a main important feature of this study. This is also confirmed by the statistics presented in the last row of Table 1.

6 Method Used for Geoid Determination

To account for the different spectral components of the Earth's gravity field, the Stokes' integral in Eq. (4) is evaluated incorporated the modified kernel of Meissl.

The contribution of the reduced gridded gravity anomalies Δg^G_{red} to the geoid $N_{\Delta g_{red}}$ on a $5' \times 5'$ grid covering the African window is given by:

$$N_{\Delta g_{red}} = \frac{R}{4\pi\gamma} \iint_{\sigma} \Delta g^G_{red}\, K^M(\psi)\, d\sigma\,. \tag{4}$$

The modified kernel $K^M(\psi)$ is defined according to Meissl (Featherstone et al. 1998)

$$K^M(\psi) = \begin{cases} S(\psi) - S(\psi_\circ) & \text{for } 0 < \psi \le \psi_\circ \\ 0 & \text{for } \psi > \psi_\circ \end{cases}\,. \tag{5}$$

An arbitrarily cap size of $\psi_\circ = 3°$ has been utilized as integration radius. The original Stokes function is $S(\cdot)$. The Meissl modified kernel was chosen since it demonstrated good performance (cf. Abd-Elmotaal and Kühtreiber 2008). Alternative modifications of the Stokes kernel are discussed in terms of their spectral filtering properties by Featherstone et al. (1998).

The window technique's complete geoid restore expression is (Abd-Elmotaal and Kühtreiber 2003)

$$N = N_{\Delta g_{red}} + N_{TI\,win} + \zeta_{GGM}\Big|_{n=2}^{n_{max}} - \\ - \zeta_{wincof}\Big|_{n=2}^{n_{max}} + (N - \zeta)_{win}\,, \tag{6}$$

where ζ_{GGM} is the contribution of the used reference geopotential model, ζ_{wincof} is the contribution of the topographic-isostatic harmonic coefficients of the utilized data window, $N_{TI\,win}$ is the contribution of the topographic-isostatic masses for the same fixed data window, and $(N - \zeta)_{win}$ is the transformation from quasi-geoid to geoid for all terms related to the quasi-geoid, i.e., ζ_{GGM} and ζ_{wincof}. The relationship between quasi-geoid and geoid given in Heiskanen and Moritz (1967, p. 327) is applied, given in Eq. (9). This allows the desired relationship to be established:

$$(N - \zeta)_{win} = \frac{H}{\bar{\gamma}} \left(\Delta g_{GGM} - \Delta g_{wincof}\right)\,, \tag{7}$$

where $\bar{\gamma}$ is the mean normal gravity and Δg_{GGM} and Δg_{wincof} are the free-air gravity anomaly contributions of the utilized reference geopotential model and the topographic-isostatic harmonic coefficients of the data window, respectively.

A number of GNSS stations with known orthometric heights throughout the continental region are required in order to adapt the gravimetric geoid model for Africa to the various regional height systems of the African nations. It is worth mentioning that the developed geoid model for Africa is gravimetrically consistent, even if it has not been fully validated for height for obvious reasons.

Alternatively, the static GOCE DIR_R6 satellite-only model (Bruinsma et al. 2014), which is comprehensive to degree and order 300, is used to de-trend the computed geoid AFRgeo2025. Abd-Elmotaal and Kühtreiber (2026) have demonstrated, that DIR_R6 is the most accurate global satellite-only geopotential model that approximates the gravity field in Africa. In the current study the DIR_R6 model was synthesized up to d/o 280. The coefficients of higher degrees are not considered because their signal-to-noise ratio is greater than one. It is expressly stated that the GOCE DIR_R6 satellite-only model has not been used for comparison, it is just been used to de-trend the gravimetric geoid by subtracting only a linear trend.

A trend model with two tilt factors and a vertical offset has been utilized to illustrate the general differences between the GOCE DIR_R6 geoid and the newly elaborated AFRgeo2025 geoid solution. The residuals between the two geoid models were used to estimate these parameters employing

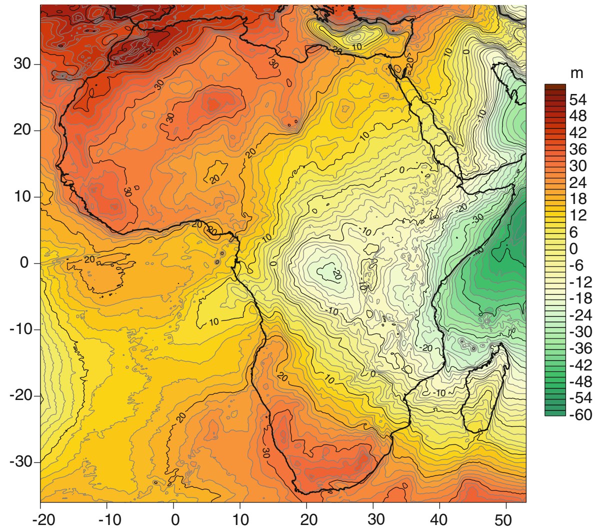

Fig. 3 The improved solution for the Geoid of the African Continent: The AFRgeo2025 African geoid model (de-trended in respect to GOCE DIR_R6 geopotential model). Contour interval: 2 m

a least-squares regression approach. This parametric model has excluded any potential trend in the computed geoid within the current investigation. Errors in the point gravity measurements or the long-wavelength components of the reference model EIGEN-6C4 could be the source of this trend.

The height anomaly ζ_{DIR_R6} based on the geopotential model DIR_R6 is related to its respective geoid undulation N_{DIR_R6} via

$$N_{DIR\_R6} = \zeta_{DIR\_R6} + (N - \zeta) \,. \tag{8}$$

The term $(N - \zeta)$ is evaluated by (Heiskanen and Moritz 1967, p. 327)

$$(N - \zeta) = \frac{H}{\bar{\gamma}} (\Delta g_{DIR\_R6} - 2\pi\rho_\circ GH) \,, \tag{9}$$

where G is Newton's gravitational constant, $\rho_\circ$ is the topographical density listed in Table 2, and Δg_{DIR_R6} is the free-air gravity anomalies calculated using the DIR_R6 geopotential model.

Accordingly, Fig. 3 displays the AFRgeo2025 African de-trended geoid. Its statistical measures range from − 55.37 m to 56.86 m, with an average of 11.73 m.

The complete method of the AFRgeo2025 geoid determination is display as flowchart in Fig. 4.

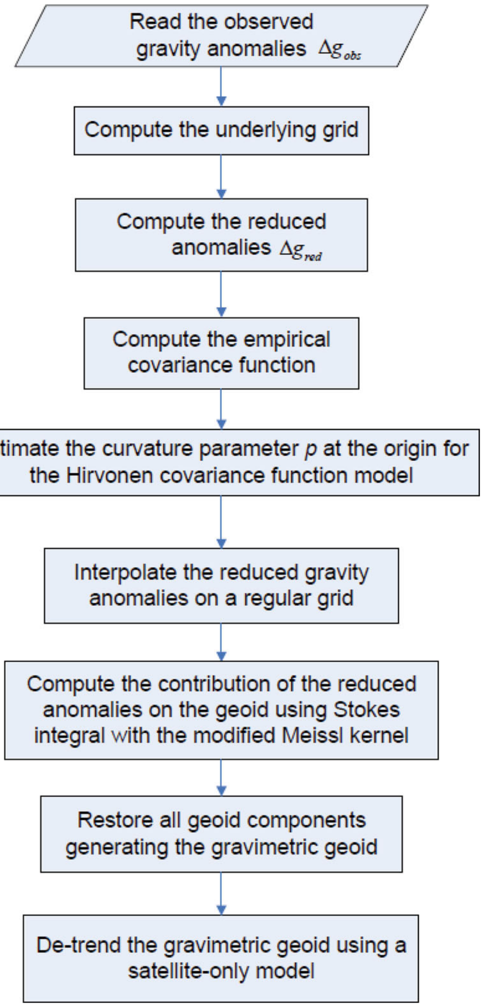

Fig. 4 Flowchart of the applied process to generate the new AFRgeo2025 geoid model for the continent of Africa

7 Geoid Comparison

The first attempt to identify a geoid model for Africa, known as AGP2003, was completed by Merry et al. (2005). The current databases have been significantly improved (Abd-Elmotaal et al. 2026). Specifically, the statistical combination of the several kinds of gravity anomalies, including new data types, has been updated and improved (AFRGDB_V3.1). Consequently, the new African geoid model AFRgeo2025 has been improved as a result.

Figure 5 demonstrates the variations between the de-trended AFRgeo2025 and the AGP2003 geoid models. The bright yellow pattern indicates magnitude differences below

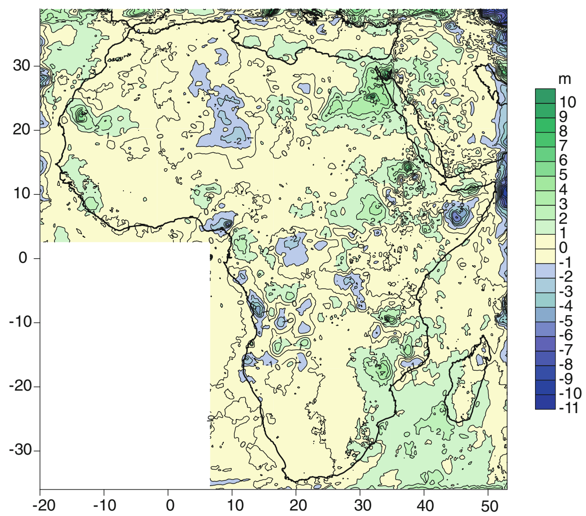

Fig. 5 Difference between the de-trended AFRgeo2025 and the AGP2003 geoid models. Contour interval: 1 m

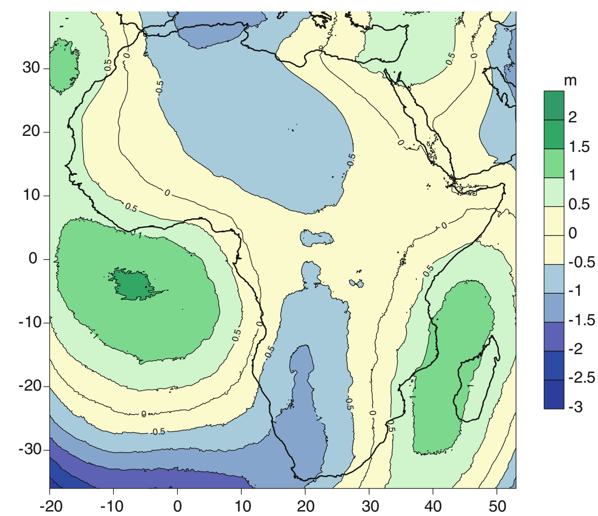

Fig. 7 Difference between the de-trended AFRgeo2025 and the AFRgeo2019 geoid models. Contour interval: 0.5 m

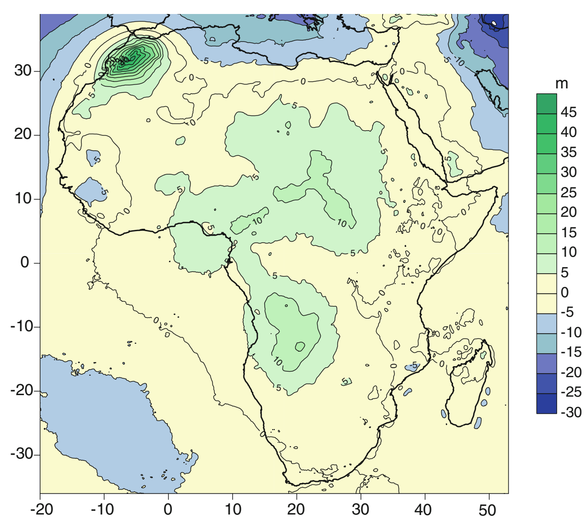

Fig. 6 Difference between the de-trended AFRgeo2025 and the AFRgeo_v1.0 geoid models. Contour interval: 5 m

1 m. In the continental region, particularly in Eastern Africa, it is illustrated that the two geoids differ by several meters. The AGP2003's failure to incorporate ocean data into the solution is the reason for the significant variations across the Atlantic Ocean. Some edge effects are visibel in the figure, which are once more a direct result of the AGP2003 solution's use of only data from the African continent.

Figure 6 shows the difference between the de-trended AFRgeo2025 and the AFRgeo_v1.0 geoid models. The difference between the two geoid models is large, especially in Morocco. This is because of wrong data set in Morocco entering the AFRgeo_v1.0 geoid model solution (cf. Abd-Elmotaal et al. 2015, 2019).

Figure 7 shows the difference between the de-trended AFRgeo2025 and the AFRgeo2019 geoid models. The difference between the two geoid models shows a long wavelength feature. The AFRgeo2019 geoid model used the same gravity data as that of the AFRgeo2025 described in Sect. 2.1.

It can therefore be concluded that the differences stems from the modeling of the Mohorovičić boundary using the Moho model shown in Fig. 1 rather using an isostatic concept as it is done for AFRgeo2019.

At any rate, most of the African continent has a smooth difference showing long wavelength residuals between the two geoid models between ±0.5 m (the bright yellow pattern in Fig. 7).

8 Conclusion

The African geoid model has been effectively revised and computed in this research. The calculated geoid model AFRgeo2025 made use of a Moho model discussed in Sect. 2.4. This alternative modeling, in conjunction with reducing the isostatic effect, leads to long-wavelength variations in the geoid solution. It can be described as an improvement, as more realistic data-driven modeling (DDM) has now been implemented in the process. This new source of information improves the interpolation of gravity data, particularly where there are significant gaps in the data. The window remove-restore approach, which provides the best minimized gravity anomalies, is the foundation for the geoid determination. This has reduced the interpolation errors, particularly where there are significant gaps in the point gravity data. The global geopotential model EIGEN-6C4 has been utilized to fill data gaps using synthetic gravity anomalies, stabilizing the interpolation process.

Because they are centered, smooth, and have a very narrow range, the reduced gravity anomalies using the Moho information exhibit extremely good statistical behavior, particularly on land (cf. Fig. 2 and Table 1). The residuals' smoothness shows that the interpolation method is generally effective and does not cause aliasing effects, particularly when there are significant gaps in the data. As a result, they provide less interpolation errors, especially in the wide gaps in gravity data.

The modified kernel function of Meissl is used instead of the Stokes classical kernel within the context of the Stokes integral for the sake of optimizing the integration of the various wavelength components within the remove-compute-restore method.

Lastly, the DIR_R6 GOCE model has been utilized to de-trend the derived geoid model for Africa. The advancement in identifying the African height reference surface is evident when compared to the earlier models AGP2003, AFRgeo_v1.0, and AFRgeo2019. The findings demonstrated that the African geoid determination procedure developed into a very reliable procedure.

Acknowledgements We are grateful for the assistance granted by the International Association of Geodesy (IAG) and the International Union of Geodesy and Geophysics (IUGG). A portion of the utilized gravity data set for Africa was provided by Dr. Sylvain Bonvalot, Director of Bureau Gravimétrique International (BGI), for which the authors are grateful.

Competing Interests The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

References

Abd-Elmotaal HA, Kühtreiber N (2003) Geoid determination using adapted reference field, seismic Moho depths and variable density contrast. J Geod 77(1-2):77–85. https://doi.org/10.1007/s00190-002-0300-7

Abd-Elmotaal HA, Kühtreiber N (2008) An attempt towards an optimum combination of gravity field wavelengths in geoid computation. Observ Chang Earth Int Assoc Geodesy Symposia Ser 133:203–209. https://doi.org/10.1007/978-3-540-85426-5_24

Abd-Elmotaal HA, Kühtreiber N (2021) Direct harmonic analysis for the ellipsoidal topographic potential with global and local validation. Surv Geophys 42(1):159–176. https://doi.org/10.1007/s10712-020-09614-4

Abd-Elmotaal HA, Kühtreiber N (2025) Gross errors detection for the African gravity database. Geophys Res Abstracts 27. https://meetingorganizer.copernicus.org/EGU25/EGU2025-6382.pdf

Abd-Elmotaal HA, Kühtreiber N (2026) Merging terrestrial and satellite gravity data for Africa: A possibility to fill-in the data gaps. Mansoura Eng J 51(1). https://doi.org/10.58491/2735-4202.3356

Abd-Elmotaal HA, Makhloof A (2023) Integrating altimetry derived gravity anomalies with ship-borne gravity data for Africa. Contribut Geophys Geodesy 53(3):191–206. https://doi.org/10.31577/congeo.2023.53.3.2

Abd-Elmotaal HA, Seitz K, Kühtreiber N, Heck B (2015) Establishment of the gravity database AFRGDB_V1.0 for the African geoid. Int Assoc Geodesy Symposia 144:131–138. https://doi.org/10.1007/1345_2015_51

Abd-Elmotaal HA, Makhloof A, Abd-Elbaky M, Ashry M (2017) The African 3″ × 3″ DTM and its validation. Int Assoc Geodesy Symposia 148:79–85. https://doi.org/10.1007/1345_2017_19

Abd-Elmotaal HA, Seitz K, Kühtreiber N, Heck B (2019) AFRgeo_v1.0: a geoid model for Africa. KIT Scientific Working Papers 125. https://doi.org/10.5445/IR/1000097013

Abd-Elmotaal HA, Kühtreiber N, Seitz K, Heck B (2020) A precise geoid model for Africa: AFRgeo2019. Int Assoc Geodesy Symposia 152:77–87. https://doi.org/10.1007/1345_2020_122

Abd-Elmotaal HA, Seitz K, Kühtreiber N, Heck B, Kutterer H (2024) AFRGDB_V2.3: The updated gravity database for Africa using RTM technique. J Adv Eng Trends 43(2):43–51. https://doi.org/10.21608/jaet.2022.149901.1219

Abd-Elmotaal HA, Seitz K, Kühtreiber N, Heck B, Grombein T, Kutterer H (2025) A Moho model for Africa. J Adv Eng Trends 44(2):33–38. https://doi.org/10.21608/jaet.2025.372553.1362

Abd-Elmotaal HA, Kühtreiber N, Seitz K, Grombein T, Heck B, Kutterer H (2026) The AFRGDB_V3.1 updated gravity database for Africa implementing Moho information. Surv Rev 1(1):1–99. https://doi.org/10.1080/00396265.2026.2664266

Bruinsma S, Förste C, Abrikosov O, Lemoine JM, Marty JC, Mulet S, Rio MH, Bonvalot S (2014) ESA's satellite-only gravity field model via the direct approach based on all GOCE data. Geophys Res Lett 41(21):7508–7514. https://doi.org/10.1002/2014GL062045

Čadek O, Martinec Z (1991) Spherical harmonic expansion of the earth's crustal thickness up to degree and order 30. Studia Geophysica et Geodaetica 35:151–165. https://doi.org/10.1007/BF01614063.

Featherstone WE, Evans JD, Olliver JG (1998) A Meissl-modified Vaníček and Kleusberg kernel to reduce the truncation error in geoid computations. J Geod 72:154–160. https://doi.org/10.1007/s001900050157

Förste C, Bruinsma SL, Abrikosov O, Lemoine JM, Marty JC, Flechtner F, Balmino G, Barthelmes F, Biancale R (2014) EIGEN-6C4 The latest combined global gravity field model including GOCE data up to degree and order 2190. GFZ Data Services. https://doi.org/10.5880/ICGEM.2015.1

Heiskanen WA, Moritz H (1967) Physical geodesy. Freeman, San Francisco. https://www.scribd.com/document/495609827/Physical-Geodesy-Heiskanen-Morits-1967-8

Laske G, Masters G, Ma Z, Pasyanos M (2013) Update on CRUST1.0 – A 1-degree global model of Earth's crust. In: Geophysical research abstracts, vol 15. https://meetingorganizer.copernicus.org/EGU2013/EGU2013-2658.pdf

Merry CL, Blitzkow D, Abd-Elmotaal HA, Fashir H, John S, Podmore F, Fairhead J (2005) A preliminary geoid model for Africa. A window on the future of geodesy. Int Assoc Geodesy Symposia 128:374–379. https://doi.org/10.1007/3-540-27432-4_64

Reguzzoni M, Sampietro D (2015) GEMMA: An earth crustal model based on GOCE satellite data. Int J Appl Earth Observ Geoinf 35:31–43. https://doi.org/10.1016/j.jag.2014.04.002

Reguzzoni M, Sampietro D, Sansò F (2013) Global Moho from the combination of the CRUST2.0 model and GOCE data. Geophys J Int 195:222–237. https://doi.org/10.1093/gji/ggt247

Sjöberg LE, Abrehdary M (2022) MOHV21: a least squares combination of five global moho depth models. J Geodesy 96:45. https://doi.org/10.1007/s00190-022-01631-y