Accuracy Analysis of Gravity Model Based on Fictitious Compress Recovery Approach

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Abstract  The potential field determined based on the fictitious compress recovery approach is influenced by the errors contained in the boundary (the Earth’s surface or the surface corresponding to the satellite altitude) values. Given the boundary value with definite accuracy, the accuracy of the field determined based on the fictitious compress recovery approach is estimated, and it is theoretically shown that the determined field has the same accuracy level as the given boundary value.

Keywords  fictitious compress recovery; error function; error estimate; accuracy of the potential field

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Introduction

Throughout history, various authors have made contributions on the geodetic boundary value problems (GBVPs), and consequently various methods have been proposed for solving GBVP. Generally, the most classical methods are referred to Stokes, Molodensky, and Bjerhammar[1-3]. We would not like to seek for the historical processes for solving GBVP, but only point out that the above-mentioned three methods are approximate, and consequently not perfect methods. To pursue a more accurate and perfect method, i.e., the method that rigorously and precisely solves GBVP, Shen put forward a new approach[4] called the method of the fictitious compress recovery for determining the Earth’s external gravity field. The basic idea of the new approach could be stated as follows[4]: choose a sphere \( K \) (so called Bjerhammar’s sphere), which is an open set and completely included in the Earth, whose center coincides with the Earth’s mass center, whose radius and boundary are denoted by \( R \) and \( \partial K \) respectively, and the region outside \( K \) is denoted by \( \bar{K} \). Such a sphere is called in literature Bjerhammar sphere. The region occupied by the Earth is denoted by \( \Omega \), which is also an open set, whose boundary is denoted by \( \partial \Omega \), and the region outside is denoted by \( \bar{\Omega} \). Suppose \( \partial \Omega \) is a simply closed surface so that there exists a one-one continuous map between the Earth’s boundary \( \partial \Omega \) and the sphere surface \( \partial K \). Compressing the gravitational potential \( V_{\partial \Omega} \), which is the value on the Earth’s boundary, on the sphere surface \( \partial K \), one gets the harmonic solution \( V^{(1)} \) outside the sphere by using Poisson integral. Compressing the residual potential \( T^{(1)} = V_{\partial \Omega} - V_{\partial \Omega}^{(1)} \) on the sphere surface \( \partial K \), one gets the harmonic solution \( V^{(2)} \). This procedure can be repeated until one gets a series solution

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\[ V^* = \sum_{n=0}^{\infty} V^{(n)}(s), \] which is a regular harmonic function outside the sphere and completely coincides with the Earth’s real gravitational potential field outside the Earth.\(^4\)

Recently, the above-mentioned approach\(^5,6\) was further developed and made more reliable with a series of studies concerning various applications in geophysics\(^6,7\). In Section 1, the approach of the fictitious compress recovery is introduced and various applications are outlined. In Section 2, concerning the gravity model based on the new approach, the accuracy estimates are provided, and Section 3 ends this paper.

1 Fictitious compress recovery approach

Based on Reference [4], in region \( \bar{K} \) there exists such a fictitious potential field \( V^* \) satisfying:
\[
\Delta V^*(P) = 0, P \in \bar{K} \\
V^* \big|_{\partial \bar{K}} = V^*_0 \\
\lim_{P \to \partial \bar{K}} V^*(P) = 0
\] (1)
and on the boundary \( \partial \Omega \) of the Earth, \( V^*(P) \) has the same value as the Earth’s real potential field \( V(P) \). It is noted that, the “fictitious potential field \( V^*(P) \)” means that it is not the real potential field generated by the Earth in the region \( \bar{K} \) outside the sphere \( K \). However, in the region \( \bar{\Omega} \) (the region outside the Earth), the fictitious potential field \( V^* \) coincides exactly with the Earth’s real potential field \( V^{\text{Earth}} \). To realize this idea, one can iteratively compress the real potential value and the (series) residual potential values on the Earth’s boundary to the boundary of the sphere until the residual potential value on the Earth’s boundary tends to zero.

Set the gravitational potential value \( V_{\text{Earth}} \) on the surface of \( K \) along the radial direction. Then, using Poisson integral one gets a regular harmonic solution \( V^{(0)} \) in region \( \bar{K} \) (the region outside the sphere \( K \)):
\[
V^{(0)}(P) = \frac{r^2 - R^2}{4\pi R} \int_{\partial K} \frac{V_{\text{Earth}}}{l^3} d\sigma = \frac{r^2 - R^2}{4\pi R} \int_{\partial K} \frac{V^{(0)}}{l^3} d\sigma, P \in \bar{K}
\] (2)
which can be taken as the first approximation of the Earth’s real potential field \( V \) in region \( \bar{\Omega} \) (outside the Earth’s surface \( \partial \Omega \)).

Using \( V^{(0)}(P) \) one calculates the boundary value \( V^{(1)}_{\partial \Omega} \). Set the first order residual boundary potential value
\[
T^{(1)}_{\partial \Omega} \equiv V^{(1)}_{\partial \Omega}.
\]
again on the surface of the sphere \( K \), one gets a second-order regular harmonic solution in \( K \):
\[
V^{(2)} = \frac{r^2 - R^2}{4\pi R} \int_{\partial K} \frac{T^{(1)}_{\partial \Omega}}{l^3} d\sigma
\] (3)
One can take \( V^{(0)}(P) + V^{(2)} \) as the second approximation of the real potential field \( V \) outside the Earth.

Similarly, using \( V^{(2)} \) one calculates the boundary value \( V^{(2)}_{\partial \Omega} \), and set the second-order residual boundary potential value:
\[
T^{(2)}_{\partial \Omega} \equiv (T^{(0)}_{\partial \Omega} - V^{(2)}_{\partial \Omega})
\]
again on the surface of the fictitious sphere \( K \), one gets a third-order regular harmonic solution in \( K \). Such a process can be repeated until one gets a series solution (8).

Remark 1 The boundary value \( V_{\text{Earth}} \) could be obtained by the observed geopotential \( W_{\text{Earth}} \) subtracting the centrifugal potential \( Q_{\text{Earth}} \). On land areas, \( W_{\text{Earth}} \) could be obtained by gravimetry and level surveying; and over the sea areas, \( W_{\text{Earth}} \) could be obtained by using gravity model. Or, theoretically, we can use frequency shift method to determine the geopotential \( W_{\text{Earth}} \).

General formulation could be stated as follows. Set:
\[
T^{(0)}(P) \equiv V(P) \\
T^{(n)}(P) = T^{(n-1)} - V^{(n)}(P), P \in \bar{\Omega}, n \geq 1
\] (4)
where \( T^{(n-1)}(P)(n \geq 1) \) is called the \( (n-1) \)th order residual potential (the zero order residual potential \( T^{(0)} \) is defined as the Earth’s real gravitational potential \( V \)). Note that the \( (n-1) \)th order residual potential (including the zero order residual potential) is only defined in the Earth’s external region \( \bar{\Omega} \) (i.e., in any other regions except for \( \bar{\Omega} \) the residual potential does not have definition), and can be expressed on the Earth’s boundary as follows:
\[
T^{(0)}(P)_{\partial \Omega} \equiv V_{\text{Earth}} \\
T^{(n)}(P)_{\partial \Omega} = T^{(n-1)}_{\partial \Omega} - V^{(n)}_{\partial \Omega}, n \geq 1
\] (5)
Compress the \( (n-1) \)th residual gravitational poten-
tential $T^{(n-1)}_{ad}$ on the spherical surface $\partial K$ along the radial direction, searching for the solution of the following boundary problem:

$$
\Delta V^{(n)}(P) = 0, \quad P \in \overline{K}
$$

$$
V^{(n)}(P)|_{\partial K} = T^{(n-1)}(P)\partial \Omega \tag{6}
$$

$$
\lim_{r \to \infty} V^{(n)}(P) = 0, \quad n \geq 1
$$

and the solution is given by Poisson integral:

$$
V^{(n)} = \frac{r^2 - R^2}{4\pi r} \int_\Omega \frac{T^{(n-1)}_{ad}}{r^2} d\sigma, \quad P \in \overline{K}, n \geq 1 \tag{7}
$$

which is a regular harmonic function in the region $\overline{K}$ (outside the sphere $K$). When the above solution is constrained in the Earth’s external region $\Omega$, it can be taken as the first approximation of the $(n-1)$ th residual potential $T^{(n-1)}(P)$, or we can take $\sum\limits_{n=1} V^{(n)}$ as the $n$th approximation of the Earth’s gravitational potential $V$.

Hence, we get a series solution outside the sphere $K$:

$$
V^*(P) = \sum\limits_{n=1} V^{(n)}(P), \quad P \in \overline{K} \tag{8}
$$

which, on the boundary $\partial K$, has the value:

$$
V^*|_{\partial K} = (\sum\limits_{n=1} T^{(n)}_{ad})|_{\partial K}
$$

where $T^{(n)}_{ad}$ is determined by Eq.(5). We note that, to determine the Earth’s external field, we do not need to find $V^*|_{\partial K}$, which is only a “by-way product”.

It has been proved that$^4$, the series (8) is uniformly convergent, and the fictitious potential field determined by Eq.(8) coincides exactly with the Earth’s real potential field $V$ outside the Earth, i.e.,

$$
V(P) \equiv V^*(P) = \sum\limits_{n=1} V^{(n)}(P), \quad P \in \Omega \tag{9}
$$

and the Earth’s external gravity field is determined by$^1$:

$$
W(P) = V(P) + Q(P) \equiv V^*(P) + Q(P)
$$

$$
g(P) = \nabla W(P), \quad P \in \Omega \tag{10}
$$

where $Q(P)$ is the centrifugal potential; $W(P)$ is the gravity potential (i.e., the geopotential); $g(P)$ is gravity vector; $\nabla$ is gradient operator.

In fact, the new approach is valid for an arbitrary regular harmonic function$^5$. Hence, we can apply this approach to solve different kinds of problems$^5$-$^7$:

1) Suppose the gravity vector $g$ on the Earth’s physical surface $\partial \Omega$ is given, based on the approach of the fictitious compress recovery, the Earth’s external gravity field could be strictly and exactly determined, provided that the given boundary value is error-free$^6$.

2) Given the second gradients $\partial \partial V$ of the potential $V$ on the Earth’s physical surface $\partial \Omega$, based on the new approach (the fictitious compress recovery), the Earth’s external gravity gradient field could be strictly and exactly determined;

3) Suppose there exists a simply closed surface $\partial S$ defined by a spacecraft (satellite or airborne), and it is assumed that on the surface $\partial S$ the relevant observation value (potential, or gravitation, or gravitation gradient) is given, then, based on the new approach, not only the gravity field outside the surface $\partial S$ but also that in the space region between the Earth’s surface and the spacecraft surface $\partial S$ could be strictly and exactly determined;

4) Given static electric field intensity $E$ or stable magnetic field intensity $B$ on the Earth’s physical surface $\partial \Omega$, based on the new approach, the corresponding (basic) field outside the Earth could be strictly and exactly determined, granted that the corresponding (basic) external field is completely determined by the boundary value;

5) Granted that $r \Delta g$ is harmonic outside the Earth (cf. Remark 2) and regular at infinity, based on the new approach, one could simply get the fictitious gravity anomaly distributed on Bjerhammar’s sphere, where the gravity anomaly plays an essential role in Bjerhammar’s theory.

Remark 2 Generally, it is considered that $r \Delta g$ is harmonic outside the Earth (in the space region without mass), if it were granted that $r \Delta g$ is defined as a function of $r^{[1,3]}$, satisfying the following equation:

$$
\Delta g = \frac{\partial T}{\partial r} - \frac{2}{r} T \tag{11}
$$

where $T(P) = W(P) - U(P)$ is the disturbing potential ($U$ and $W$ are the normal potential generated by a reference ellipsoid and the geopotential generated by the Earth, respectively); $\Delta g$ is the gravity anomaly, the definition of which is referred to Reference [1]. However, strictly speaking, if one investigates the
nature of $r \Delta g$ carefully, one will find that it is not harmonic, or one gets the conclusion that $r \Delta g$ is approximately harmonic. The confirmation in details is beyond the scope of the present paper.

## 2 Accuracy analysis

In practical applications for determining the Earth’s external field (potential field or gravitational field) based on the observed boundary values (such as potential $V_{\text{obs}}$ or gravitation $\partial V_{\text{obs}}$), the errors existing in the observation values on the boundary will be transferred to the determined field. However, if the boundary value errors are not large, the determined field will not be significantly influenced, because the solution based on the approach of the fictitious compress recovery is stable. That means, if the boundary value varies little, the corresponding field also varies little.

Now, let us suppose that the boundary value $V_{\text{obs}}$ contains the error function $F_{\text{obs}}$, which could be assumed as continuous on the boundary (by technique tricks), so that one can assume that there exists an error distribution function $F(P)$, which is a regular harmonic function in the region outside the Earth, and takes the boundary value $F_{\text{obs}}$ on the Earth’s surface. Such an assumption is reasonable, the argument is as follows. Set:

$$V_{\text{obs}}(P) = V(P) + F(P), \quad P \in \mathcal{Q}$$  \hspace{1cm} (12)

where $F(P)$ is the observation error function; $V(P)$ is the real field. And on the boundary one has:

$$V_{\text{obs}}|_{\partial \Omega} = V|_{\partial \Omega} + F|_{\partial \Omega}$$  \hspace{1cm} (13)

By applying the approach of the fictitious compress recovery one gets (cf. Remark 3):

$$V_{\text{obs}}^*(P) = V^*(P) + F^*(P), \quad P \in \mathcal{Q}$$  \hspace{1cm} (14)

We know that $V^*$ is a regular harmonic function, so is $V_{\text{obs}}^*$, because one can always assume that $V_{\text{obs}}|_{\partial \Omega}$ is continuous. Then, from Eq.(14) one concludes that $F^*(P)$ as well as $F(P)$ are regular and harmonic in the region outside the Earth.

Since $F(P)$ is harmonic outside the Earth, and regular at infinity, it achieves its maximum and minimum values on the boundary $\partial \Omega$. Hence, we have the following relation:

$$|F'(P)| \leq |F|_{\partial \Omega}, \quad P \in \mathcal{Q}$$  \hspace{1cm} (15)

In the sequel, let us investigate the property of $F(P)$ (equivalent to $F'(P)$ in the region outside Earth), to see how it varies with field point $P$. We expect that $|F(P)|$ decreases with the increase of the distance between the field point and the Earth’s mass center. This is really true; the confirmation could be stated as follows.

The field $F'(P)$ is determined by the boundary value $F|_{\partial \Omega}$, and mathematically, it can be determined by Green theorem:

$$F(P) = \frac{1}{4\pi} \int_{\partial \Omega} F \frac{\partial G}{\partial n} \, d\sigma = \frac{1}{4\pi} \int_{\partial \Omega} F|_{\partial \Omega} \frac{\partial G}{\partial n} \, d\sigma$$  \hspace{1cm} (16)

where the Green’s function $G_r$ is to be determined. It should be pointed out that $\frac{\partial G}{\partial n}$ must be positive, otherwise, one can constitute such a function so that contradiction occurs. However, the proof of this conclusion is beyond the scope of the present paper. Hence, from the above equation one gets:

$$|F(P)| \leq \frac{1}{4\pi} \int_{\partial \Omega} F|_{\partial \Omega} \frac{\partial G}{\partial n} \, d\sigma \leq \frac{1}{4\pi} \int_{\partial \Omega} \max F|_{\partial \Omega} \frac{\partial G}{\partial n} \, d\sigma, \quad P \in \Omega$$  \hspace{1cm} (17)

where $\max F|_{\partial \Omega}$ is the maximum value of the function $|F(P)|$ on the boundary $\partial \Omega$. Further, from Eq.(17) one gets:

$$|F(P)| \leq \frac{1}{4\pi} \int_{\partial \Omega} \max F|_{\partial \Omega} \frac{\partial G}{\partial n} \, d\sigma = \frac{r^2 - R^2}{4\pi R} \int_{\partial \Omega} \max F|_{\partial \Omega} \, d\sigma, \quad P \in K'$$  \hspace{1cm} (18)

where $K'$ denotes the minimum sphere (Brillouin sphere) that completely includes the Earth; $\partial K'$ the boundary of that sphere and $K'$ the space region outside the sphere. From Eq.(18) one gets immediately:

$$|F(P)| \leq \frac{R'}{r} \max F|_{\partial \Omega}, \quad P \in K'$$  \hspace{1cm} (19)

and consequently

$$|F(P)| \leq \frac{R'}{r} \max F|_{\partial \Omega}, \quad P \in \mathcal{Q}$$  \hspace{1cm} (20)

This equation gives the error distribution function $F(P)$ a definite constraint that, it takes the value
between $-\frac{R'}{R_{\text{min}}}|F_{\alpha\beta}|_{\text{max}}$ and $\frac{R'}{R_{\text{min}}}|F_{\alpha\beta}|_{\text{max}}$, and it tends to zero with the increase of $r$, where $R_{\text{min}}$ is the smallest distance between the Earth’s surface and the Earth’s mass center. In practical application, since the difference between $R'$ and $R_{\text{min}}$ is around 30 km$^{[4,7]}$, far less than the Earth’s average radius $R_{\text{r}}$, Eq.(18) can be simplified as follows:

$$|F(P)| \leq \frac{R_{r}}{r}|F_{\alpha\beta}|_{\text{max}}, \quad P \in \mathcal{D} \quad (21)$$

Roughly speaking, based on Eq.(21), if the boundary value $V_{\text{obs}}|_{\alpha\beta}$ has an accuracy characterized by $\sigma$, the accuracy of the field $F(P)$ might be expressed as:

$$\sigma_{\alpha}(r) \leq \frac{R_{r}}{r}\sigma \quad (22)$$

which holds outside the Earth.

If we investigate the relative accuracy $\sigma_{\alpha}(r)/V(P)$ ($\equiv \lambda$), we conclude that it holds constant with a good approximation in the whole region outside the Earth, because the main part (first order) of $V(P)$ could be expressed as:

$$V(r)_{\text{min}} = \frac{R_{r}}{r} \frac{GM}{R_{u}} = \frac{R_{r}}{r}V_{0}$$

where $G$ is the gravitational constant; and $M$ the Earth’s mass. Hence, the relative accuracy $\lambda$ could be expressed as a constant:

$$\lambda = \frac{\sigma}{V_{0}} \quad (23)$$

where $V_{0} = GM / R_{u}$.

Remark 3 From Eqs.(7) and (13), one gets:

$$V_{\text{obs}}^{(n)}(P) = \frac{\rho^{2} - R^{2}}{4\pi R} \int_{\mathcal{K}} \frac{T_{\alpha\beta}^{(n-1)}|_{\alpha\beta}}{l^{3}} d\sigma =$$

$$= \frac{\rho^{2} - R^{2}}{4\pi R} \int_{\mathcal{K}} \frac{T_{\alpha\beta}^{(n-1)}|_{\alpha\beta} + T_{\beta\alpha}^{(n-1)}|_{\alpha\beta}}{l^{3}} d\sigma, \quad P \in \mathcal{K}, n \geq 1 \quad (24)$$

where $T_{\alpha\beta}^{(n-1)}(P), T_{\beta\alpha}^{(n-1)}(P)$, and $T_{\alpha\beta}^{(n-1)}(P)$ denote the $(n-1)$th order residual fields corresponding to the fields of the observational potential $V_{\text{obs}}(P)$, real potential $V(P)$, and error distribution $F(P)$, respectively. From Eq.(24) one gets:

$$V_{\text{obs}}^{(n)}(P) = V^{(n)}(P) + F^{(n)}(P), \quad P \in \mathcal{K}, n \geq 1 \quad (25)$$

and

$$\sum_{n=1}^{\infty} V_{\text{obs}}^{(n)}(P) = \sum_{n=1}^{\infty} [V^{(n)}(P) + F^{(n)}(P)], \quad P \in \mathcal{K} \quad (26)$$

Since the above series (left-hand side of the equation) converges uniformly, one gets immediately the following relation:

$$\sum_{n=1}^{\infty} V_{\text{obs}}^{(n)}(P) = \sum_{n=1}^{\infty} V^{(n)}(P) + \sum_{n=1}^{\infty} F^{(n)}(P), \quad P \in \mathcal{K} \quad (27)$$

from which one concludes that $\sum_{n=1}^{\infty} F^{(n)}(P)$ is harmonic outside the Earth and regular at infinity; therefore, Eq.(14) holds just by setting $\sum_{n=1}^{\infty} F^{(n)}(P) \equiv F'(P)$ etc.

### 3 Discussions

Generally, we have only the measured boundary values $V_{\text{obs}}|_{\alpha\beta}$ at discrete points $A$, which are distributed on the Earth’s surface. To make an estimate of the error field $F(P)$ based on the discrete values $V_{\text{obs}}|_{\alpha\beta}$, we must know the errors contained in $V_{\text{obs}}|_{\alpha\beta}$, but it is impossible. However, based on the nature of the instrument and various experiment results, the accuracy $\sigma|_{\alpha\beta}$ of the measured value $V_{\text{obs}}|_{\alpha\beta}$ might be provided. Choosing the maximum value $\sigma_{\max} \in \{\sigma|_{\alpha\beta}\}$, we know that the accuracy of the determined field $V_{\text{obs}}(P)$ could be expressed as:

$$\sigma_{\text{max}}(r) \leq \frac{R_{r}}{r}\sigma_{\max} \quad (28)$$

To confirm our conclusion, it is possible to choose a simple model: the Earth is taken as a uniform sphere $K_{r}$. In this case we know the real value on the surface of the sphere $K_{r}$. With a random function $F$, one can create the “observation value” $V_{\text{obs}}$ on the boundary $\partial K_{r}$. That means, the boundary value $F_{\text{obs}}$ is known. Then, based on the approach of the fictitious compress recovery, one can determine the whole error field $F(P)$ outside the Earth. Zhong studied this problem recently$^{[9]}$, and the primary results support our conclusion. Final confirmation might be expected by various simulation calculations by using a more complicated model.

In fact, it is straightforward to know that, the first approximation of the error field $F(P)$ could be ex-
pressed as:

\[ F(P) = \frac{R}{r} F_{\partial \Omega}, \quad P \in \partial \Omega \quad (29) \]

where \( R \) is the radius of the smallest sphere including the Earth. Suppose \( R \) is very close to \( R_s \), on the Earth’s boundary \( \partial \Omega \) we have approximately \( F(P) \big|_{\partial \Omega} = F_{\partial \Omega} \), which means that Eq.(29) denotes the error field to be determined, with a very good approximation.

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Detailed schedule is as follows. Submission of extended abstracts: January 12, 2008; notification to authors: February 11, 2008; submission of final papers: April 29th, 2008; early registration: April 29th, 2008; symposium: June 25th -27th, 2008.

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