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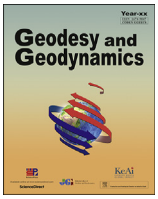

Influencing factors on the accuracy of local geoid model

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ABSTRACT

Different modification methods and software programs were developed to obtain accurate local geoid models in the past two decades. The quantitative effect of the main factors on the accuracy of local geoid modeling is still ambiguous and has not been clearly diagnosed yet. This study presents efforts to find the most influential factors on the accuracy of the local geoid model, as well as the amount of each factor's effect quantitatively. The methodology covers extracting the quantitative characteristics of 16 articles regarding local geoid models of different countries. The Statistical Package of Social Sciences (SPSS) software formulated a strong multiple regression model of correlation coefficient $r = 0.999$ with a high significance coefficient of determination $R^2 = 0.997$ and adjusted $R^2 = 0.98$ for the required effective factors. Then, factor analysis is utilized to extract the dominant factors which include: accuracy of gravity data (40%), the density of gravity data (25%) (total gravity factors is 65%), the Digital Elevation Model (DEM) resolution (16%), the accuracy of GPS/leveling points (10%) and the area of the terrain of the country/state under the study (9%). These results of this study will assist in developing more accurate local geoid models.

1. Introduction

The geoid is a level surface, which is defined as a closed equi-geopotential surface of the Earth's gravity nearest to the Mean Sea Level (MSL). Determination of the geoid or a local geoid model is crucial in establishing vertical height control after the widespread use of modern GNSS techniques in surveying [1,2].

Determining the orthometric height of the Earth's surface depends on leveling and gravimetry. Whereas, the error in such measurements increases with the length of the leveling net. It is almost impossible to achieve centimeter-level accuracy, especially in mountainous areas [3]. Furthermore, terrestrial leveling process consumes more cost and time especially in rough and mountainous areas [4]. In this case, GNSS replaces the classical spirit leveling by satellite techniques and eliminates physical and instrumental errors in spirit leveling, but the latter produces significant error for long distances of more than 40 cm in a route of about 300 km. This error is due to the non-parallelism of equipotential surfaces affecting the local vertical axes deviated in reality [5,6].

If one can obtain (by proper computation) the geoidal height N (the height above or below the reference ellipsoid) for any required point of a terrain using a model, then the model is termed a geoid model. Consequently, the development of different methodologies for computing this model is known as geoid modeling [5,7,8]. Geoid modeling is regarded as the most challenging topic in geodesy which has encouraged researchers to use different methodologies since 1980 [9]. Stokes' formula provides the possibility to determine the geoid and the geoid heights N from gravity data [10]. It

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means that the shape and size of a geoid can be determined indirectly by gravity measurements [8].

Computing geoid from Stokes' formula needs to know the density of masses at every point between the ground and the geoid. However, this is theoretically impossible, and therefore some assumptions for the density anomaly issue must be made. Whereas, the influences of these assumptions are so small in which Molodenskiĭ in 1945 was able to prove that the determination of the earth could be done using geodetic measurements alone without density of the crust. Certainly, this requires the concept of the geoid be abandoned. The gravity anomalies now refer to the ground, and no longer to sea level [11].

Geoid modeling based on gravity anomalies as one of a basic data. Free-air anomaly depends on the topography due to the attraction itself affected by topographic masses. It can be computed for every points on the terrain based on the absolute gravity of observed point or the station after applying the gravity correction and the theoretical gravity value of the same observed point which is determined by Clairut's formula as well as the free-air correction [11,12].

Basically, geoid modeling is the third boundary problem of the potential theory [11]. Stokes' (1849) and Molodenskiĭ's (1962) methods are two classical geoid methods for providing Boundary-Value Problem (BVP) solutions for computing the geoid and the quasi-geoid respectively [13]. Now-a-days, the gravity anomalies can be computed via the Global Geopotential Model (GGM), in which the Stokes' kernel function makes the geoid modeling for remote areas with sparse gravity data also possible [14]. Researchers developed three different software programs during the past two decades for geoid model computation. These well-known software programs include SHGEO, GRAVSOFT and KTH GEOLAB which have so far been used widely for computing various local geoids all over the world [7].

The key problem lies in the absence of knowledge about the quantitative contribution effectiveness of factors, including input data set to the geoid modeling software in achieving precise global or local geoid modeling. Generally, geodesists try to consider the numerical effect of extracted limited numbers from many variables in the local geoid modeling separately. This allows researchers to pay attention to these effective variables to achieve better accuracy for the local geoid model.

2. Data

Different datasets were extracted from 16 reviewed local geoid model articles which were developed all over the world. Some of these data are utilized as an input to the software programs of the geoid modeling, and the others are utilized as the spatial description of the area where the local geoid model is developed for it (see Table 1). The detail data can be summarized as follows:

2.1. Gravity data

Gravity measurements are regarded to be essential to compute free-air anomaly for the geoid modeling. It can be measured directly on land (terrestrial), from the air (air-borne), at sea (ship-borne) and on satellites (space-borne) [28].

2.2. DTM or DEM

Digital Terrain Model (DTM) or Digital Elevation Model (DEM) is required in gravity reductions to correct it from terrain effects and in gravity interpolation/prediction to smooth the gravity field. The spherical grid resolution of DTM or DEM indicates its accuracy, for instance the common spatial resolution used for geoid

Table 1
Summary of extracted datasets and extra variables from the reviewed articles of local geoid models.

Geoid No.	Country/State[a]	Geoid methodology	Year	Geoid accuracy (RMSE)[b] (cm)	Area of the country/ state (km^2)	No. of terrestrial gravity points	Gravity accuracy (mGal)	Gravity density (km^2/1 Gravity pt)	DEM or DTM resolution[c] (m^2)	No. of GPS/ leveling points	GPS density (km^2/1 GPS pt)	Accuracy of GPS pts (cm)	Longitude 1 (degree)	Longitude 2 (degree)	Latitude 1 (degree)	Latitude 2 (degree)	Difference in longitude (degree)	Difference in latitude (degree)
1	France/Auvergne [15]	SH	2017	3.3	26,013	243,889	1.5	0.1	8586	75	347	1.5	43	49	−1	7	6	8
2	Poland [16]	KTH	2016	2.2	312,679	1,000,000	0.05	0.3	8586	98	3191	1.0	14	24	49	55	10	6
3	Argentina [17]	RCR-FFT	2016	25.0	2,780,400	180,000	25	15.4	8586	1891	1470	14.0	−76	−52	−57	−20	24	37
4	Ghana [18]	SH	2015	49.7	239,567	9964	0.2	24.0	8586	13	18,428	25.0	−4	2	4	12	6	8
5	Brazil/Sao Paulo [19]	RCR-FFT	2014	24.5	248,223	46,290	0.1	5.4	8586	363	684	6.0	−54	−44	−26	−19	10	7
6	Brazil/Sao Paulo [19]	RCR-LSC	2014	28.0	248,223	46,290	0.1	5.4	8586	363	684	6.0	−54	−44	−26	−19	10	7
7	Malaysia/Peninsular [20]	KTH	2014	32.1	130,590	3224	20	40.5	8586	70	1866	6.0	100	104.5	0	7.5	4.5	7.5
8	Turkey/Konya Closed Basin [14]	KTH	2012	6.7	59,000	3073	7	19.2	8586	20	2950	3.0	31.5	35	37	39	3.5	2
9	Turkey/Konya Closed Basin [14]	RCR-FFT	2012	9.8	59,000	3073	7	19.2	8586	20	2950	3.0	31.5	35	37	39	3.5	2
10	Turkey/Konya Closed Basin [21]	KTH	2012	6.4	59,000	2681	7	22.0	8586	20	2950	3.6	31.5	34.5	37	39	3	2
11	South Korea [22]	RCR-FFT	2012	5.4	100,032	14,287	0.224	7.0	8586	1096	91	3.0	125	129.5	34.5	38.5	4.5	4
12	Tanzania [23]	KTH	2009	27.8	945,087	39,677	6.7	23.8	8586	19	49,741	10.0	26	44	−15	4	18	19
13	New Zealand [24]	RCR-FFT	2007	8.1	267,710	40,737	0.3	6.6	3091	1422	188	14.0	176.5	178	−46.6	−35.2	1.5	11.4
14	Argentina [25]	RCR-FFT	2007	20.7	2,780,400	164,125	0.15	16.9	8586	393	7075	5.0	−75	−53	−56	−21	22	35
15	Jordan [26]	RCR-FFT	2007	40.0	87,000	2994	2	29.1	8586	55	1582	3.0	35	39	29	33	4	4
16	Hungary [27]	RCR-FFT	2000	4.4	93,030	120,000	0.1	0.8	1,431,055	308	302	2.0	45.5	49	16	23	3.5	7

[a] The local geoids are sorting from the newest to the oldest based on the reference numbers which are illustrated beside the name of countries.
[b] Root Mean Square Error (RMSE).
[c] Digital Elevation Model (DEM). Digital Terrain Model (DTM).

modeling is 3″ × 3″ (equivalent to 8586 m^2 on the ground) (see Table 1).

2.3. GPS/leveling points

The geoid model is affected by the number of the GPS/leveling point, its density and the accuracy measurement of both orthometric (H) and ellipsoidal height (h) for calculating the geometric geoidal heights (N). The values of GPS/leveling points are used for validating the geoid model. It gives the geometric difference of N by subtracting both orthometric and ellipsoidal height. Whereas the geoid model provides the computed geoid. The amount of error of N of each GPS/leveling point will be known via subtracting the N and the computed N. Then the overall accuracy of the local geoid model can be obtained via computing the Root Mean Square Error (RMSE) of all GPS/leveling points in the area under study (see Table 1).

2.4. Additional spatial data

Extra variables are taken into account other than the required data set for the geoid modeling process. These additional data are related mainly to the spatial characteristics of the area under study which may affect the accuracy of the local geoid model, such as the geographical location of the study area to demonstrate its boundary in terms of latitudes and longitudes. Also the total area of the country or the part of the country under the study is another factor to compute the density of both gravity data and GPS/leveling points inside or/and adjacent to the study area (see Table 1).

3. Methods

The methods in which they utilized for computing the local geoid models in the reviewed articles will be discussed in brief. Moreover, the analytical methods of this study include both multiple linear regression and the factor analysis will also be described.

3.1. Methods of computing local geoid model

Accuracy of the dataset input to the geoid model software directly affects the accuracy of the geoid model. Other crucial factors influencing the accuracy are considered to be: merging different data sources, different assumptions and different computation methods respectively [15].

Depending on the geoid model theories, three different methods have been developed by three universities. First of all, Remove-Compute-Restore (RCR) method was developed by the University of Copenhagen, Denmark. This methodology was established by Forsberg (1985), Dahl and Forsberg (1999) and Yildiz et al. (2012), which computed the quasi-geoid. This method used Fast Fourier Transform (FFT) or Least Squares Collocation (LSC) to solve the Stokes' integral. Secondly, Stokes-Helmert (SH) method was developed by the University of New Brunswick (UNB), Canada. This methodology was based on the methodology of the Stokes-Helmert's methods for the computation of geoid, which was briefly described by Tenzer et al. (2003), Ellmann and Vaníček (2007) and Vaníček et al. (2013). Thirdly, Least Squares Modification of Stokes Formula with Additive Correction (LSMSA) or Royal Institute of Technology (KTH) method was developed by Sjoberg (2001, 2003) [7].

Recently, the Shen method (2006) or shallow-layer method (Shen et al., 2013) of global geoid determination has been proposed, which is quite different from the aforementioned methodologies. In the Shen method, instead of solving boundary problem of the Stokes' integral or the Molodenskiĭ's integral, it reduces the problem to determine the gravitational potential on the geoid, since the centrifugal potential is known [3,12]. Table 2 shows the summary of all geoid computation methods used as well as the Shen method which is not interested in using the terrestrial gravity data in the geoid modeling.

3.2. Multiple linear regression model and factor analysis

The regression analysis assists to delineate the most associated variable(s) (x) related to their effectiveness on the accuracy of the local geoid models (y) through the multiple regression model (see Eq. (1)). However, the correlation coefficient (r) tells if relationship between two variables is very strong or very weak, its value between −1 and 1. The closer r to 1 or −1 the stronger relationship between two variables directly or inversely [29].

Indeed, the coefficient of determination is known as R squared (R^2) which is also used as a measure of how well the regression equation actually describes the relationship between the dependent variable (y) and the independent variable(s) (x). R^2 always takes on a value between 0 and 1. The closer R^2 is to 1, the better estimated regression equation fits or explains the relationship between x and y. Whereas, the adjusted coefficient of determination (also called adjusted R^2) is used instead of the R^2 because it dislikes R^2 increasing only when you add new independent variable(s) that do increase the explanatory of the regression line [30].

Moreover, factor analysis can reduce a large number of detected variables via a multiple regression model to a smaller number of statistically unrelated variables. Therefore, the most effective variable(s) are separated by the factor analysis to achieve the research objective. The advantage of the factor analysis lies in that it can extract few dependent variables from many variables ($x_1, x_2, \ldots, x_k$). Finally it gives numerical value (percentages) for each variable which represents its potential of variability on the dependent variable (y) that represents the accuracy of local geoid model in this research [31,32].

$$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon \quad (1)$$

Table 2
Summary of the geoid modeling methods and software programs.

No.	Name of methodology	University producer	Country	Methodology
1	Remove- Compute-Restore (RCR)	Copenhagen	Denmark	Fast Fourier Transform (FFT) or Least Squares Collocation (LSC)
2	Stokes- Helmert (SH)	New Brunswick (UNB)	Canada	Stokes- Helmert (SH)
3	KTH	Royal Institute of Technology, Division of Geodesy, KTH	Sweden	Least Squares Modification of Stokes Formula with Additive Correction (LSMSA)
4	Shen	Wuhan University	China	Shallow-Layer

where,

y: dependent variable
$x_1, ..., x_k$: independent variables
$\alpha, \beta_1, \ldots, \beta_k$: parameters of the regression model
ε: error estimates of the regression model.

4. Results and discussion

This study analyzed 16 local geoid model articles all over the world. The datasets and extra variables are summarized in Table 1 and then they are processed in this study. Each derived model used one or two different methodologies named RCR, SH and KTH respectively. Generally, the utilization of the methods for computing the local geoid models of the reviewed articles were as follows: 2 (13%) SH, 5 (31%) KTH and 9 (56%) RCR.

Both articles of Abbak et al. (2012a,b) show the accuracy of KTH methodology in geoid modeling compared to FFT methodology. The amount of improvement in the geoid model using the KTH method was 3.4 cm for the mountainous area, in which the area is characterized by sparse and limited gravity data [14,21] (see Table 1).

Multiple linear regression analysis is used in this study via Statistical Package for Social Sciences (SPSS) software because it has an easy access for repetitions and trials in selecting the effective independent variable(s) [33]. Accordingly, the accuracy amount of the geoid model is the dependent variable (y). Whereas, the independent variable(s) (x) are 13 variables represented by ($x_1, x_2, \ldots, x_{13}$) which include: area of the country/state under the study (x_1), number of gravity points (x_2), gravity accuracy (x_3), density of the gravity points (x_4), DEM resolution (x_5), number of the GPS/leveling points (x_6), density of the GPS/leveling points (x_7), accuracy of the GPS/leveling points (x_8) The remaining variables from (x_9) to (x_{13}) are related to the geographical coordinates of the country/state in terms of lower and upper limits of longitudes and latitudes (x_9, x_{10}, x_{11}) combined with difference in longitudes and latitudes (x_{12}, x_{13}).

In order to obtain the best multiple regression model, several trials have been made via SPSS software to process the extracted datasets of 16 local geoid models as shown in Table 1. Therefore, a very strong correlation coefficient (r close to 1) of $r = 0.999$ and a very good coefficient of determination (R^2 close to 1) of $R^2 = 0.997$ as well as a very good adjusted $R^2 = 0.98$ can be obtained. Furthermore, there are good F-test results of the Analysis of Variance (ANOVA) being $F = 53.594$ and $p = 0.018$. This means that the regression model has a good potential to interpret 98% (close to 100%) of the variation influencing the geoid accuracy and it has a high significance prediction ability because the p-value of 0.018 which is less than 0.05. Indeed, all coefficients of the regression model are significant because their p-values are less than 0.05 (see Table 3, Table 4, Table 5 and Appendix, Table A1).

Table 3
Variables entered/removed.

Variables entered	Variables removed	Method
area of the country/state, number of the gravity points, density of the gravity points, accuracy of the gravity points, DEM resolution, number of the GPS/leveling points, density of the GPS/leveling points, accuracy of the GPS/leveling points, upper limit of longitude, lower limit of the latitude, upper limit of the latitude, difference in longitude, difference in latitude		enter

Table 4
The formulated multiple linear regression model from the reviewed goeid model datasets.

Model	r	R^2	Adjusted R^2	Std. error of the estimate	Durbin–Watson
1	0.999	0.997	0.979	2.1570	3.000

Table 5
The ANOVA of the multiple linear regression model.

Model	Sum of squares	df	Mean square	F	Significance (Sig.)
Regression	3241.514	13	249.347	53.594	0.018
Residual	9.305	2	4.652		
Total	3250.819	15			

5. Factor analysis

Factor analysis helps to reduce and determine the number and the amount of the most effective variables which have the variation effects on the accuracy of the local geoid model. The Kaiser-Meyer-Olkin (KMO) and Bartlett's test shows the suitability of the sample size (n = 16) of the reviewed geoid models. This evidence is shown through the value of 0.477 which is close to 0.5 as shown in Table 6.

The SPSS software extracts 7 variables with good correlations (see the Rotated Component Matrix Table in the Appendix, Table A1) and 3 sorts of the most effective variables. The amount of dominant variability on the geoid model of impact 81%, which include accuracy of gravity points (40%), density of the gravity points (25%) and DEM resolution (16%). Whereas, the remaining two variables have an influence of about 19%, which include accuracy of GPS/leveling points (10%) and area of the terrain under the study (9%) (see Table 7, Fig. 1 and Appendix, Table A1).

6. Conclusions

The research demonstrates that the accuracy of the local geoid model is influenced more by the gravity data especially its number, well spatial distribution and the accuracy. On the other hand, the DEM is another factor besides the gravity data as well as the GPS/leveling points for validating the geoid model and the area under the study. The area under study also has its effect on the accuracy of the geoid model. This can be justified based on the distribution density of gravity data in the area of the terrain itself. As the geoid model software depends on gridding the area under study to interpolate the gravity data inside a geometric shape, more fine grids and more data are needed in order to achieve a more accurate geoid model. Another factor affecting the accuracy of the geoid model is the algorithm for computing via the geoid model methodology itself. The reviewed articles of Abbak et al. prove that the accuracy of the KTH method for the local geoid modeling is better than the FFT method. The amount of improvement in the geoid model using the KTH method was conducted to be 3.4 cm for the mountainous area, which is

Table 6
KMO and Bartlett's test.

KMO measure of sampling adequacy		0.477
Bartlett's test of sphericity	Approx. chi-Square	83.861
	df	21
	Sig.	0.000

Table 7
Total explained variance.

Component	Initial eigen values			Extraction sums of squared loadings			Rotation sums of squared loadings		
	Cumulative (%)	Variance (%)	Total	Cumulative (%)	Variance (%)	Total	Cumulative (%)	Variance (%)	Total
1	39.602	39.602	2.772	39.602	39.602	2.772	31.550	31.550	2.208
2	64.379	24.777	1.734	64.379	24.777	1.734	60.065	28.515	1.996
3	80.816	16.436	1.151	80.816	16.436	1.151	80.816	20.751	1.453
4	90.905	10.089	0.706						
5	99.441	8.536	0.598						
6	99.791	0.351	0.025						
7	100.000	0.209	0.015						

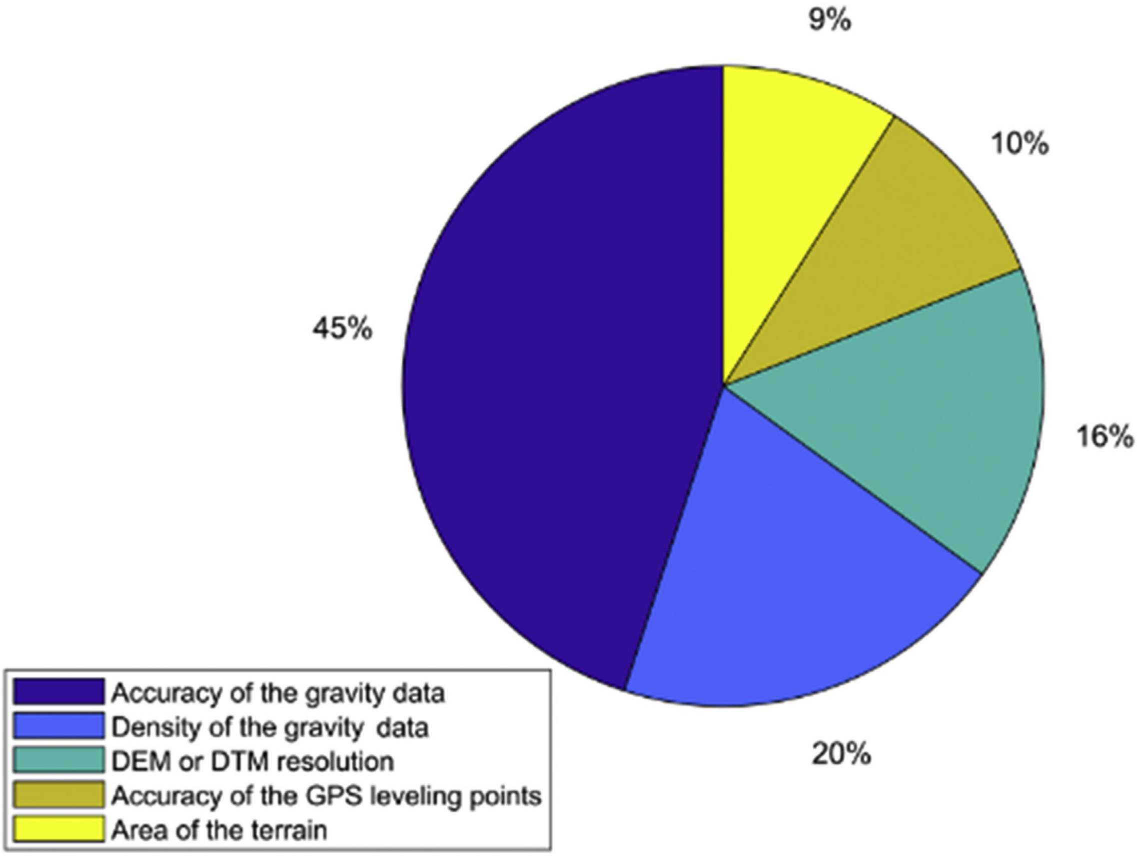

Fig. 1. The percentage of factors affecting the accuracy of local geoid model.

characterized by poor distribution and limited number of gravity data. In this case, the KTH method has the ability to develop a more accurate local geoid model compared to other methods because of well designed corrections which have been carried out via the software algorithm.

Conflicts of interest

The authors of this article declared that there is no any commercial or conflict of interest concerning this submitted work.

Appendix A

Table A1
Coefficients of the multiple linear regression model[1]

Model	Unstandardized coefficients		Standardized coefficients	t	Sig.
	B	Std. error	Beta		
(Constant)	187.779	16.604		11.309	0.008
Number of the gravity pts.	0.000	0.000	7.606	11.479	0.008
Area of country/state	0.000	0.000	12.175	11.135	0.008
Accuracy of the gravity pts.	−4.978	0.420	−2.543	−11.843	0.007
Density of the gravity pts.	−1999.759	160.820	−41.784	−12.435	0.006
DEM resolution	0.002	0.000	42.388	12.442	0.006
Number of the GPS/leveling pts.	0.060	0.007	2.329	8.297	0.014
Density of the GPS/leveling pts.	−0.003	0.000	−2.804	−12.545	0.006
Upper limit of longitude	1.140	0.090	5.046	12.736	0.006
Lower limit of latitude	−1.137	0.134	−2.766	−8.497	0.014
Upper limit of latitude	−2.786	0.243	−4.875	−11.468	0.008
Difference in longitude	35.859	2.646	17.468	13.553	0.005
Difference in latitude	−44.638	3.572	−32.500	−12.495	0.006
Accuracy of the GPS/leveling pts.	4.669	0.294	2.010	15.898	0.004

[1] Dependent variable: RMSE of the geoid model.

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