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E-Mail :
editor.ijasem@gmail.com
editor@ijasem.org

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Accurate Geoid Modeling Using Global Navigation Satellite Systems and Elevation Data from a Geographic Information System

Dr.K.Pandu,S Ramyakala,Touseeqanwarwasif

ABSTRACT: *This work provides a simple, efficient, and rapid method for geoid refinement inside a Geographic Information Systems (GIS) setting as an alternative to the time-consuming process of completely re-developing a geoid model whenever new geodetic datasets become available. In this study, we look at many mathematical strategies for incorporating GNSS/Levelling datasets. Among them are the Inverse Weighted Distance (IDW) technique, the kriggingggeostatistical method, and the 2-, 4-, and 7-parameter regression approaches. The latest SRI 2021 national geoid model has been improved with the use of these five methods and 220 additional GNSS/Levelling data points based on the available data. In light of the data and the outcomes, it has become clear that all of the explored approaches provide around the same degree of accuracy, and an increase of over 10% has been accomplished. It's possible that the disparate geographical distribution of the used datasets throughout the nation is to blame for the very modest degree of improvement seen. Overall, the precision of the completed geoid model, dubbed SRI 2022, is equivalent to 0.14 m. It is proposed that Egypt update/establish both GNSS and Levelling networks, with a good homogeneous geographical distribution, in order to attain a geoid model accuracy of 1-5 centimeters.*

INTRODUCTION

Given the widespread use of GNSS technology, geoid modeling has emerged as a crucial role for geodesists everywhere. Most often used in surveying, mapping, and civil engineering, a geoid model is responsible for transforming the GNSS-based ellipsoidal heights into orthometric heights or elevations relative to Mean Sea Level (MSL) datum. In recent years, researchers in several nations, including Indonesia [1], Chile and Spain [2], and Vietnam [3], have examined many national and regional geoid models. Local geoid models, such as those for the west desert of Egypt [4] and Jeddah city in Saudi Arabia [5], have also been produced inside countries. Inaccuracies in geoid models are often attributed to differences in the quality, quantity, and geographic distribution of information used in a given area. There are reports of geoid models with an accuracy of 1 cm in Colorado, USA [6] and 5 mm in Estonia [7]. Many geoid models, some at the national level (Saadon et al., for example) and others at the regional level (Elshewy et al., for example), have been constructed in Egypt.

Incorporating additional fresh geodetic datasets is a step taken to improve an existing geoid model, either global or national. Several scientists have looked at this mechanism during the last ten years. For instance, Al-Kherayef et al.

Department of civil
pandu.ouce@gmail.com,ramyakala9@gmail.com, touseeqwasif@gmail.com
ISL Engineering College.
International Airport Road, Bandlaguda, Chandrayangutta Hyderabad - 500005 Telangana, India.

[10] looked at how the Saudi geoid, KSA-Geoid17, might change if additional observed GNSS/Levelling datasets were added. Incorporating terrestrial, marine, and aircraft gravity measurements, Pasuya et al. [11] have evaluated the revision of Malaysia's gravimetric geoid. In a similar vein, Wang et al. [12] advocated for the inclusion of satellite altimetry levelling data in the Chinese geoid model. An important area of study, with several hypotheses presented, is the mathematical and statistical techniques of such geoid refining. Some examples of such models are the finite element based bivariate [16], the minimal curvature surface [17], the 4-parameter elimination [15], and the moving least squares technique [13].

In the past, whenever fresh GNSS/Levelling information were available, a new geoid national model was produced using one of the geoid modelling tools like the GravSoft scientific software. This research instead suggests a quick and easy method for improving upon an existing geoid model. As such, the present study, which is based on one of the most up-to-date Egyptian geoid models, looked into whether or not adding additional GNSS/Levelling information would increase the model's accuracy on a national scale. Such a strategy for improvement is carried out in a Geographic Information Systems (GIS) setting, where a number of different mathematical and statistical approaches are used and contrasted.

METHODOLOGY

For different geodetic applications, many mathematical and statistical models have been developed for interpolating scatter data points and building a 3D geographic surface. As a result, the regression approach is widely used but

$\Delta N1 = a + a_{o}\cos\phi + a_{1}\cos$ $_{2}$

The4-parametersand7-parametersregressionmodelsusedinseveralgeodetica

$\Delta N2 = a + a_{o}\cos\phi\cos_{1}$ (4)

e2isthesecondeccentricityoftheWGS84ellipsoid,and εrepresentstheresidualsorerrorsoftheregressionprocess.

Using the least-squares adjustment approach, we will concurrently solve all observation equations (of either 1 or 3) and get independent estimates of the unknowns. There are a variety of models available in a geographic information system (GIS) setting for translating scatter data points into a grid or a three-

jisthegeoidalerroroftheunknownpoints,

isthegeoidal erroroftheknownpoints,represents the distance between a known and an unknown point, andr

isapowerweightingfunction,usuallyinpracticeequals 2.

whereis themeasuredquantityattheithlocation represents an unknown weight for point i,so

is thepredictionlocation, andB equalsthenumberofmeasurements. Accordingly, each equation (Eq. 1 to 6) will be utilized in a GIS

Enh $_{i}$ $_{i}$

Finally,theaccuracyofallenhancedgeoidmodelswillbeexternallyevaluated,intermsofstandarddeviations,overtheknowncheckpoints.TheoverallprocessingstepsaredepictedinFig.1.

comes at a high price in a variety of mathematical guises. Geoidal errors (N) as a function of latitude () and longitude () may be calculated using the simple linear equation formula [18]::

pplications[15]couldbewrittenas:

dimensional surface. Krigging, splines, trends, natural-neighbor, and the Inverse Distance Weighted (IDW) method are all examples of such approaches. The IDW is a deterministic approach in mathematics that uses the average of the values of nearby known points to determine the value of an unknown point. In contrast, IDW accounts for the distances to each known location, making the weights negative in relation to the distances. The IDW approach may be summed up in the following fo

Moreover,thekriggingisageostatisticalanalysisthattakesintoaccountthespatialdistributionofthesamplepointstoexplainthevariationsinthe3Dsurface.Thegeneralformofthekrigginginterpolatoris(ibid):

^

environment to model spatially thegeoidal errors and construct a 3D corrector surfaces. Each corrector surface will be added to the original geoidmodeltoattainamodifiedorenhancedversion:

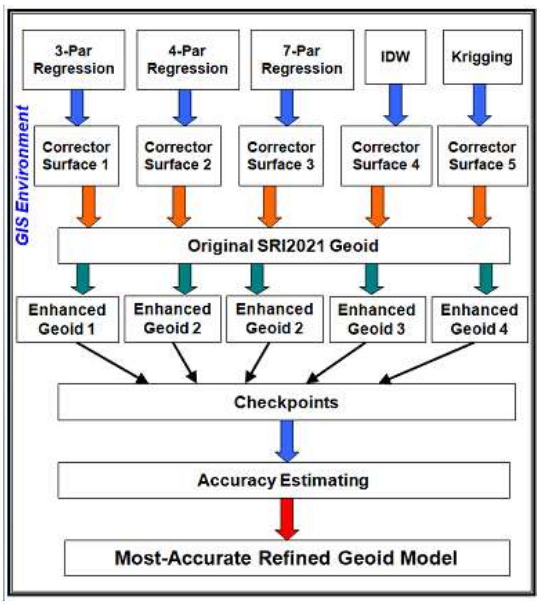


Fig.1:Workflowof theProcessingStrategy

I. AVAILABLEDATA

The SRI2021 geoid model created by Al- Krargy and Dawod [20] serves as the foundation for our investigation. Several Global Geopotential Models (GGMs) and Global Digital Elevation Models (GDEMs) were analyzed in this study to determine which combination is best for geoid modeling in Egypt. Also, 1100 GNSS/Leveling points were used to fine-tune the gravimetric geoid that was derived using data from 247 terrestrial gravity stations. The best national geoid model that resulted, SRI2021, was found to be accurate to within 0.151 m at 100 different GNSS/Levelling reference locations (Fig. 2). In addition, throughout the course of the previous several years, the Survey Research Institute (SRI) has amassed a total of 245 GNSS/Levelling points from their various initiatives. Mainly, they extend to the coasts of the Red Sea, the Gulf of Suez, and the Gulf of Aqaba. Two sets of available points have been employed here: 223 stations for the processing phase, and 22 stations for evaluating the final product (Fig. 3).

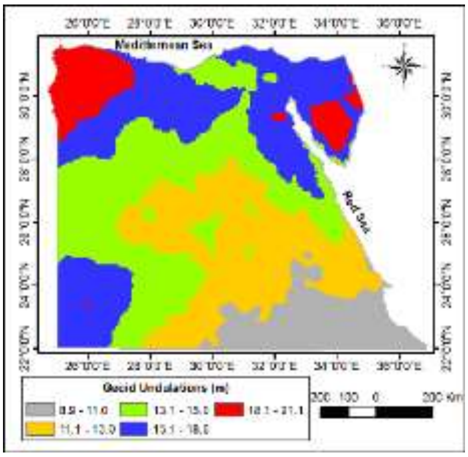


Fig.2: TheSRI2021GeoidModelofEgypt
(afterAl-KrargyandDawod2021)

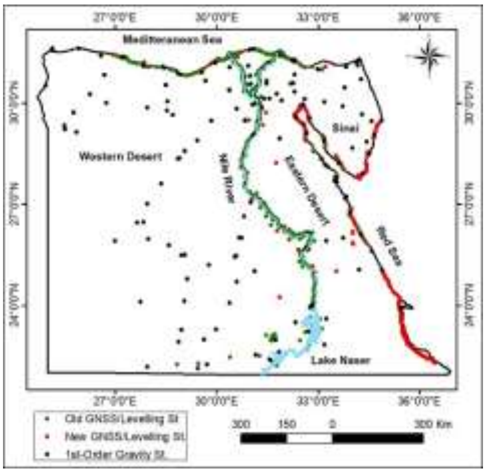


Fig3:AvailableGNSS/LevellingStations

PROCESSINGANDRESULTS

Thefirststephasbeenperformedusingthek nowngeoidundulations,N,attheutilized223GNSS/ Levellingstations andcomparingthemto the correspondingvalues of the SRI2021geoidto computetheir residuals ΔN.Next, the different investigated regression equations (Eq. 1, 2, and 3) have been solved.Theattainedregressionmodelsare:

$\Delta N1 = -2.3288$

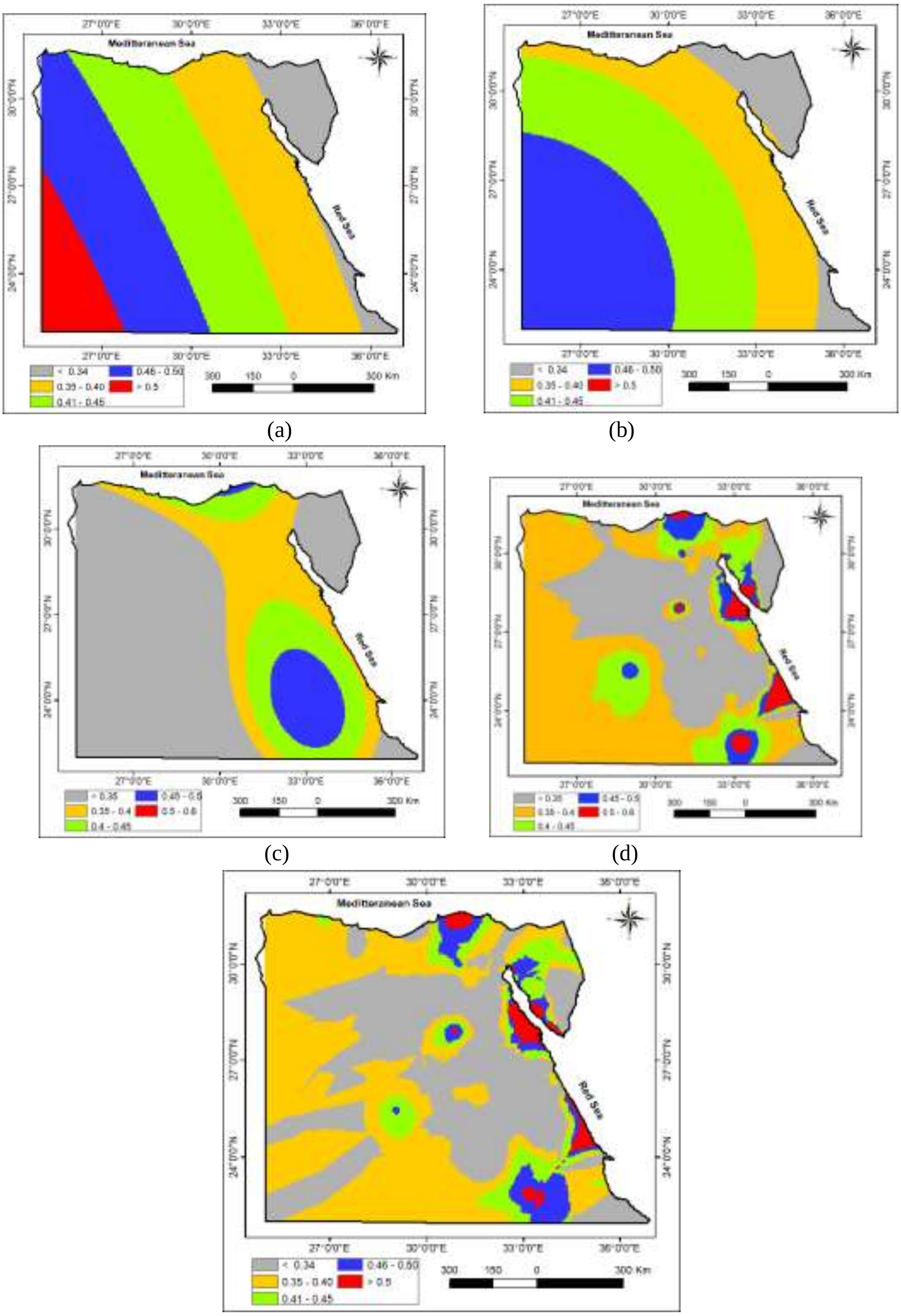
(10)

With thecoefficientofdetermination,R2,equals0.029,0.033,and0.147respectively.

The next step was to establish a grid encompassing the whole country of Egypt, with each square measuring 2 kilometers by 2 kilometers. Equations (8, 9, and 10) have been approximated at each node of that grid using the Arc GIS 10.8 software. The three surfaces achieved here are the corrective surfaces for the respective regression models. Next, the geoidal errors of SRI2021 have been modeled using the IDW and Krigging tools (Eq. 5 and 6). As a result, five correction surfaces for the five studied refinement models have been created (Fig. 4). Table 1 displays summary data for these corrective models. Table 1 demonstrates that there are no statistical variances in the overall performance of the models throughout Egypt, despite Fig. 4's depiction of large discrepancies in the geographical distribution of geoid errors for the used models. As a result, it can be concluded that the accuracy of geoid augmentation is not reflected in the standard deviation figures, but rather in the precision of the models that were examined.

Table1:StatisticsofCorrection Surfaces(m)

Model	CorrectionSurfaces			
	Minimum	Maximum	Average	StandardDeviation
2-ParametrsRegression	0.303	0.545	0.426	±0.054
4-ParametrsRegression	0.303	0.544	0.426	±0.055
7-ParametrsRegression	0.301	0.545	0.425	±0.055
IDW	0.302	0.545	0.426	±0.055
Krigging	0.302	0.544	0.425	±0.054



(e)

(a)2-parametrregression,(b) 4-parametrregression,(c) 7-parametrregression,
(d)IDW,and(e)Kriging

Fig. 4:TheAttainedCorrectionSurfaces

The five new geoid models were then created using Equation 7, which included adding each corrector surface to the baseline SRI 2021 geoid. These geoid models have been evaluated across the 22 known checkpoints to determine their correctness. Our results are summarized in Table 2. The first thing to notice about this table is that the accuracy levels produced by all the approaches under study are quite close to one another. And second, a contrast between the

When comparing the latest refinement geoid model to the baseline SRI 2021 model, a near-10% improvement is shown. When compared to other methods, the amount of improvement provided by the 4-parameter regression technique is the highest. The exterior overall accuracy of the SRI 2022 geoid is 0.136 m, which is an increase of 9.3 percent over the previous model. The precision of this model is comparable to that of other recent Egyptian geoid models (e.g. Saadon et al. 2021). The results show that the suggested GIS-based method of geoid refining is easy to use, effective, and quick. As long as updated GNSS/Levelling datasets are accessible, it should be carried out

.

Table2:Statisticsof UndulationsofDifferentGeoidModelsOverCheckpoints(m)

GeoidModel	GeoidUndulation				
	Minimum	Maximum	Average	StandardDeviation	Improvement%
SRI2021Geoid	7.158	16.799	12.753	±3.049	NA
Geoidof2-ParametrsRegression	7.046	16.866	12.768	±2.768	9.2%
Geoidof4-ParametrsRegression	7.066	16.860	12.766	±2.766	9.3%
Geoidof7-ParametrsRegression	6.934	16.316	12.518	±2.773	9.1%
GeoidofIDW	6.966	16.240	12.517	±2.774	9.0%
GeoidofKrigging	6.966	16.234	12.515	±2.779	8.9%

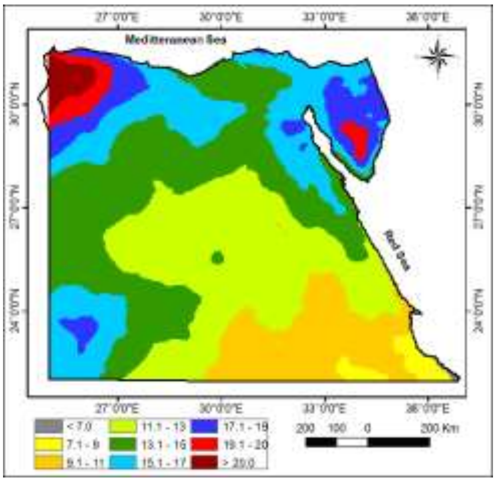


Fig.5:TheSRI2022EgyptianGeoid

The results also show that improving Egypt's current national geoid by adding about two hundred GNSS/Levelling sites improves its accuracy by just around 10%. This might be because the datasets being used have a varied distribution throughout the nation (Fig. 3). Each and every attempt to create a precise Egyptian geoid faces this same problem. Researchers and academics in the geodetic community may see the distribution of the most popular geodetic datasets in Fig. 6. That map illustrates how the Eastern Desert, Western Desert, and Sinai Peninsula all have substantial gaps in coverage. Regarding the authors' concerns, other agencies, such as the Geological Survey Authority (terrestrial gravity data) and the Nuclear Energy Authority, also hold their own databases (airborne gravity data). All available data sets should be collected, examined, and applied to the problem of creating an accurate Egyptian national geoid

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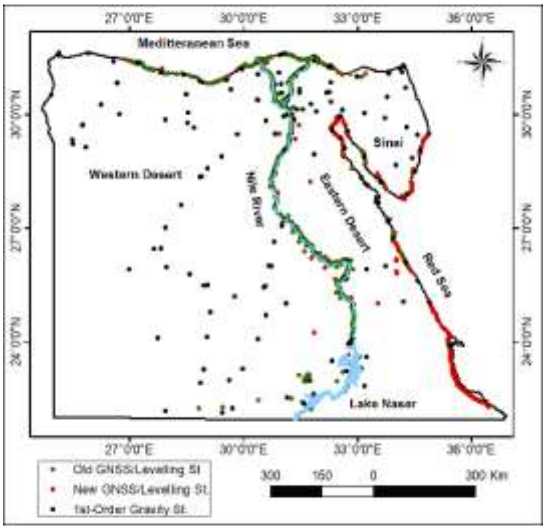

Fig.6:TheCurrentlyAvailableGeodeticDatasetsforGeoid Modelling

II. CONCLUSIONS

This study recommends a quick and easy method for improving an already existing geoid model on a national or regional scale. Using one of the most up-to-date geoid models of Egypt, this study looked at how adding additional GNSS/Levelling datasets may boost the model's accuracy on a national scale. There have been several analyses of various statistical and mathematical approaches. Several examples of such models include the inverse weighted distance and the krigging method, as well as the 2-parameter, 4-parameter, and 7-parameter regression models. All of these models were used in conjunction with two hundred global navigation satellite system (GNSS)/leveling stations in a geographic information system (GIS) to simplify and expedite the geoid refining process in Egypt.
Conclusions drawn from the work done show that the accuracy levels generated by the various approaches examined are comparable. Also, using the current data, a near-10% enhancement has been accomplished. The geographical inhomogeneity of the used datasets throughout the nation may account for the relatively low amount of improvement seen. Overall, the SRI 2022 geoid model that was constructed is accurate to within 0.136 m. The observed results suggest that the expected GIS-based approach of geoid refining should be carried out so long as fresh GNSS/Levelling datasets are available.

Based on the findings of this research, many suggestions may be made, such as: 1. Obtaining all accessible geodetic datasets from all local organizations, analyzing them, and using them to construct an accurate national geoid of Egypt.
Second, modernizing and establishing GNSS and Levelling networks with a good homogeneous distribution throughout Egypt is necessary for generating geoid models with an accuracy of a few centimeters.
As part of the massive Spatial Data Infrastructures (SDP) project now under progress, a Geodetic Data Infrastructures (GDI) should be built and made available to experts in the field

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