

Theoretical aspects in gravity modeling

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Received 2018 Month XX; in original form 2018 Month XX

SUMMARY

Gravity anomalies have long been used by geophysicists for the purpose of determining density distributions in subsurface.

However, gravity anomalies

In this paper, we discuss the fundamental concepts

URGENTE: (Marussi et al. 1974), (Torge & Müller 2012), section 4.2.1

Key words: potential fields – gravity disturbance – gravity anomaly – gravity modeling.

1 INTRODUCTION

The resultant of gravitational force and centrifugal force acting on a body at rest on the Earth's surface is called *gravity vector* and its intensity is called *gravity* (Heiskanen & Moritz 1967; Hofmann-Wellenhof & Moritz 2005). In the case of gravimetry on moving platforms (e.g., airplanes, helicopters, marine vessels), there are additional non-gravitational accelerations due to the vehicle motion, such as Coriolis acceleration and high-frequency vibrations (Glennie et al. 2000; Nabighian et al. 2005; Baumann et al. 2012). Geophysicists use gravity for estimating the Earth's internal density distribution whereas geodesists use gravity to estimate the geoid (Li & Götze 2001). Hence, geophysicists are usually interested in the gravitational component of the observed gravity, which is produced by the Earth's internal density distribution.

The first step of the procedure for isolating this gravitational component consists in removing the non-gravitational effects due to the vehicle motion and also the time variations such as Earth tides, instrumental drift and barometric pressure changes, for example. If these effects are properly removed, the resultant gravity data can be considered as the sum of a centrifugal component due to the Earth's rotation and a gravitational component produced by the whole Earth's internal density distribution. The isolation of this particular gravitational component and its subsequent use for estimating density distributions related to geological structures in subsurface are the main goals in applied geophysics (Blakely 1996). The computation of the gravitational effect produced by the geological structures is commonly known in geophysics as *gravity modeling*. This term is different from *gravity field modeling*, which is commonly used in geodesy to denote the characterization of the gravity field in a local, regional or global scale.

Based on well-established concepts of the literature, we present a discussion aiming at bringing some light to the following question: in geophysical applications, should we use the gravity

disturbance or gravity anomaly? It seems that this theoretical issue has been debated within the scientific community from a more geodetic than geophysical point of view (LaFehr 1991; Chapin 1996; Li & Götze 2001; Fairhead et al. 2003; Hackney & Featherstone 2003; Hinze et al. 2005). Our reasoning suggests that the gravity disturbance is more appropriated than the gravity anomaly for geophysical purposes.

2 NORMAL EARTH AND NORMAL GRAVITY

Traditionally, the Earth's gravity field is approximated by the gravity field produced by a reference ellipsoid (or level ellipsoid), which is rigid and geocentric. This reference ellipsoid has the minor axis b coincident with the mean rotating axis of the Earth Z , the same total mass (including the atmosphere) and also the same angular velocity of the Earth (Heiskanen & Moritz 1967; Vaníček & Krakiwsky 1987; Hofmann-Wellenhof & Moritz 2005; Torge & Müller 2012). Another characteristic of this model is that its limiting surface coincides with a particular equipotential of its own gravity field. Here, we follow (Torge & Müller 2012) and call this model as *normal Earth*.

Similarly to the gravity vector and gravity, the resultant of the virtual gravitational and centrifugal forces exerted by the normal Earth on a body at rest at a point P is called *normal gravity vector* and its intensity is called *normal gravity*. In geodesy, any model used to represent the normal gravity field can be arbitrarily defined for the only purpose of keeping the difference from the actual gravity field as small as possible (Vaníček & Krakiwsky 1987).

It is worth noting that, although the normal Earth has the same total mass (including the atmosphere) of the Earth, its internal density distribution is unknown. The search for physically meaningful mass distributions that generate a required normal gravity field has geophysical rather than geodetic motives (Marussi et al. 1974). The only condition imposed on its internal density distribution is that it produces a gravity field having a particular equipotential which coincides with its limiting surface. For convenience, we denote any

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density distribution satisfying this condition as a *normal density distribution*.

3 TERRESTRIAL REFERENCE SYSTEMS USED IN GRAVITY MODELING

For geophysical purposes, there are three important Terrestrial Reference Systems used in gravity modeling. They rotate with the Earth and are used for describing positions and movements of objects on and close to the Earth's surface (Torge & Müller 2012).

The first one is a geocentric system of Cartesian coordinates having the Z -axis coincident with the mean Earth's rotational axis, the X -axis pointing to the Greenwich meridian and the Y -axis directed so as to obtain a right-handed system (Figure A1). This reference system can be found in the literature with different names: Mean Terrestrial System (e.g., Soler 1976), Earth-fixed geocentric Cartesian system (e.g., Torge & Müller 2012) or Earth-centered Earth-fixed system (e.g., Bouman et al. 2013), for example. Here, we opted for simply using the term Geocentric Cartesian System (GCS).

Other important reference system is a geocentric system of geodetic coordinates, which is defined by the reference ellipsoid used in the Normal Earth model (Heiskanen & Moritz 1967; Soler 1976; Torge & Müller 2012; Bouman et al. 2013). In this coordinate system, the position of a point is defined by the *geometric height* h , *geodetic latitude* φ and *longitude* λ (Figure A1). For convenience, we call this system Geocentric Geodetic System (GGS). At a given point (h, φ, λ) , there are three mutually-orthogonal unit vectors (Figure A1) given by (Soler 1976):

$$\begin{aligned}\hat{\mathbf{u}} &= \begin{bmatrix} \cos \varphi \cos \lambda \\ \cos \varphi \sin \lambda \\ \sin \varphi \end{bmatrix} \\ \hat{\mathbf{v}} &= \begin{bmatrix} -\sin \varphi \cos \lambda \\ -\sin \varphi \sin \lambda \\ \cos \varphi \end{bmatrix} \\ \hat{\mathbf{w}} &= \begin{bmatrix} -\sin \lambda \\ \cos \lambda \\ 0 \end{bmatrix}\end{aligned}\quad (1)$$

The required equations to convert coordinates (h, φ, λ) referred to the GGS into coordinates (X, Y, Z) referred to the GCS (Figure A1) and vice versa can be easily found in the literature (e.g., Heiskanen & Moritz 1967; Torge & Müller 2012; Bouman et al. 2013).

In a local or regional study, geophysicists commonly use a topocentric Cartesian coordinate system (TCS) with origin at a point P on or close to the Earth's surface and axes x, y and z (Figure A3). In the TCS, the axes x and y are parallel to the unit vectors $\hat{\mathbf{v}}_P$ $\hat{\mathbf{w}}_P$, respectively, whereas the z -axis is opposite to the unit vector $\hat{\mathbf{u}}_P$ (equation 1) and points downward.

Consider a TCS (Figure A3) with origin at a point P with coordinates (X_P, Y_P, Z_P) referred to the GCS (Figure ??). In this case, the relationship between the coordinates (X, Y, Z) of a point in the GCS and the coordinates (x, y, z) of the same point in the TCS is given by:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \mathbf{R}^T \begin{bmatrix} X - X_P \\ Y - Y_P \\ Z - Z_P \end{bmatrix}, \quad (2)$$

where \mathbf{R} is an orthogonal matrix whose columns are defined by the

unit vectors $\hat{\mathbf{u}}$, $\hat{\mathbf{v}}$ and $\hat{\mathbf{w}}$ (equation 1) as follows:

$$\mathbf{R} = [\hat{\mathbf{v}} \quad \hat{\mathbf{w}} \quad -\hat{\mathbf{u}}]. \quad (3)$$

4 BASIC CONCEPTS

It is worth noting that, by definition, the centrifugal component of the normal gravity field is equal to the centrifugal component of the Earth's gravity field if they are evaluated at the same point. Then, the differences between the gravity vector (corrected from non-gravitational effects) and the normal gravity vector, at the same point, represents a purely gravitational and consequently harmonic disturbing field. This gravitational disturbance is caused by contrasts between the actual internal density distribution of the Earth and the internal density distribution of the normal Earth. In applied geophysics, these density differences are generally called *anomalous masses* (e.g., Hammer, 1945; LaFehr, 1965), *density anomalies* (e.g., Forsberg, 1984) or *gravity sources* (e.g., Blakely, 1996). Here, we opted for using the last term.

The difference between the observed gravity and the normal gravity, at the same point, is called *gravity disturbance* (Heiskanen & Moritz 1967; Hofmann-Wellenhof & Moritz 2005). Notice that the gravity disturbance is not equivalent to the magnitude of the difference between the gravity vector and the normal gravity vector at the same point (Barthelmes 2013; Sansò & Sideris 2013). As properly pointed out by Hackney & Featherstone (2003), the gravity disturbance is a very-well established quantity in geodesy, but appears to be less well known in geophysics.

The gravity anomaly is the commonly used quantity in applied geophysics. It is defined as the difference between the gravity on the geoid and the normal gravity on the ellipsoid, both at the same geodetic latitude and longitude. Notice that, by definition, the gravity anomaly depends on longitude and latitude only and is not a function in space (Barthelmes 2013). Different gravity anomalies can be calculated, depending on the corrections applied to them (Blakely 1996; Hofmann-Wellenhof & Moritz 2005). These corrections are usually called gravity reductions. For example, the Free-air anomaly is an approximation of the gravity disturbance whereas the Bouguer anomaly is an approximation of the terrain corrected gravity disturbance. The last one is commonly used by geophysicists as the gravitational effect produced by the gravity sources. Although this approximation is valid for most practical applications, it is important to bear in mind not only the terminology changes, but also the conceptual assumptions.

There was a certain lack of comprehension regarding the geophysical meaning of gravity anomalies until the mid 90's. As properly pointed out by Chapin (1996) at that time, "although the corrections which bring about a Bouguer gravity anomaly are well established, the reasons for doing them are not well understood. One cause of this common misunderstanding is that the subject has been poorly presented in many of the basic texts". In his seminal book, Blakely (1996) brought some light on the geophysical meaning of gravity anomalies from the perspective of applied geophysics. Blakely (1996) correctly defined gravity sources as density contrasts between the actual internal density distribution of the Earth and the internal density distribution of the normal Earth. However, he did not stress that, by removing the normal gravity evaluated on the ellipsoid from the gravity measured on the Earth's surface, the remaining disturbing field will reflect not only the effect produced by the gravity sources, but also a small combination of gravitational and centrifugal effects. This additional, non-harmonic and unde-

sired effect is simply due to the calculation of the normal gravity at a point other than that where the gravity is measured.

5 MATHEMATICAL DESCRIPTION OF THE GRAVITY DISTURBANCE IN A LOCAL COORDINATE SYSTEM

In this coordinate system, the observed gravity vector \mathbf{g}_i , at a point (x_i, y_i, z_i) , $i = 1, \dots, N$, can be represented by

$$\mathbf{g}_i = \boldsymbol{\gamma}_i + \Delta\mathbf{g}_i, \quad (4)$$

where $\boldsymbol{\gamma}_i$ and $\Delta\mathbf{g}_i$ are, respectively, the normal gravity vector and a disturbing gravitational attraction produced by the anomalous masses at the point (x_i, y_i, z_i) .

For each point (x_i, y_i, z_i) in the topocentric Cartesian coordinate system (Figure A3b), there is a corresponding point $(h_i, \varphi_i, \lambda_i)$ in the geodetic coordinate system (Figure A1).

By definition, the gravity disturbance δg_i , at the point (x_i, y_i, z_i) , is given by (Heiskanen & Moritz 1967; Hofmann-Wellenhof & Moritz 2005):

$$\delta g_i = g_i - \gamma_i, \quad (5)$$

where $g_i = \|\mathbf{g}_i\|$ and $\gamma_i = \|\boldsymbol{\gamma}_i\|$ are, respectively, the observed gravity and the normal gravity at the point (x_i, y_i, z_i) . Fortunately, the condition $\gamma_i \gg \|\Delta\mathbf{g}_i\|$ is met at all points located above or on the Earth's surface. By combining this condition and the definition of observed gravity vector (equation 4), we can approximate the observed gravity g_i by a first order Taylor's expansion as follows (Sansò & Sideris 2013):

$$g_i \approx \gamma_i + \hat{\gamma}_i^\top \Delta\mathbf{g}_i, \quad (6)$$

where $^\top$ denotes transposition, $\hat{\gamma}_i = -\hat{\mathbf{u}}_i$ is a unit vector with the same direction as the normal gravity vector $\boldsymbol{\gamma}_i$ at the point (x_i, y_i, z_i) , in the topocentric Cartesian coordinate system (Figure A3b), and $\hat{\mathbf{u}}_i$ is the unit vector $\hat{\mathbf{u}}$ (equation 1) evaluated at the corresponding point $(h_i, \varphi_i, \lambda_i)$ in the geodetic coordinate system (Figure A1).

This approximation, which is known in geodesy (e.g., Sansò & Sideris 2013), is largely used in applied geophysics for representing total-field anomalies (e.g., Blakely 1996). Notice that, in local- or regional-gravity studies, the unit vector $\hat{\gamma}_i$ (equation 6) may be considered constant throughout the study area and parallel to the z axis of the topocentric Cartesian coordinate system (Figure A3b). Consequently, by using the approximation defined in equation 6, the gravity disturbance (equation 5) can be rewritten as follows

$$\delta g_i \approx \hat{\gamma}_P^\top \Delta\mathbf{g}_i, \quad (7)$$

where $\hat{\gamma}_P$ represents the unit vector with the same direction as the normal gravity vector $\boldsymbol{\gamma}_P$ at the origin P of the topocentric Cartesian coordinate system (Figure A3). This equation shows that the gravity disturbance δg_i (equation 5) is different from the magnitude of the disturbing gravitational attraction $\Delta\mathbf{g}_i$ produced by the gravity sources. Rather, it represents the component of the $\Delta\mathbf{g}_i$ on the direction of the normal gravity vector. In the topocentric Cartesian coordinate system, the gravity disturbance δg_i (equation 7) can be defined as the vertical component of the gravitational attraction exerted by the gravity sources at the point (x_i, y_i, z_i) . As a consequence, the gravity disturbance produced by a homogeneous gravity source with density contrast $\Delta\rho$ (in kg/m^3) can be represented by the following harmonic function:

$$d_i = k_g G \Delta\rho \partial_z \phi_i, \quad (8)$$

where G is the Newtonian constant of gravitation (in $m^3/(kg s^2)$), $k_g = 10^5$ is a constant factor transforming from m/s^2 to milligal (mGal), and $\partial_z \phi_i$ is a harmonic function representing the first derivative, evaluated at the observation point (x_i, y_i, z_i) , $i = 1, \dots, N$, of the function

$$\phi(x, y, z) = \int \int \int_v \frac{1}{\sqrt{(x-x')^2 + (y-y')^2 + (z-z')^2}} dv \quad (9)$$

with respect to the variable z . The integral is conducted over the coordinates x' , y' and z' within the volume v of the gravity source. This equation can be easily generalized for the case of multiple gravity sources.

Practically all the literature about gravity modeling use the quantity d_i (equation 8) to represent the gravity anomaly produced by gravity sources (e.g., Blakely 1996). Consequently, almost all the geophysicists use the gravity anomaly as an approximation of the gravity disturbance produced by the gravity sources. Notice that d_i (equation 8) does not depend on the geoidal surface. Rather, it depends on the relative position of the observation points (x_i, y_i, z_i) with respect to the gravity sources in a topocentric Cartesian coordinate system (Figure A3b).

6 CONCLUSIONS

We debate the conceptual differences between the gravity disturbance and the gravity anomaly. Our reasoning suggests that the gravity disturbance is the more appropriated quantity for representing the gravity effect produced by the gravity sources. In summary, we point out that:

(i) Almost all interpretation techniques assume, implicitly or directly, that the gravity data is harmonic (e.g., upward/downward continuation, data processing with equivalent layer, conversions between gravity and magnetic data, computation of vertical derivatives via Fourier and Hilbert transforms). As a consequence, they implicitly or directly assume that the gravity data approximates the gravitational disturbance.

(ii) Almost all forward modeling techniques compute the vertical component of the gravitational attraction exerted by the geological bodies at the observation points. Notice that the gravity anomaly requires the computation of gravity on the Geoid, which is generally within the topographic masses. Hence, almost all geophysicists implicitly compute the gravity disturbance.

(iii) The gravity anomaly is defined as the difference between the gravity on the Geoid and the normal gravity on the reference ellipsoid, both at the same geodetic latitude and longitude. Consequently, the gravity anomaly is a function of the geodetic latitude and longitude only and cannot be calculated at arbitrary heights. On the other hand, the gravity disturbance can be computed at arbitrary points outside the sources.

The principal theoretical implication of this study is that is that, although the gravity anomaly may be used as a good approximation of the gravity effect produced by the sources for most practical applications, the more appropriated quantity for gravity modeling is the gravity disturbance. We stress that, more important than the terminology changes, the geophysicist must bear in mind the conceptual assumptions used in gravity modeling.

ACKNOWLEDGMENTS

The authors would like to thank the editor and all the reviewers for their criticisms and corrections.

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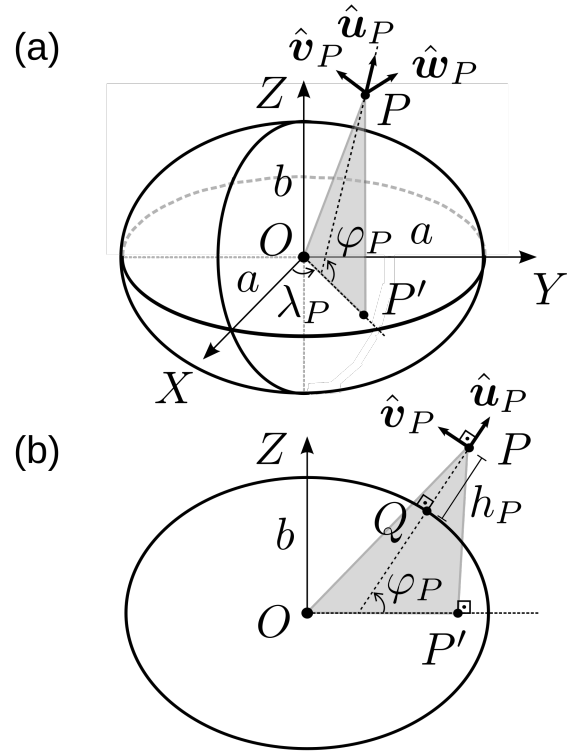


Figure A1. Schematic representation of the Geocentric Cartesian System (GCS) and the Geocentric Geodetic System (GGG). The GCS has the Z -axis coincident with the mean Earth's rotational axis, the X -axis pointing to the Greenwich meridian and the Y -axis directed so as to obtain a right-handed system. The GGG is defined by an oblate ellipsoid with semi-minor axis b , coincident with the Z -axis of GCS, and a semi-major axis a . In this coordinate system, the position of a point is determined by the geometric height h , the geodetic latitude φ and longitude λ . The Earth's center of mass is represented by O , P represents a point ($h_P, \varphi_P, \lambda_P$) and P' its projection onto the plane XY (Equatorial plane). The plane containing O , P and P' is represented in gray in (a) and (b). The unit vectors \hat{u}_P , \hat{v}_P and \hat{w}_P define three mutually orthogonal directions at P (equation 1). In (b), Q represents a point ($h_Q, \varphi_Q, \lambda_Q$), which is the projection of P onto the reference ellipsoid, at the same latitude and longitude ($\varphi_Q = \varphi_P$ and $\lambda_Q = \lambda_P$).

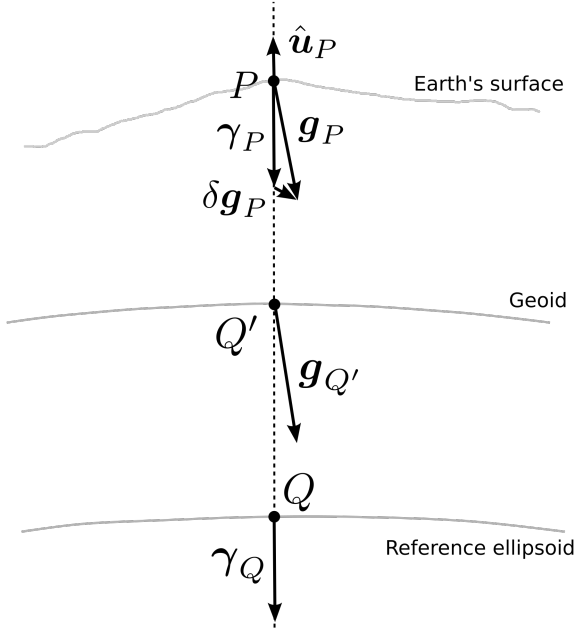


Figure A2. text text text text

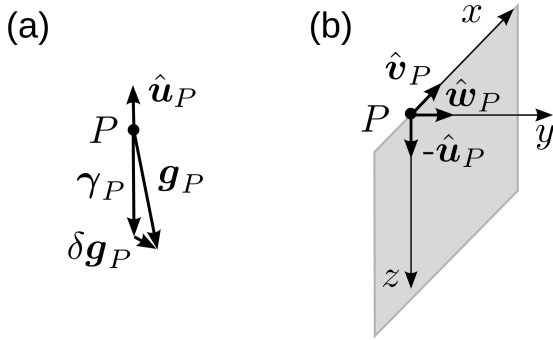


Figure A3. (a) Schematic representation of the gravity vector \mathbf{g}_P , normal gravity vector γ_P , disturbing gravitational attraction $\Delta\mathbf{g}_P$ (equation 4), unit vector $\hat{\mathbf{u}}_P$ (equation 1) and the normal gravity vector γ_Q at the point Q on the reference ellipsoid. At P , the normal gravity vector γ_P is opposite to the unit vector $\hat{\mathbf{u}}_P$ and, at Q , the normal gravity γ_Q is opposite to the unit vector $\hat{\mathbf{u}}_Q$. These unit vectors are close to each other. (b) Schematic representation of a topocentric Cartesian coordinate system with origin at a point P . The axes x and y are parallel to the unit vectors $\hat{\mathbf{v}}_P$ and $\hat{\mathbf{w}}_P$ (equation 1 and Figure A1), respectively. The z axis is opposite to the unit vector $\hat{\mathbf{u}}_P$ (equation 1 and Figure A1) and points downward.