Journal of Geovisualization and Spatial Analysis (2022) 6:32
https://doi.org/10.1007/s41651-022-00128-8

Calculation and Analysis of Multi-scale Earth Gravity Field Parameters Based on Self-developed EIGEN-5C Model Software

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Accepted: 16 October 2022 / Published online: 2 November 2022
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Abstract

There are many calculation model schemes with practical value for calculating the critical parameters of the Earth's gravity field. However, the research work of systematically using the EIGEN-5C model for multi-scale inversion of the earth's gravity field needs to be supplemented. To solve the above problems, this study uses the 360-order EIGEN-5C model to calculate the four parameters of the Earth's gravity field: disturbance potential, geoid height, gravity anomaly, and gravity disturbance. This study first calculates the normalized-associated Legendre function, reads the coefficients of the EIGEN-5C gravity field model, then calculates the normal gravity and converts the geodetic coordinate system into the spherical coordinate system. On this basis, the spherical harmonic series expansion of the gravity field parameters is carried out. Through experiments, it is found that the calculation process introduced in this study can better calculate and express the critical parameters of the multi-scale Earth's gravity field. For the local scale, the researchers calculated from the experimental areas of low, medium, and high latitudes. For the global scale, the researchers also calculated the above indicators. The calculation results can sufficiently express the geophysical situation of the study area. Additionally, to better realize the above process, we creatively developed a set of software for calculating the parameters of the Earth's gravity field based on the EIGEN-5C model. The software can calculate all the above key parameters of gravity field, and realize the visual expression of the results. All in all, this study systematically explains using the EIGEN-5C model to carry out the inversion and result in the expression of multi-scale Earth's gravity field parameters. And our self-developed software has a certain reference value for the research field of geographic information mapping technology.

Keywords Earth gravity field · Disturbance potential · Geoid height · Gravity anomaly · Gravitational disturbance · EIGEN-5C · Geographic information

Introduction

Since 2000, the launch missions of CHAMP, GRACE, GOCE, and other Earth gravity satellites have been successfully implemented internationally. Chinese and foreign scholars have researched the Earth's gravity field model by gravity satellites. Relevant scholars believe that satellite gravity measurement is the basis of subsequent inversion of high-precision, high-spatial resolution Earth's gravity field, inversion of the global geomagnetic field, and prediction of global climate change (Zheng et al. 2010; Tingtao et al. 2020; Junyong 2006). Significant progress has been made in retrieving the earth's gravity field, and various institutions have released their global gravity field models. For example, the EIGEN series Champ-only model developed by the German Research Center for Geosciences Potsdam (GFZ) in Germany, GGM series GRACE-only models developed by the Center for Space Research (CSR) of the University of Texas in the USA (Tingtao et al. 2020). The early EIGEN-1, EIGEN-2, EIGEN-CHAMP03s, and other models are completely based on the observation data of the CHAMP satellite, with the lower highest order and rapid error accumulation speed. Because of the shortcomings of CHAMP's

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slight improvement in the accuracy and spatial resolution of gravity field models, the later EIGEN-GRACE01S and EIGEN-GRACE02S models were completely based on the observation data of the GRACE satellite. The maximum inversion order was increased to 150, which improved the accuracy of the model in the short wave stage. In contrast, the EIGEN-5C model combined the two gravity satellite data of GRACE and LAGEOS and was enhanced by ground observation data. The maximum order was increased to 360. The accuracy of the model has also been greatly improved. It is a good gravity field model; there are also other good models such as EGM2008, GOCO06, and EIGEN-6C.

The EIGEN-5C model is widely used in earthquake research, land hydrology, glacier ice cover research, and other fields and has achieved good results. The gravity gradient experiment of Johannes Bouman et al. (Bouman et al. 2011; Arabelos and Tscherning 1998) shows that EIGEN-5C has strong consistency with the current general ultra-high order gravity field model EGM2008 in the ocean but low consistency on the continent. On this basis, Alexandre Bernardino Lopes et al. (Lopes and Harari 2012) made an oceanographic evaluation of EIGEN-5C. Using this model and the EGM2008 model, the geostrophic current at the Brazil Malvinas junction was calculated, respectively. The results were similar to those of the numerical hydrodynamic model, which proved the consistency of the two models in large-scale aspects. Dimitrios Tsoulis et al. (Tsoulis and Papanikolaou 2013) used GOCE satellite orbit analysis to evaluate different gravity models. They found that EIGEN-5C has the smoothest root mean square change in the whole spectral range, proving the stability of the model. Christoph Förste et al. (Förste et al. 2011) improved the combination procedure of satellite and ground data because of the shortcomings of EIGEN-5C in the Andes, Africa, and the Himalayas due to the low quality of surface observation data and significant model errors.

Chinese scholars have also carried out many studies on the EIGEN-5C model. Zhang Chuanyin et al. (Chuanyin et al. 2009) tested the accuracy of the EIGEN-5C model in the Chinese mainland using GPS-measured elevation anomaly data. They found that the global accuracy of elevation anomaly was more than 50% lower than that of EGM2008, especially in western China. Lu Biao et al. (Lu et al. 2018) combined EIGEN-5C as a priori model and GOCE GGs signal to obtain a new gravity field model IGGT_ R1, which effectively improves the model accuracy in these areas. On this basis, Cai Lin et al. (Cai et al. 2021) developed a gravity field model called I3GG with EIGEN-5C as a priori model. It was verified that the average model value affected by noise was reduced by about 20%. The gravity field model has a smaller root mean square value than IGGT_R1 in all regions outside the Netherlands and has stronger consistency with EIGEN-5C in the whole-frequency range. Moreover, in recent years, other scholars have also explored and applied a series of gravity field models in different experimental areas on different gravity field models to analyze the local geophysical environment further and further elaborate on the research value of parameter inversion of the earth's gravity field model in many sub-fields (Shu et al. 2011; Yilmaz and Karaali 2011; Förste et al. 2014; Belay et al. 2022; Förste et al. 2012; Yuping 2018; Zhou et al. 2016; Meijde et al. 2013; Fielding and McKenzie 2012; Zhou et al. 2014; Li et al. 2014).

Although significant progress has been made in the inversion of the earth's gravity field, there is still some research space for understanding the gravity field and its application at different scales. And intelligent supporting software for the calculation of Earth's gravity field parameters needs to be developed. Therefore, it is necessary to explore the feasibility of the calculation results of the gravity field model at different scales and further use the software to make a geographic information map containing the key earth's gravity field parameters. Among them, for the EIGEN-5C gravity field model used in this paper, how to give a complete set of calculation flow and calculation software in different scales and different research areas so that it can better analyze and calculate the critical parameters of the Earth's gravity field in the area to be studied, the research on the above content is still insufficient. The critical parameters of the earth's gravity field mentioned above mainly include disturbance potential, geoid height, gravity anomaly, gravity disturbance, and other vital parameters, which will be discussed in our research. Therefore, this study will discuss the above problems.

The objectives of this study are as follows:

(1) Aiming at the EIGEN-5C gravity field model, this study introduces the download platform of the model in the second part.
(2) Quantitatively describes the gravity field inversion algorithm based on the model and gives the detailed implementation process.
(3) Explains several critical parameters of the gravity field to be calculated and their quantitative expressions.

On this basis, a program that can stably calculate the gravity field parameters of different regional scales at 360-order is written. In the third part, this paper introduces the results of the calculation of the critical parameters of the gravity field using the method and software proposed in this paper at different scales and makes some geographic information maps containing those parameters. The fourth part is the summary and outlook of the full text.

Calculation Method of Gravity Field Inversion Based on EIGEN-5C Model

Algorithm Flow

The algorithm flow we designed is shown in Fig. 1. First, download the EIGEN-5C gravity field model file in the international Global Earth Model Center (ICGEM, http://icgem.gfz-potsdam.de/tom_longtime). After spherical harmonic expansion, the key parameters of gravity field can be expressed by fully normalized coefficients, Legendre series, normal gravity, and other parameters. The EIGEN-5C Earth gravity field model can provide basic data for the calculation of these parameters, such as normalized coefficient and orders.

In particular, the reason why EIGEN-5C is used instead of other models is that researchers intend to realize the visualization process from the Earth gravity field file to the Earth gravity field parameters through software, while EIGEN-5C is only used as the data basis.

Prepare the data:

(1) Recursively calculate the normalized Legendre function value corresponding to each series expansion.
(2) Normalize the gravity field coefficient.
(3) Calculate the normal gravity at each latitude (the global-scale resolution is 1°, and the regional scale resolution is 5′).
(4) Convert the geodetic coordinates into the spherical coordinate system.
(5) Substitute these data into the spherical harmonic series expansion of the gravity field parameters for the calculation.
(6) Finally, map and display the gravity field parameter data for analysis at each longitude and latitude.

Method and Implementation

Calculation of Normalized-associated Legendre Function

In order to calculate the spherical harmonic series of the gravity parameters of the Earth's gravity field, the normalized-associated Legendre function value corresponding to each series expansion is required first. In this experiment, the standard forward recursion method is used to calculate the value of Legendre function. The basic calculation formula is as follows:

$$\begin{aligned} \overline{P}_{00}(\cos\theta) &= 1 \\ \overline{P}_{10}(\cos\theta) &= \sqrt{3}(\cos\theta) \\ \overline{P}_{11}(\cos\theta) &= \sqrt{3}(\sin\theta) \end{aligned} \tag{1}$$

Then, according to the standard, the Legendre function value of the series expansion of any term is recursively derived from the forward column (in formula (2): "n ≥ 2" and "n > m"; in formula (3): "m ≥ 2"):

$$\overline{P}_{nm}(\cos\theta) = a_{nm}\cos\theta\overline{P}_{n-1,m}(\cos\theta) - b_{nm}\overline{P}_{n-2,m}(\cos\theta) \tag{2}$$

$$\overline{P}_{mm}(\cos\theta) = c_{nm}\sin\theta\overline{P}_{m-1,m-1}(\cos\vartheta) \tag{3}$$

Among them:

$$a_{nm} = \sqrt{\frac{(2n-1)(2n+1)}{(n+m)(n-m)}} \tag{4}$$

$$b_{nm} = \sqrt{\frac{(2n+1)(n+m)(n-m-1)}{(n-m)(n+m)(2n-3)}} \tag{5}$$

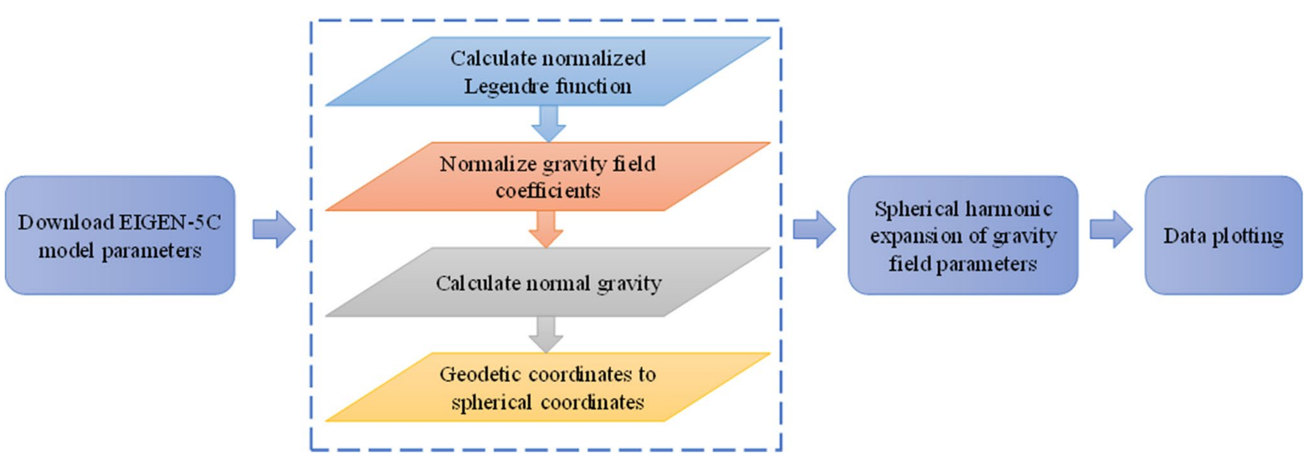


Fig. 1 Algorithm flow diagram

$$c_{nm} = \sqrt{\frac{2m+1}{2m}} \tag{6}$$

The pseudo-code table of the above algorithm flow is shown in Table 1.

Read EIGEN-5C Gravity Field Model Coefficient

In order to obtain the parameters of the gravity field through spherical harmonic series, we also need to know and normalize the gravity field model coefficients $\overline{c}_{nm}$、 $\overline{s}_{nm}$. Each line of the EIGEN-5C model file indicates in turn: n、 m、 $\overline{c}_{nm}$、 $\overline{s}_{nm}$、 $\delta\overline{c}_{nm}$、 $\delta\overline{s}_{nm}$. In addition, it is necessary to correct the moment of inertia of the coefficient according to the ellipsoid parameters. GRS80 ellipsoid is used in this experiment, and the first four terms are just enough to meet the calculation accuracy. The correction formula is as follows:

$$\overline{C}_{nm}^{T} = -\overline{C}_{nm} - \overline{C}_{nm}^{U} \tag{7}$$

$$\overline{S}_{nm}^{T} = -\overline{S}_{nm} \tag{8}$$

$$\overline{C}_{2n,0}^{U} = \overline{C}_{2n}^{U} = -\frac{J_{2n}}{\sqrt{(2(2n)+1)}} \tag{9}$$

The pseudo-code table of the above algorithm flow is shown in Table 2.

Table 2 Read EIGEN-5C gravity field model coefficient

Step number	Step description
Step1	Create a class to read the EIGEN-5C txt file *read.ReadFile_CS(file_path);*
Step2	Read the coefficients of lines 2, 4, 6, and 8, respectively *string line = reader.ReadLine();* *Cnm = double.Parse(line.Substring());*
Step3	Read the normal gravitational potential coefficient of the GRS80 ellipsoid *float J2,J4,J6,J8;* *read.ReadEllipsoid(out J2,out J4,out J6,out J8);*
Step4	Perform the following step to the first four line *C20 = C20 + J2/sqrt(5);* …… *C80 = C80 + J8/sqrt(17);*

Calculate Normal Gravity γ_Q

To calculate the gravity anomaly $\Delta g(r, \theta, \lambda)$, the normal gravity at each latitude is also required, and the calculation formula is as follows:

$$\begin{cases} \gamma_a = \frac{GM}{ab}\left(1 - m - \frac{m}{6}\frac{e' q'}{q_0}\right) \\ q_0 = \frac{1}{2}\left(\left(1 + 3\frac{b^2}{E^2}\right)\tan^{-1}\frac{E}{b} - 3\frac{b}{E}\right) \end{cases} \tag{10}$$

$$\begin{cases} \gamma_b = \frac{GM}{a^2}\left(1 + \frac{me' q_0'}{3q_0}\right) \\ q_0' = 3\left(1 + \frac{b^2}{E^2}\right)\left(1 - \frac{u}{E}\tan^{-1}\frac{b}{E}\right) - 1 \end{cases} \tag{11}$$

Normal gravity at any point on the ellipsoid:

$$\gamma_Q = \frac{a\gamma_a\cos^2\varphi + b\gamma_b\sin^2\varphi}{\sqrt{a^2\cos^2\varphi + b^2\sin^2\varphi}} \tag{12}$$

Among them, φ is the geodetic latitude.

Table 1 Calculation of normalized Legendre function

Step number	Step description
Step1	Calculating the initial value of the Legendre function *cal.initial_value(theta, out P[0,0], out P[1,1], out P[1,0]);*
Step2	When m is less than n, if m of Legendre function is less than or equal to n-2, perform the following step *cal.P_nm(theta, l, m, P[n-1,m],P[n-2,m],out P[n, m]);*
Step3	When m is less than n, if m of Legendre function is greater than n-2, perform the following step *cal.P_nm(theta, n, m, P[n-1,m], 0, out P[n, m]);*
Step4	If m of Legendre function is equal to n, perform the following step *cal.P_mm(m, theta, P[n-1,m-1], out P[m, m]);*
Step5	Implement cal.P_mm function *float c = sqrt(2 m + 1)/sqrt(2 m);* *return P_mm = sin(theta)*c*P[n-1,n-1];*
Step6	Implement cal.P_nm function *float a = sqrt(4n*(n-1))/sqrt(n*n-m*m);* *float b = sqrt((2n + 1)*(n + m-1)*(n-m-1))/sqrt((2n-3)*(n + m)*(n-m));* *return P_nm = a*cos(theta)*P[n-1,m] – b*P[n-2,m];*

Table 3 Calculation of the normal gravity

Step number	Step description
Step1	Read GRS80 ellipsoid parameters *float omega, a, b, GM, γa, γb;* *read.ReadEllipsoid(out omega, out a, out b, out GM, out γa, out γb);*
Step2	Cycle the latitude according to the resolution and calculate the normal gravity *for (double B = B1; B < = B2; B + = resl)* *{ γQ = cal.γ(B, omega, GM, a, b,γa,γb)};*

The pseudo-code table of the above algorithm flow is shown in Table 3.

Convert Geodetic Coordinate System BLH to Spherical Coordinate System $r\theta\lambda$

The spherical harmonic series expansion of gravity field parameters is completed in the spherical coordinate system, while the data of EIGEN-5C is given in the geodetic coordinate system, so it is necessary to convert the geodetic coordinate system into the spherical coordinate system, and the conversion formula is as follows:

$$W = \sqrt{1 - e^2 \sin\varphi^2} \tag{13}$$

$$N = \frac{a}{W} \tag{14}$$

$$\begin{cases} X = (N + H)\cos\varphi\cos L \\ Y = (N + H)\cos\varphi\sin L \\ Z = \left(N\left(1 - e^2\right) + H\right)\sin\varphi \end{cases} \tag{15}$$

$$\begin{cases} r = \sqrt{X^2 + Y^2 + Z^2} \\ \theta = \arctan \frac{\sqrt{X^2+Y^2}}{Z} \\ \lambda = \arctan \frac{Y}{X} \end{cases} \tag{16}$$

The pseudo-code table of the above algorithm flow is shown in Table 4.

Spherical Harmonic Series Expansion Calculation of Gravity Field Parameters

In order to simplify the calculation in geodesy, we need to change the parameters of the Earth's gravity field into the form of spherical harmonic function. The spherical harmonic expansion of each gravity field parameter is as follows:

$$T(r,\theta,\lambda) = \frac{GM}{r}\left\{\sum_{n=2}^{N}\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}\left[\left(\overline{C}_{nm}^T \cos(\mathrm{m}\lambda) + \overline{S}_{nm}^T \sin(\mathrm{m}\lambda)\right)\overline{P}_{nm}(\cos\theta)\right]\right\} \tag{17}$$

Table 4 Convert geodetic coordinate system to spherical coordinate system

Step number	Step description
Step1	Read ellipsoid parameters and geodetic coordinates *float a,e2;* *read.ReadEllipsoid(a, e2);*
Step2	Read out the coefficients of lines 2, 4, 6 and 8 respectively *string line = reader.ReadLine();* *Cnm = double.Parse(line.Substring());*
Step3	Read the normal gravitational potential coefficient of the GRS80 ellipsoid *float J2,J4,J6,J8;* *read.ReadEllipsoid(out J2, out J4, out J6, out J8);*
Step4	Perform the following step to the first four line *C20 = C20 + J2/sqrt(5);* …… *C80 = C80 + J8/sqrt(17);*

$$N(r,\theta,\lambda) = \frac{GM}{r\gamma_Q}\left\{\sum_{n=2}^{N}\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}\left[\left(\overline{C}_{nm}^T \cos(\mathrm{m}\lambda) + \overline{S}_{nm}^T \sin(\mathrm{m}\lambda)\right)\overline{P}_{nm}(\cos\theta)\right]\right\} \tag{18}$$

$$\Delta g(r,\theta,\lambda) = \frac{GM}{r^2}\left\{\sum_{n=2}^{N}(n-1)\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}\left[\left(\overline{C}_{nm}^T \cos(\mathrm{m}\lambda) + \overline{S}_{nm}^T \sin(\mathrm{m}\lambda)\right)\overline{P}_{nm}(\cos\theta)\right]\right\} \tag{19}$$

$$\delta q(r,\theta,\lambda) = \frac{GM}{r^2}\left\{\sum_{n=2}^{N}(n-1)\left(\frac{a}{r}\right)^n \sum_{m=0}^{n}\left[\left(\overline{C}_{nm}^T \cos(\mathrm{m}\lambda) + \overline{S}_{nm}^T \sin(\mathrm{m}\lambda)\right)\overline{P}_{nm}(\cos\theta)\right]\right\} \tag{20}$$

Among them, T stands for disturbance potential, N stands for geoid height, Δg stands for gravity anomaly, δg stands for gravity anomaly. GM, a, and other parameters in the formula can be obtained from the reference ellipsoid GRS80. And their common parameters are shown in Table 5.

The pseudo-code table of the above algorithm flow is shown in Table 6.

Key parameters of Gravity Field

Disturbance Potential

To accurately obtain the Earth's gravitational potential W, we need to know the shape of the Earth's surface and the internal density distribution. The shape of the Earth's surface is what we want to study, and its internal density distribution is also irregular, so we cannot directly obtain the earth's gravitational potential.

In order to study the gravity potential, an approximate gravity potential can be introduced. Its functional relationship is straightforward and close to the real geopotential, which is called the normal geopotential and represented by the symbol U. We call the slight difference between the real gravity potential W and the normal gravity potential U the disturbance potential, which is represented by the symbol T, and its definition formula is as follows:

Table 5 GRS80 ellipsoid parameters

GRS 1980-derived constants	Values
a	6,378,137 m
b	6,356,752.3141 m
GM	$3{,}986{,}005 \times 10^{8} m^{3} s^{-2}$
J2	$1082{,}63 \times 10^{8}$
J4	-2.371×10^{-6}
J6	6.083×10^{-9}
J8	1.427×10^{-11}
e^2	6.694×10^{-3}

Table 6 Spherical harmonic series expansion calculation of gravity field parameters

Step number	Step description
Step1	Calculation of the disturbance potential *T* *cal.T(r, θ, λ, P[n,m], C[n,m], S[n,m], GM, a);*
Step2	Calculation of the geoid height N *cal.N(r, θ, λ, P[n,m], C[n,m], S[n,m], GM, a, γQ);*
Step3	Calculation of the gravity anomaly *Δg* *cal.delta_g(r, θ, λ, P[n,m], C[n,m], S[n,m], GM, a);*
Step4	Calculation of the gravity disturbance δ_g *cal.sigma_g(r, θ, λ, P[n,m], C[n,m], S[n,m], GM, a)*
Step5	Traverse each longitude and latitude grid point to calculate gravity field parameters *for(double B=B1;B<=B2;B+=resl)* *{ for(double L=L1;L<=L2;L+=resl)* *{T=cal.T(r, θ, λ,P[n,m], C[n,m], S[n,m], GM, a);* *N=cal.N(r, θ, λ, P[n,m], C[n,m], S[n,m], GM, a, γQ);* *delta_g=cal.delta_g(r, θ, λ, P[n,m], C[n,m], S[n,m], GM, a);* *sigma_g=cal.sigma_g(r, θ, λ, P[n,m], C[n,m], S[n,m], GM, a);}}*
Step6	Write calculation results to txt file *StreamWriter sw=new StreamWriter("..\\save.txt");* *sw.Write(str);* *sw.Close();*

$$T = W - U \tag{21}$$

Since the disturbance potential is a small quantity, the existence of its solution can be guaranteed. Therefore, the solution of the Earth's gravity field can be simplified as the solution of the disturbance field.

Geoid Height

The positional relationship between the geoid and the reference ellipsoid is shown in Fig. 2. Suppose a point *P* on the geoid is projected along the normal *n′* of the reference ellipsoid to point *Q* on the ellipsoid. In that case, the distance of *PQ* is called the geoid height, also known as geoid fluctuation, and is represented by the symbol *N*.

According to Bruns formula, there is also a relationship between geoid height, disturbance potential, and normal gravity:

$$N = \frac{T}{\gamma} \tag{22}$$

Gravity Anomaly

The difference between gravity vector g_p of point *P* on geoid and the normal gravity vector γ_Q of point *Q* on the reference ellipsoid is called gravity anomaly vector, and the size of this vector is called gravity anomaly, which is defined as follows:

$$\Delta g = g_p - \gamma_Q \tag{23}$$

According to the different objects considered, the gravity anomaly can be divided into simple-Bouguer gravity anomaly, Bouguer gravity anomaly, and Faye's gravity anomaly. In practical operation, the gravity anomaly can be used to reduce the measured gravity observation value on the ground to the geoid through gravity reduction, and then the shape of the geoid can be determined by using Stokes integral model.

Gravity Disturbance

On the same point *P* of geoid, the difference between gravity vector g_p and normal gravity vector γ_P is called gravity disturbance vector, and the size of this vector is called gravity disturbance, which is defined as follows:

$$\Delta g = g_p - \gamma_p \tag{24}$$

The gravitational disturbance can also be expressed as a function of the disturbance potential:

$$\Delta g = g_p - \gamma_p = -\left(\frac{\partial W}{\partial n} - \frac{\partial U}{\partial n'}\right) \approx -\left(\frac{\partial W}{\partial n} - \frac{\partial UU}{\partial n}\right) = -\frac{\partial T}{\partial n} \tag{25}$$

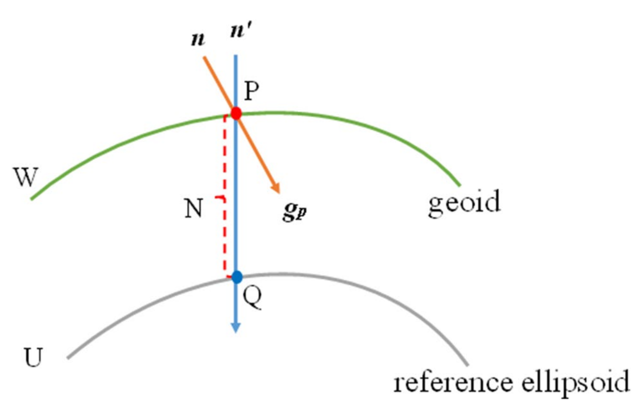


Fig. 2 Geoid and reference ellipsoid

Experiment and Verification

Self-developed Software Introduction

In this study, we use the self-developed software to calculate the parameters of the Earth's gravity field in the following areas (shown in Fig. 5). The program chart is shown in Fig. 3.

The program mainly includes four function classes:

(1) *Read.cs* Class: read EIGEN-5C data file, and return the coefficients Cnm, Snm of the spherical harmonic function.
(2) *Calculator.cs* Class: it includes functions for calculating the parameters of the earth's gravity field and functions for coordinate system transformation. In this part, T function realizes the calculation of disturbance potential; N function realizes the calculation of geoid height; Δg function realizes the calculation of gravity anomaly; δg function realizes the calculation of gravity disturbance.
(3) *Legendre.cs* Class: this function contains functions for calculating Legendre series. P_{nm} function is the standard forward recursion method to realize Legendre function.
(4) *Form.cs* Class: realize the initialization of interactive forms and the functions of various controls.

The calculation flow of the program is as follows. First, input the EIGEN-5C data file and GRS80 ellipsoid parameters, call *Read.cs* Class to read the coefficients of spherical harmonics Cnm, Snm, and use GRS80 ellipsoid parameters to correct the coefficients, and then check whether the accuracy of the obtained coefficients meets the requirements.

At the same time, input the GRS80 ellipsoid parameters, the latitude and longitude range to be calculated and the resolution, and call class *Calculator.cs* to convert the latitude and longitude into coordinates in the spherical coordinate system. Call class *Legendr.cs*, input spherical coordinates, and get the Legendre series of 360 orders Pnm. Then, input the corrected spherical harmonic coefficients Cnm, Snm, and Legendre series Pnm, call class *Calculator.cs* to calculate each gravity field parameter, and save it as TXT file. Then, the calculation results are displayed on the interactive interface, and TXT is imported into Matlab to draw the two-dimensional contour map of each gravity field parameter.

The software interface is shown in Fig. 4. After testing, the software can stably calculate the gravity field parameters of each region or the world, taking into account the calculation efficiency and accuracy, and can provide data support for the study of the Earth's gravity field.

As one of the important contributions of this paper, this paper presents the calculation software of the key parameters of the Earth's gravity field based on the EIGEN-5C model. Our software can quickly calculate the key parameter information and better realize the inversion of the Earth's gravity field in the study area. In order to better verify the computing power of the software, the key parameters of the earth's gravity field are calculated and verified at the local scale and the global scale in the subsequent two parts of this paper.

Calculation of Gravity Field Parameters at Regional Scale

In order to verify the feasibility of the calculation process of this method, we selected three experimental sample areas (resolution 5′) of ABC on a local scale, and their longitude and latitude information is shown in Table 7. Among them, region A is the representative of high latitude samples, region B is the representative of mid latitude samples, and region C is the representative of low latitude samples. The above regions are distributed at the junction of the Earth plates, and the geophysical parameters in these regions have certain complexity in the inversion process, which is suitable for verifying the stability of the algorithm in this experiment.

Representative of High Latitude Sample—Region A

Iceland is located on the ridge of the North Atlantic Ocean, which is formed by volcanic rocks. Most of the islands are plateau areas, and the volcanic activity nearby is intense. Researchers chose Iceland as a high latitude region to calculate the gravity field parameters. Figure 6 reflects the geophysical situation of Iceland.

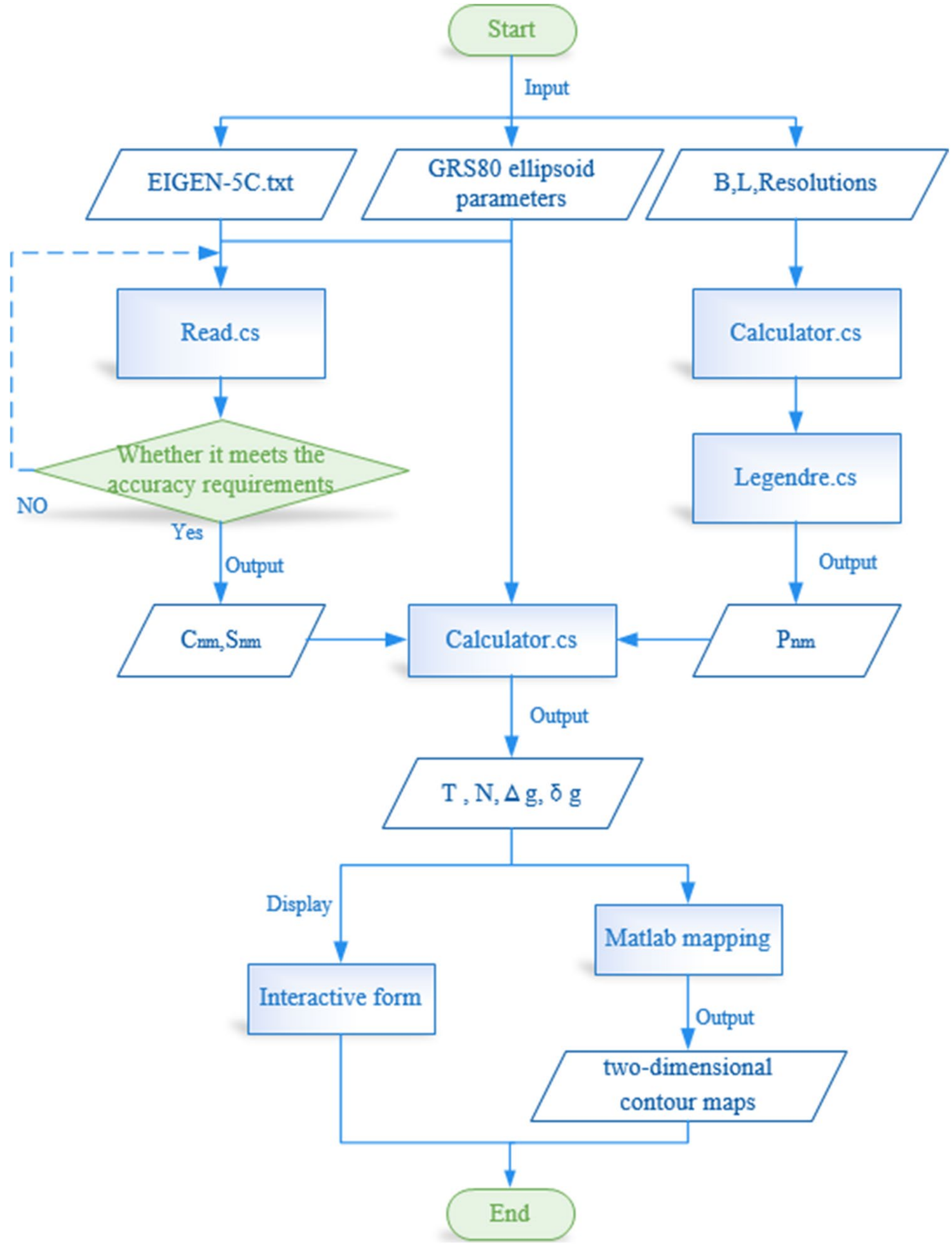
On the island and the oceanic ridge in the southwest region, the values of disturbance potential, geoid height, gravity anomaly, and gravity disturbance are large, and the maximum values of the four occur in the central plateau of Iceland, which are 673.7781$\mathrm{m^2/s^2}$, 68.5943 m, 94.0109mgal, and 115.1332mgal respectively. In the northeast, southeast, and northwest regions, the terrain fluctuates greatly, and the values of these parameters decrease sharply, and the minimum values appear in the southeast sea area, which are 546.7848 $\mathrm{m^2/s^2}$, 55.6854 m, −38.5189mgal, −21.3301mgal respectively.

The numerical changes of disturbance potential and geoid height are highly consistent with the local terrain distribution, which shows the accuracy of the calculation method in this experiment from another point of view.

Representative of Mid Latitude Sample—Region B

Taiwan province is located in the southeast sea area of China, facing the Pacific Ocean in the east and facing Fujian province across the Taiwan Strait in the west. In this study, Taiwan island and its adjacent sea areas are selected as the mid latitude sample area to calculate the gravity field parameters.

Fig. 3 Program chart

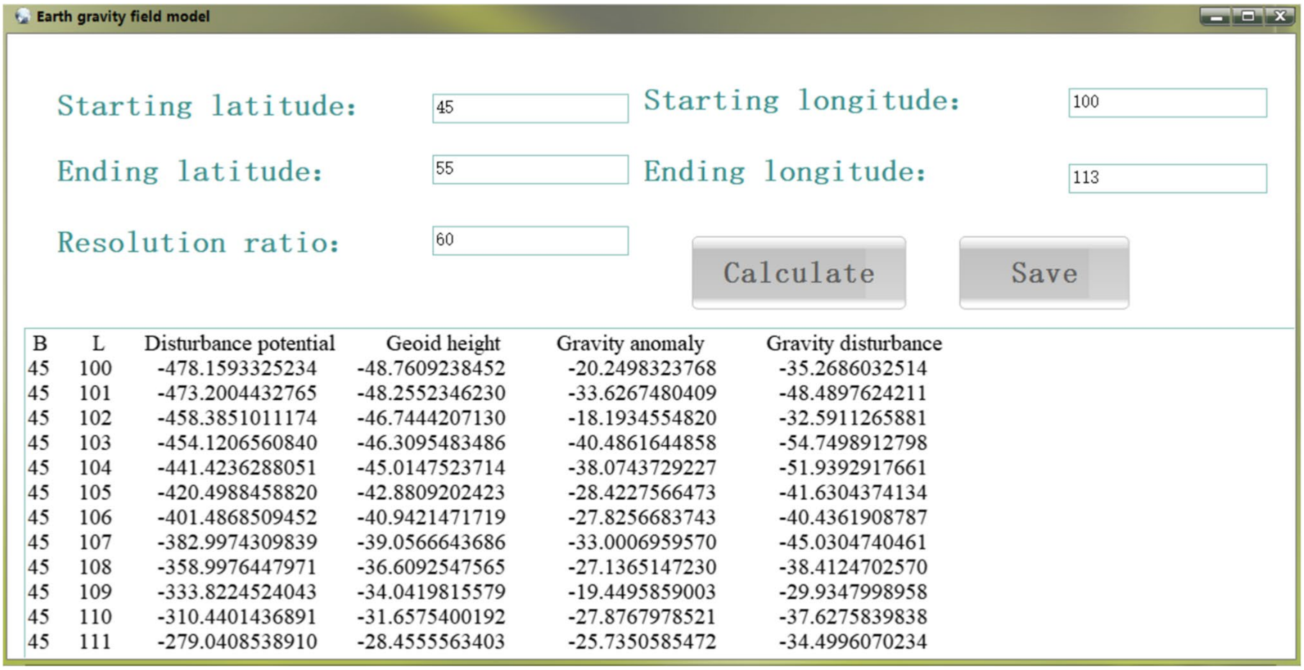


It can be seen from Fig. 7 that the values of disturbance potential and geoid height are large in the central mountain range of the island and the eastern sea area, in which the maximum disturbance potential can reach 361.7042m^2/s^2, the maximum geoid height can reach 36.96 m, and the value in the western sea area is low, in which the minimum disturbance potential is 106.4693m^2/s^2, and the minimum geoid height is 10.8734 m. There is an obvious dividing line in the east of the island. The overall value of gravity anomaly and gravity disturbance is large, in which the maximum value of gravity anomaly can reach 161.3363mgal, and the maximum value of gravity disturbance can reach 169.5144mgal. There are negative values in some areas in the east and south of the island, in which the minimum value of gravity anomaly can reach – 162.067mgal, and the maximum value of gravity disturbance can reach – 157.7213mgal.

Judging from the topographic distribution of Taiwan island, the central and eastern part of Taiwan island is the central mountain range of Taiwan, and there is a maximum physical altitude in this area, which is completely consistent with the calculation results of disturbance potential and geoid height.

Representative of Low Latitude Sample—Region C

Southeast Asia is located at the junction of the Eurasian Plate and the Indian plate. It is located in the Pacific Rim



B	L	Disturbance potential	Geoid height	Gravity anomaly	Gravity disturbance
45	100	-478.1593325234	-48.7609238452	-20.2498323768	-35.2686032514
45	101	-473.2004432765	-48.2552346230	-33.6267480409	-48.4897624211
45	102	-458.3851011174	-46.7444207130	-18.1934554820	-32.5911265881
45	103	-454.1206560840	-46.3095483486	-40.4861644858	-54.7498912798
45	104	-441.4236288051	-45.0147523714	-38.0743729227	-51.9392917661
45	105	-420.4988458820	-42.8809202423	-28.4227566473	-41.6304374134
45	106	-401.4868509452	-40.9421471719	-27.8256683743	-40.4361908787
45	107	-382.9974309839	-39.0566643686	-33.0006959570	-45.0304740461
45	108	-358.9976447971	-36.6092547565	-27.1365147230	-38.4124702570
45	109	-333.8224524043	-34.0419815579	-19.4495859003	-29.9347998958
45	110	-310.4401436891	-31.6575400192	-27.8767978521	-37.6275839838
45	111	-279.0408538910	-28.4555563403	-25.7350585472	-34.4996070234

Fig. 4 Software interface

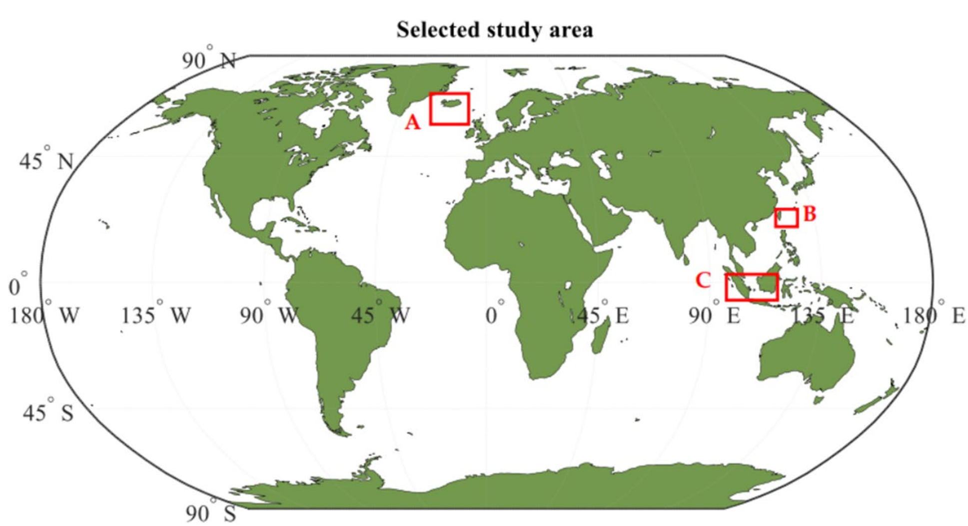
Table 7 Longitude and latitude range of the study area

Study area	Longitude range	Latitude range
A area in Fig. 5	60° N ~ 68° N	10° W ~ 26° W
B area in Fig. 5	20° N ~ 28° N	120° E ~ 128° E
C area in Fig. 5	5° S ~ 5° N	100° E ~ 120° E

seismic belt and has solid crustal activity. In this experiment, Indonesia and the sea area near Malaysia are selected as low latitude areas for gravity field parameter calculation.

It can be seen from Fig. 8 that there is an obvious dividing line between the disturbance potential and the geoid height. In the west of the dividing line, the value is negative, the minimum disturbance potential is – 182.1987m^2/s^2, and the minimum geoid height is – 18.6284 m. In the east of the dividing line, the value is positive, the maximum disturbance potential can reach 637.5512m^2/s^2, and the maximum geoid height can reach 65.1865 m. The value changes sharply on the dividing line. The values of gravity anomaly and gravity disturbance are relatively small. The lowest value of gravity anomaly is – 79.4894mgal, and the lowest value of gravity disturbance is – 85.0148mgal. There are large values in the Iban

Fig. 5 Selected study area (region A stands for the high latitude area sample, region B stands for the mid latitude area sample, region C stands for the low latitude area sample)



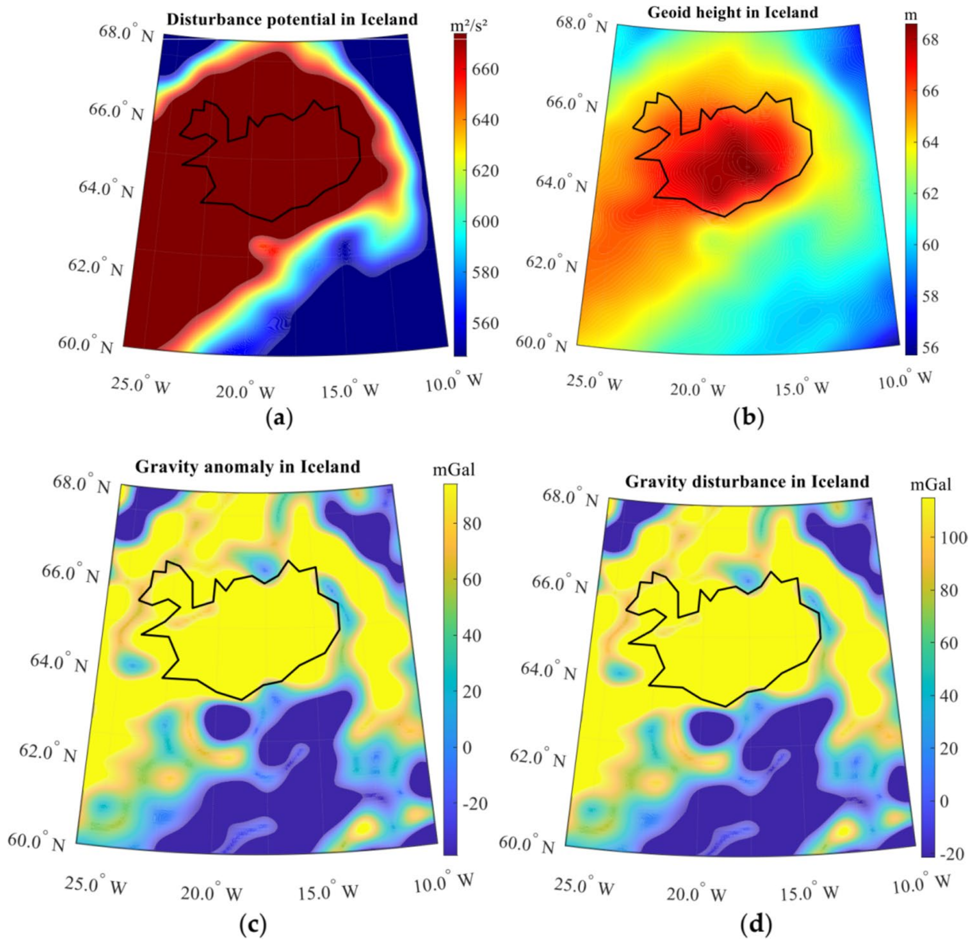


Fig. 6 Gravity field parameters in Iceland region. (**a**) Disturbance potential in Iceland area; (**b**) geoid height in Iceland area; (**c**) gravity anomaly in Iceland; (**d**) gravity disturbance in Iceland

mountains of Kalimantan island in the East and the Barisal mountains of Sumatra Island in the west, of which the maximum gravity anomaly can reach 195.104mgal, and the maximum value of gravity disturbance can reach 214.7673mgal.

The distribution of the dividing line reflects the junction of the Eurasian and Indian plates, which is consistent with our inversion results in geophysical space.

Calculation of Gravity Field Parameters at Global Scale

EIGEN-5C model cannot only get good calculation results of gravity field parameters on a local scale but also get competitive results on a global scale (resolution of 1°), as shown in Fig. 9 below.

It can be seen from Fig. 9 that the distribution of disturbance potential and geoid height is complex. It changes violently in the Pacific Rim seismic belt, Mediterranean Himalayan seismic belt, and seismic ridge belt. The maximum disturbance level can reach 819.3976m^2/s^2, and the maximum geoid height can reach 83.7761 m. The lowest value appears in the sea area near the Maldives, of which the lowest value of disturbance potential is – 1040.7 m^2/s^2, and the lowest value of geoid height is – 106.3993 m. The distribution of gravity anomaly and gravity disturbance is relatively stable, and the value is relatively low. There are high values in the Qinghai Tibet region of China, Greenland, and the Andes mountains of South America. Among them, the maximum value of gravity anomaly is 289.7696mgal, the maximum value of gravity disturbance is 285.9281mgal, and the value around the seismic ridge belt is relatively low, in which the minimum value of gravity anomaly is – 338.6184mgal, and the minimum value of gravity disturbance is – 360.0623mgal.

Among them, the larger values of gravity anomaly and gravity disturbance appear in the plate boundary zone, which clearly outlines the distribution of the eight plates, and further explains the correctness of the calculation results in this experiment.

Discussion

In this study, the calculation of the Earth's gravity field parameters at the regional scale is analyzed, and three

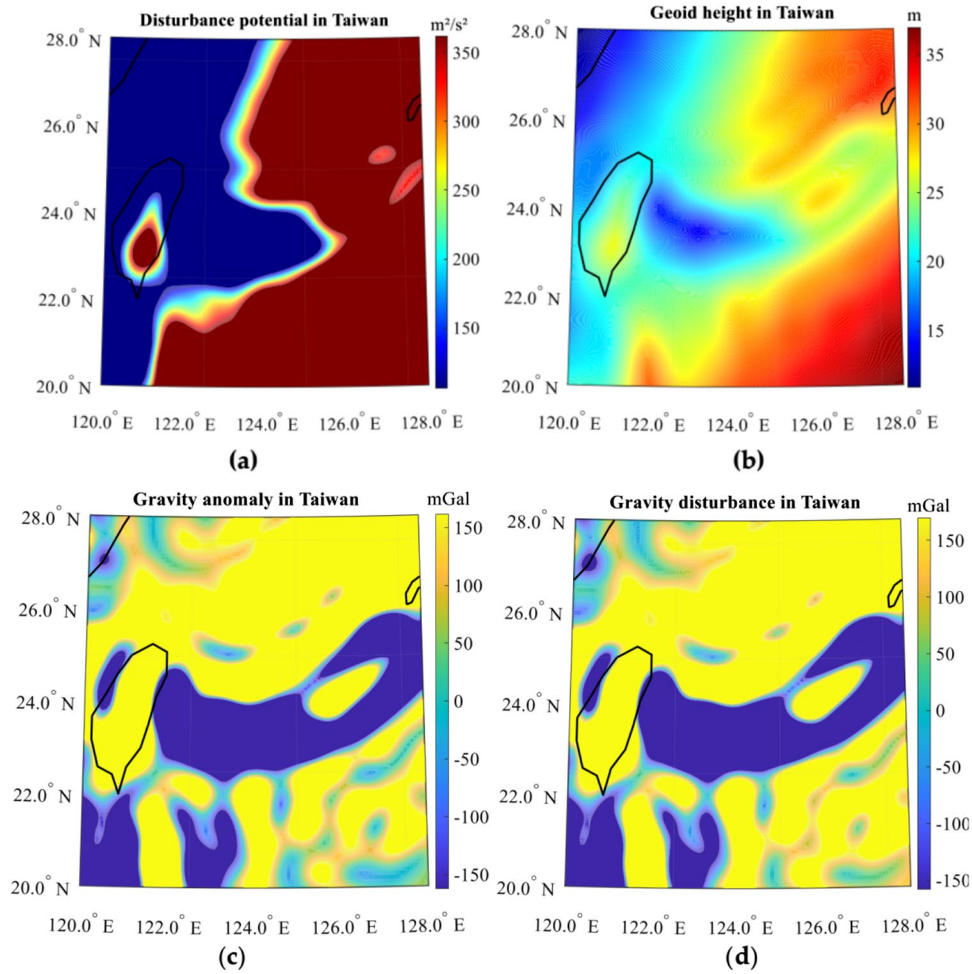


Fig. 7 Gravity field parameters in Taiwan. (**a**) Disturbance potential in Taiwan; (**b**) geoid height in Taiwan; (**c**) gravity anomaly in Taiwan; (**d**) gravity disturbance in Taiwan

sample areas of ABC are selected to represent the high latitude area, the middle latitude area, and the low latitude area for analysis. From the analysis results, the results of the regional analysis are consistent with the local topographic relief in the expression of two key parameters, disturbance potential and geoid height, which further shows the correctness of our calculation results. From the two indicators of regional gravity anomaly and gravity disturbance, they can better reflect the specific changes in the local gravity field.

In order to verify the correctness of the experimental results, the researchers used the calculation function provided by ICGEM website to compare the calculation results of EGM2008 model with the calculation results of this study. It is evaluated by RMS and STD. As the ICGEM website cannot calculate the grid disturbance potential data at present, the verification of experimental results only involves geoid height, gravity anomaly, and gravity disturbance.

We selected Iceland for experimental analysis for the high latitude region at the regional scale. The longitude and latitude range of the sample region is shown in Table 7. Among them, the maximum values of the four gravity field parameters in Iceland appear in the plateau area in the center of the island, with values of 673.7781m^2/s^2, 68.5943 m, 94.0109mgal, and 115.1332mgal, respectively. The lowest values appear in the southeast sea area, with 546.7848 m^2/s^2, 55.6854 m, −38.5189mgal, and −21.3301mgal, respectively. As shown in Table 8, the maximum and minimum values of geoid height calculated in this study do not deviate more than 2 m from the calculation results of ICGEM website, and the errors of RMS and STD are within 1 m. The deviation of the maximum value of gravity anomaly is 3.2768mgal, the deviation of the minimum value of gravity anomaly is 26.5824mgal, the STD deviation is 1.3994mgal, and the RMS deviation is 0.5199mgal. The deviation of the maximum value of gravity disturbance is 3.7729mgal, the deviation of the minimum value of gravity disturbance is 26.5017mgal, the STD deviation is 1.3945mgal, and the RMS deviation is 0.6135mGal.

We selected Taiwan for experimental analysis for the mid latitude region at the regional scale. The longitude and latitude range of the sample region is shown in Table 7. Among

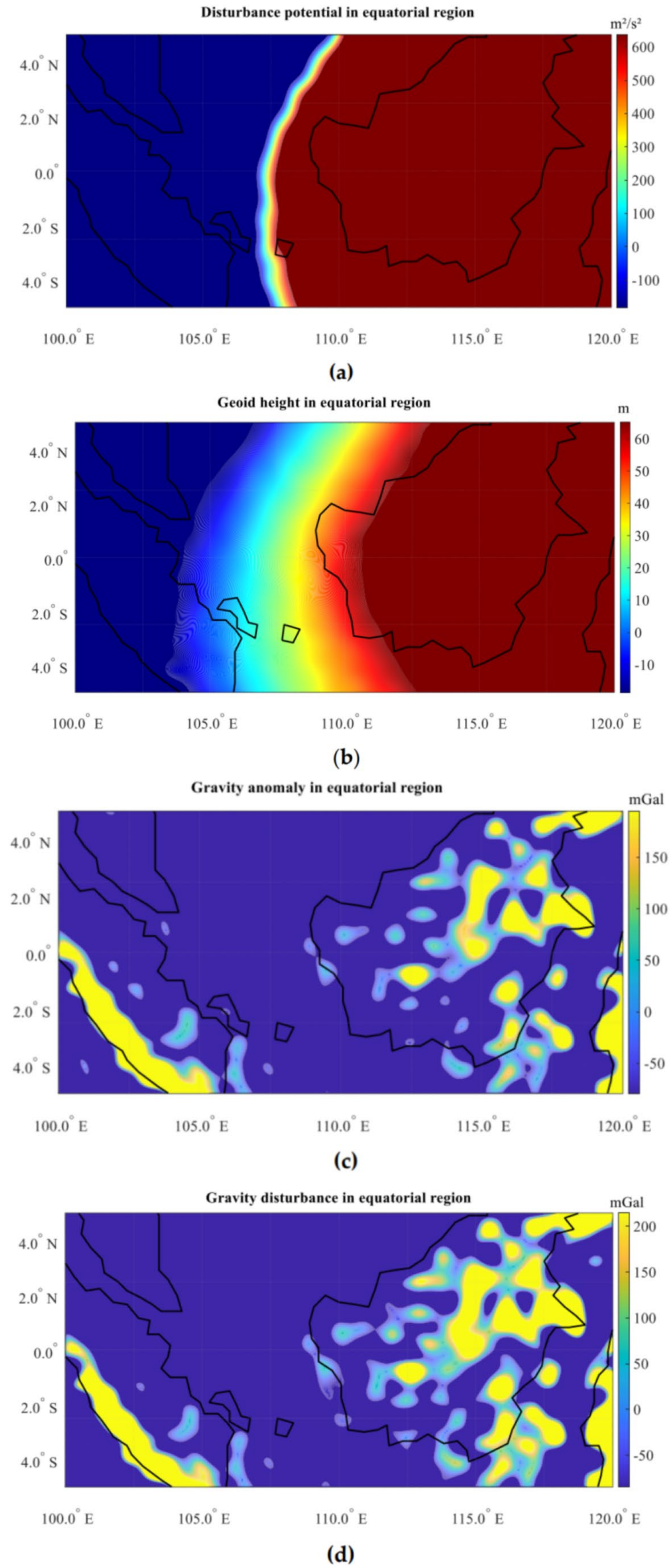


Fig. 8 Gravity field parameters in equatorial region. (**a**) Disturbance potential in equatorial region; (**b**) geoid height in equatorial region; (**c**) gravity anomaly in equatorial region; (**d**) gravity disturbance in equatorial region

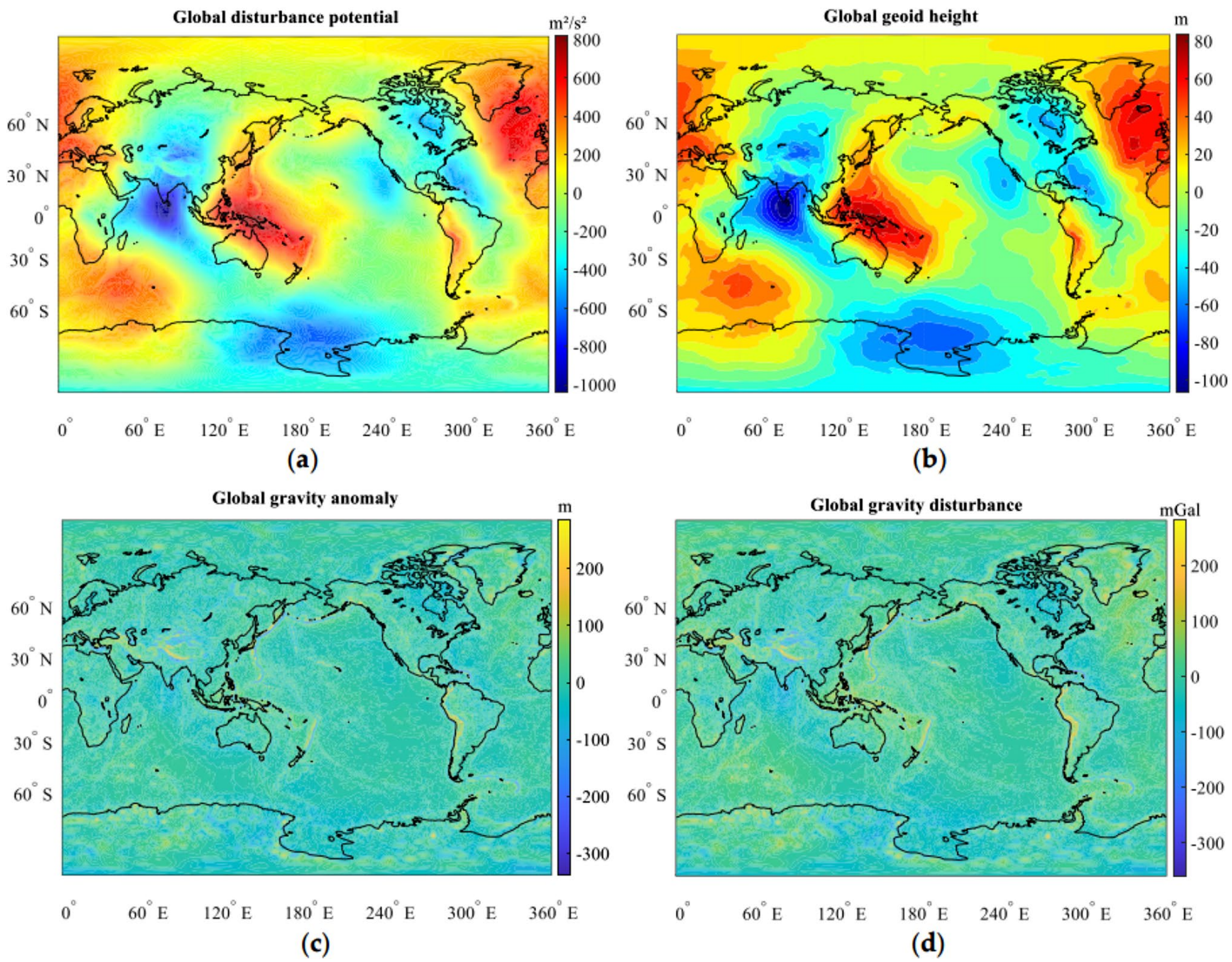


Fig. 9 Global gravity field parameters. (**a**) Global disturbance potential; (**b**) global geoid height; (**c**) global gravity anomaly; (**d**) global gravity disturbance

them, the maximum values of Taiwan's disturbance potential and geoid height appear in the central mountain range of Taiwan island, with values of 361.7042m^2/s^2 and 36.96 m, respectively, and the minimum values appear in the western sea area of Taiwan island, with values of 106.4693m^2/s^2 and 10.8734 m respectively. The maximum values of gravity anomaly and gravity disturbance appear on Taiwan island and the northern sea area, with values of 161.3363mgal and 169.5144mgal, respectively, and the minimum values appear in the eastern part of the island and – 162.067mga and – 157.7213mgal respectively. As shown in Table 9, the maximum and minimum values of geoid height calculated in this study do not deviate more than 1 m from the calculation results of ICGEM website, and the errors of RMS and STD are within 1 m. The deviation of the maximum value of gravity anomaly is 19.808mgal, the deviation of the minimum

Table 8 Verification of regional scale results (region A)

Gravity field parameter (unit)		Maximum	Minimum	STD	RMS
Geoid height (m)	This study	68.5943	55.6854	2.5358	63.3349
	ICGEM	67.3115	55.3241	2.5066	62.3849
Gravity anomaly (mgal)	This study	94.0109	-38.5189	18.1483	37.7155
	ICGEM	90.7340	-11.9365	16.7489	37.1956
Gravity disturbance (mgal)	This study	115.1332	-21.3301	18.7423	55.8451
	ICGEM	111.3603	5.1716	17.3478	55.2316

value of gravity anomaly is 16.3518mgal, the STD deviation is 21.6666mgal, and the RMS deviation is 15.6953mgal. The deviation of the maximum value of gravity disturbance is 19.4901mgal, the deviation of the minimum value of gravity disturbance is 16.5329mgal, the STD deviation is 2.5799mgal, and the RMS deviation is 2.5645mgal.

For low latitudes at the regional scale, we selected Indonesia around the equator and the sea area near Malaysia for experimental analysis. The longitude and latitude of the sample area are shown in Table 7. Among them, the maximum values of disturbance potential and geoid height in the equatorial region appear in Kalimantan island and nearby sea areas, with values of 637.5512m^2/s^2 and 65.1865 m respectively, and the minimum values appear in Sumatra islands and nearby sea areas, with values of − 182.1987m^2/s^2 and − 18.6284 m respectively. Gravity anomaly and gravity disturbance have maximum values in the Iban mountain range of Kalimantan island in the east and Barisal mountain range of Sumatra island in the west, which are 195.104mgal and 214.7673mgal respectively. In contrast, the values in other regions are low, and the minimum values are − 79.4894mgal and − 85.0148mgal, respectively. As shown in Table 10, the maximum and minimum values of geoid height calculated in this study do not deviate more than 2 m from the calculation results of ICGEM website, and the errors of RMS and STD are within 1 m. The deviation of the maximum value of gravity anomaly is 26.7863mgal, the deviation of the minimum value of gravity anomaly is 4.6153mgal, the STD deviation is 14.3041mgal, and the RMS deviation is 1.3398mgal. The deviation of the maximum value of gravity disturbance is 27.0078mgal, the deviation of the minimum value of gravity disturbance is 3.6761mgal, the STD deviation is 1.9981mgal, and the RMS deviation is 1.3336mgal.

Based on the calculation of the critical parameters of the Earth's gravity field at the local scale with good results, we further extend the application of the EIGEN-5C model in calculating the Earth's gravity field parameters to the numerical calculation of the global gravity field. From the calculation results, the disturbance potential and geoid height change violently in the Pacific Rim seismic belt, the Mediterranean Himalaya seismic belt, and the seismic ridge belt, with the highest values of 819.3976m^2/s^2 and 83.7761 m, respectively, and the lowest values of − 1040.7 m^2/s^2 and − 106.3993 m respectively in the sea area near the Maldives. Gravity anomaly and gravity disturbance have the highest values in the Qinghai Tibet region of China, the Greenland rim, and the Andes mountains of South America. Their values are 289.7696mgal and 285.9281mgal, respectively. There are the lowest values around the seismic ridge belt, of which the lowest value of gravity anomaly is − 338.6184mgal and the lowest value of gravity disturbance is − 360.0623mgal.The calculation results of the following two indicators better reflect the distribution and junction of plates, which also shows the accuracy and correctness of the calculation results of this model and related software. As shown in Table 11, the maximum and minimum values of geoid height calculated in this study do not deviate more than 1 m from the calculation results of ICGEM website, and the errors of RMS and STD are within 0.1 m. The deviation of the maximum value of gravity anomaly is 24.3865mgal, the deviation of the minimum value of gravity anomaly is 68.3720mgal, the STD deviation is 2.3501mgal, and the RMS deviation is 2.3511mgal. The deviation of the maximum value of gravity disturbance is 5.9542mgal, the deviation of the minimum value of gravity disturbance is 88.8712mgal, the STD deviation is 2.082mgal, and the RMS deviation is 2.0754mgal.

From the verification results of regional scale and global scale, the calculation of geoid height in this study

Table 9 Verification of regional scale results (region B)

Gravity field parameter (unit)		Maximum	Minimum	STD	RMS
Geoid height (m)	This study	36.9600	10.8734	5.4993	25.6477
	ICGEM	35.9850	10.0361	5.4770	24.7155
Gravity anomaly (mgal)	This study	161.3363	− 162.0670	17.3478	55.2316
	ICGEM	181.1443	− 145.7152	39.0144	39.5363
Gravity disturbance (mgal)	This study	169.5144	− 157.7213	42.2309	44.5644
	ICGEM	189.0045	− 141.1884	39.6510	41.9999

Table 10 Verification of regional scale results (region C)

Gravity field parameter(unit)		Maximum	Minimum	STD	RMS
Geoid height (m)	This study	65.1865	-18.6284	20.5120	35.9013
	ICGEM	63.8780	-19.4012	20.5029	35.1140
Gravity anomaly (mgal)	This study	195.1040	-79.4894	39.6510	42.9346
	ICGEM	168.3177	-84.1047	25.3469	41.5948
Gravity disturbance (mgal)	This study	214.7673	-85.0148	29.4784	51.3421
	ICGEM	187.7595	-88.6909	27.4803	50.0085

Table 11 Verification of global-scale results

Gravity field parameter(unit)		Maximum	Minimum	STD	RMS
Geoid height (m)	This study	83.7761	−106.3993	29.2148	29.2238
	ICGEM	83.1362	−106.9833	29.2111	29.2708
Gravity anomaly (mgal)	This study	289.7696	−338.6184	29.7306	29.7345
	ICGEM	265.3831	−270.2464	27.3805	27.3834
Gravity disturbance (mgal)	This study	285.9281	−360.0623	34.6721	34.6794
	ICGEM	279.9739	−271.1911	32.5901	32.6040

is relatively accurate, the difference between the calculated maximum and minimum values and the ICGEM calculation results is not more than 2 m, and the difference between the STD and RMS indicators and the ICGEM calculation results is not more than 1 m, which indicates that the calculation results of geoid are very close to the ICGEM calculation results. Except that the calculated results of STD and RMS of gravity anomaly in region B are quite different from those of ICGEM, STD, and RMS of other scales are in good agreement with the calculated results of ICGEM.

Summary and Prospect

Summary and Conclusions

1. The method of downloading and using the EIGEN-5C gravity field model file is given in detail. The calculation formulas of the spherical harmonic series expansion of gravity field parameters such as disturbance potential, geoid height, gravity anomaly, and gravity disturbance are introduced, and the calculation process is shown in the form of a pseudo-code table.
2. Based on the calculated data at different regional scales, we use self-developed software to draw two-dimensional contour maps of different gravity field parameters at global and regional scales and make a quantitative and qualitative analysis of the images.
3. For the versatility and efficiency of the calculation, we have developed software independently, so that the users only need to input the latitude, longitude, and resolution of the area to be calculated in the interactive interface, and then the numerical value and the two-dimensional contour maps of the gravity field parameters in the area can be obtained.

Prospect

In this study, the EIGEN-5C model is used to carry out the inversion and result in the expression of the Earth's gravity field parameters in different scale regions. This work has a specific reference value for the field of gravity field parameter calculation and research, but limited to equipment factors, the accuracy of the calculation results of this study can be improved, and the calculation efficiency can be further improved.

Acknowledgements This work was supported by the Wuhan University Innovation Training Program for College Students (W2021214026). Thanks for the precise data provided by ICGEM. You can know more information about the program in this research from this link: https://github.com/pineappleBBL/Earth-gravity-field-model.

Author Contribution Conceptualization, B.Y., J.S., Q.S.; methodology, B.Y.; software, B.Y.; validation, B.Y.,Y.L.; formal analysis, B.Y., Q.S.; investigation, B.Y.,Y.L; resources, J.S.; data curation, B.Y; writing—original draft preparation, B.Y; writing—review and editing, Y.L., J.S.; visualization, B.Y.,Q.S.; supervision, L.Y.; project administration, J.S; funding acquisition, J.S. All authors have read and agreed to the published version of the manuscript.

Funding This research was funded by Frontier Physics Experiment Facility for Extremely Deep Underground Extremely Low Radiation Background of Key National Technology Infrastructure Construction-Subproject of pre-research project (Total No. 2018–000052-73–01-002125) and Wuhan University undergraduate innovation and entrepreneurship training program (No. W2021214026).

Declarations

Conflict of Interest The authors declare no competing interests.

Ethics Approval We confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere.

Informed Consent.

All authors know this article, and all authors agree with this publication.

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