Recommended Standards and Format for the North American Gravity Database

by

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Executive Summary

Recognizing the need for improved regional gravity databases, an international effort by governmental agencies, universities, professional organizations, and private industry is underway to update the publicly available North American Gravity Database. The current database that was released roughly two decades ago needs revision to improve its overall quality, coverage, observation density, and versatility. Considerable data have been made available in the intervening period and improvements are possible in the calculation of gravity anomalies by taking advantage of available terrain and geodetic models and high-

speed data processing procedures and facilities. Data will be made available in a web-based system as part of the U.S. Geoinformatics Program and through other governmental agencies. The Geoinformatics Program is a fully integrated data system that has software for accessing and processing the data, including mapping, profiling, modeling, and filtering and provides useful tutorials.

The database will have a comprehensive menu making it useful for those with differing scientific interests and backgrounds. The user will be able to select desired corrections to the gravity data, units, datums, and type of gravity anomaly and retrieve information on the predicted errors in the data. The default gravity anomalies (in milligals) of the database based on internationally accepted datums and constants will be useful for geological studies and most geophysical investigations. In contrast to the current U.S. gravity database the preferred (default) vertical datum for the gravity correction calculations is the Earth's ellipsoid rather than the geoid (sea level), although users of the database may select an option that uses the geoid as the vertical datum. The difference in the gravity anomalies calculated using the ellipsoid vertical datum rather than the geoid will be negligible to most users. Database fields and formats will accommodate the increasingly available high-resolution, airborne, satellite, marine, and gradient gravity data and will be modified appropriately as additional data are obtained and improvements are made in data processing. The database will be continually updated as additional data are obtained and improvements are made in data processing.

A consensus viewpoint on the recommendations for standards and formats of the North American Gravity Database reached by an international Working Group are specified in this report. These recommendations follow internationally accepted procedures. Differences remain among the Group pertaining to details of the procedures and emphasis; accordingly, alternatives to the consensus or default views are presented. The major differences pertain to the divergence in views regarding nomenclature and methods of calculating anomalies between geophysicists and geodesists. The majority of the users of the database are anticipated to be geophysicists or those interested in using the data for geological purposes. Thus, precedent is given to the geophysical view, but alternatives are provided in the database to make it useful to geodesy as well. These recommendations may be useful in designing national gravity databases.

Introduction

Recognizing the need for improved regional gravity databases, an international effort by governmental agencies, universities, professional organizations, and private industry is underway to update the publicly available North American Gravity Database. The current database consisting of both land and marine data that was released roughly two decades ago needs revision to improve its overall quality, coverage, observation density, and versatility. Considerable data have been made available in the intervening period and improvements are possible in the calculation of gravity anomalies by taking advantage of available terrain and geodetic models, geodetic datums, and high-speed data processing procedures and facilities.

The revision process was initiated during a meeting of the North American Gravity Database Committee at the 2002 Fall AGU Meeting building upon current efforts in substantially improving the digital gravity database of the United States. Plans and progress in the U.S. program are reported by Keller et al. (2002) and Hildenbrand et al. (2002a) and in U.S. Geological Survey Open-File Report 02-463 (Hildenbrand et al., 2002b). The Open-File Report is available at http://geopubs.wr.usgs.gov/open-file/of02-463. These publications explain the importance of the revised gravity databases and the operational plan for implementing the U.S. database.

The long-term goal of the U.S. and North American gravity database revisions is *"…to facilitate the creation of an open and flexible data system populated and maintained by user members of the Earth Science community."* Gravity data contributed to the North American Gravity Database (NAGDB) by agencies, universities, companies, and individuals will be processed in a uniform manner from the principal facts of the gravity observations. These data will be made available in a web-based data system as part of the U.S. Geoinformatics Program and through other governmental agencies. The Geoinformatics Program is a fully integrated data system that has software for accessing and processing the data, including mapping, profiling, modeling, and filtering.

The database will provide a comprehensive menu making it useful for those with differing scientific interests and backgrounds. The user will be able to select desired corrections to the gravity data, units used, datums employed, and type of gravity anomaly and retrieve information on the predicted errors in the data. The default gravity anomalies (in milligals) of the database based on internationally accepted datums and constants will be useful for geological studies and most geophysical investigations. In contrast to the current U.S. gravity database the preferred (default) vertical datum for the gravity correction calculations is the ellipsoid rather than the geoid (sea level), although users of the database may select an option that uses the geoid as the vertical datum. The difference in the gravity anomalies calculated using the ellipsoid vertical datum rather than the geoid will be negligible to most users. Database fields and formats will accommodate the increasingly available high-resolution, airborne, satellite, marine, and gradient gravity data.

This web-based system, including data, analysis and processing support, and useful tutorials will be available to gravity experts, both geophysicists and geodesists, as well as to the growing body of non-specialists interested in gravity data. Plans call for upgrading the North American Gravity Database as additional data are obtained and improvements are made in data processing.

Role and Procedures of the Standards/Format Working Group

An important objective of the revision of the North American Gravity Database is to improve and standardize the methodology and formulae used in preparing and presenting the principal facts of the observations and correction of these data into gravity anomalies. The Standards/Format Working Group, consisting of representatives of the involved North American countries and the various constituencies using and developing the database, was established to make recommendations for achieving this goal building on internationally accepted protocols, formulae, and parameters. Each nation may choose standards and formats to comply with their national interests, procedures, and standards, but the mission of the Working Group is to reach a consensus on recommendations for the standards and formats to be used in preparing the North American Gravity Database for public web-based distribution. These recommendations may prove useful in designing gravity databases for individual nations.

In considering the standards and formats to be used in the NAGDB the Working Group used as a starting point the operational plan of the U.S. Gravity Database as specified in Open-File 02-463. The decisions regarding the U.S. database were developed from presentations and discussions at an August 2002 workshop and subsequent communications among the gravity data community. Members of the Standards/Format Working Group for the NAGDB were solicited for their views together with supporting material on procedures, formats, formulae, and parameters. These recommendations were sent to appropriate focus group leader who had the responsibility of organizing suggestions on a specific component of the problem, e.g., datums, anomalies, and terrain and bathymetry effects.

A consensus viewpoint on the recommendations, as specified in this report, was developed from this input. However, differences remain among the Group pertaining to details of the procedures and emphasis. Wherever possible alternatives are presented to the consensus or default views. The major differences pertain to the divergence in views regarding nomenclature and methods of calculating anomalies between geophysicists and geodesists (Hackney and Featherstone, 2003; Li, 2003). The majority of the users of the database are anticipated to be geophysicists or those interested in using the data for geological purposes. Thus, precedent is given to the geophysical view, but alternatives are provided in the database to make it as useful as possible to geodesy. The collateral information provided with the NAGDB needs to emphasize this and provide specific and clear definition of nomenclature and procedures used in preparing and presenting the database and options for use of the data in geodesy.

A Steering Committee of representatives of interested governmental units and the Co-Chairmen of the North American Gravity Database Committee, Tom Hildenbrand and Randy Keller, guided the overall effort of the Working Group. The members of the Working Group, Steering Committee, and the focus group leaders are listed at the end of this report.

Recommendations

A basic premise of the recommendations of the Working Group, as explained in the U.S.G.S. Open-File Report 02-463 is that procedures and formats should be based on internationally accepted standards and methodologies that are referenced in the geophysical literature and applicable to the entire North American continent. The emphasis is on making the dataset of broad use to the geophysics community. However, international standards and formats do differ depending on the proposed use of the data and accuracy requirements. Procedures also may vary depending on available computational power, software, and collateral data. As a result there is no single universal accepted standard or format. The recent discussion of standardization and errors in Bouguer gravity corrections between LaFahr (1991a; 1991b; and 1998) and Talwani (1998) is evidence that differences in procedures remain a matter of scientific debate.

A fundamental goal of the methodologies is a standardized procedure that provides the observed and theoretical (or predicted) gravity values and, thus, the gravity anomalies at observation sites to an accuracy of the order of a few hundredths of a milligal. This accuracy serves most geologic, geophysical, and geodetic purposes and is compatible with those obtainable in observations and corrections. However, increasing interest in data to a higher accuracy for engineering, environmental, and subsurface reservoir studies indicate that it is advisable to provide formats for gravity data repositories that will accept and maintain data to a higher precision than a hundredth of a milligal.

The long-term goal for gravity anomaly calculations is to provide procedures for specifying the theoretical (or predicted) gravity at an observation site that account for the Earth's sphericity, terrain, and bathymetry in a single correction based on local, regional, and global digital elevation models using appropriate earth-material densities. These calculations may be based on radial elements of a spherical Earth corrected for the appropriate ellipticity. Limitations in current procedures and auxiliary data do not permit achievement of this long-term goal. Clearly, movement toward this goal will be an incremental process with the standards and formats for a North American Gravity Database subject to change. As a result they should be reviewed and evaluated on a regular basis.

Rather than suggest an unrealistic goal that cannot be reached in the near term, the Working Group recommends the acceptance of several currently used assumptions and approximations in the computation of the observed and theoretical gravity values and anomalies. The resulting gravity data for North America will serve most purposes. The goal is to achieve an accuracy approaching a few hundredths of a milligal in the current database, but it is understood that this accuracy will not be reached for all gravity observations and calculations of theoretical gravity at observation sites and anomalies. Many observations, corrections, and anomalies will have an accuracy approaching a tenth of a milligal.

For the most part the recommendations of the Working Group follow closely those made for the U.S. Gravity Database as explained in U.S.G.S. Open-File Report 02-463, but there are notable differences particularly with regard to geodetic datums and resulting modifications in the correction procedure. The overall recommendations specified below include those of the U.S. Gravity Database where appropriate and modifications plus documentation with appropriate references. Alternative approaches are noted where there is significant support for them in the community. Specific recommendations are presented in bold type.

1. Data and Metadata Formats

ASCII format should be used for principal facts and metadata. Separate formats will be needed for land and

marine data. The fields should include not only the principal facts (location, station height, observed gravity, and terrain correction) together with an estimate of their errors, but collateral data such as the source of the data, date of acquisition, date of submission to the NAGDB, observational procedures, instrumentation, type of gravity observation, reference datums used (e.g., the datum used to calculate the ellipsoid height), density used in Bouguer and terrain corrections, related height data such as water depth for marine and lake observations, depth to underground observations, and height above ground surface for airborne surveys, reference (base) gravity station, etc. The standard format of the International Association of Geodesy's Bureau Gravimetrique International should be used wherever possible with additions, deletions, and modifications as recommended for the NAGDB.

Users of the database should be provided with a menu from which they can request specified fields and units. Gravity values should be available in milligals and the SI unit of acceleration, m/s^2. Longitude should be available in either a +360° field or in West longitude degrees. The vertical position of the gravity observation should be available in meters and feet and with reference to the ellipsoid (height) and to the geoid (elevation). The default (preferred) unit for gravity is milligal and meter for vertical distance referenced to the ellipsoid.

Fields should be provided in the format for measurements of the vertical gradient of gravity in Eötvös units and the estimated accuracy of the measurement. It will be desirable to include fields for tensor gravity measurements, when these observations are available to the database.

Geographical coordinates should be in decimal degrees to 7 places, heights (elevations) in meters to 3 places, and gravity observations and anomalies in milligals to 4

places. Digits beyond the accuracy of the data should not be given, i.e., they should be blank filled, not zero filled. If error estimates are unavailable these error fields should be blank. The source of the data should be provided in a field that is keyed to a collateral data set providing metadata on standards, references, procedures, errors, etc.

Components of terrain and isostatic corrections determined by different procedures or to different accuracies should be listed independently. The errors of each component should be estimated and the procedures used in the calculation of the component should be specified.

- Most data sets will not justify the accuracy of the prescribed data format, but the additional digits in the data fields will allow retention of the accuracy of increasingly available high-resolution gravity data that may reach these limits.
- Gravity values included in this format are observed gravity, gravity corrections, and anomalies.
- Metadata that give information on data sources and their attributes as currently residing in databases such as those of the U.S. National Imagery and Mapping Agency should be retained because of their importance in appraising the data set. Similar information should be solicited from all data sets contributed to the NAGDB and placed in the appropriate fields.
- Error estimates should be solicited for station locations, heights, observed gravity, terrain and isostatic corrections, and gravity anomalies of all new data provided to the NAGDB.
- The date of acquisition of the gravity observations as well as the date the data are placed in the NAGDB should be provided. The latter will permit users to interrogate the database for data contributed since the user's last update.
- The preferred (default) observed gravity and gravity anomalies are based on the recommended datums,

constants, and procedures in this report, but it is understood that some users may wish to have gravity values based on other standards. This is particularly true when merging the new data with existing data sets based on other standards. Wherever possible these needs should be met by providing gravity data using alternative datums, constants, and procedures specified by the user.

- Web links should be provided to available descriptions of North American gravity benchmarks (base stations).
- The format for satellite-derived gravity observations should follow standardized procedures used by the U.S. National Imagery and Mapping Agency.

2. Datums

a. Horizontal

The International Terrestrial Reference Frame (WGS84) should be used for the horizontal datum with provision made for optimal conversion to other horizontal datums, e.g., NAD83, NAD27.

- The International Terrestrial Reference Frame (ITRF) is internationally accepted and agrees with the WGS84 reference frame to the one-centimeter level. However, it should be noted that plate motion causes annual movements that may exceed this precision. Precise WGS84 coordinates agree with ITRF coordinates at the ten-centimeter level because WGS84 is a realization of the ITRF using broadcast satellite ephemeris precise to ten centimeters.
- WGS84 has been subject to change. Its third version (National Imagery and Mapping Agency, 2000) is slightly different from the first version of WGS84 and GRS80. GRS80 has not changed since its inception. Although we recommend WGS84 as the vertical and horizontal datums and GRS80 as the reference ellipsoid for theoretical gravity, the two different datums produce no significant relative gravity differences. The gravity difference

between the latest (third) version of WGS84 and GRS80 (or the first version of WGS84) is less than 0.5 microgal for ellipsoid height up to 3000 m worldwide after removing an absolute level of 0.1433 mGal. The gravity difference is mainly caused by the GM difference (0.582) between WGS84 (3896004.418) and GRS (3896005). To avoid confusion among datums of WGS84, we recommend the use of the ITRF datum.

- ITRF is the coordinate system for satellite radar-derived gravity data sets over the oceans.
- Software is readily available for converting from one horizontal coordinate system to another.

b. Vertical

Ellipsoidal height relative to the ITRF (WGS84) datum should be used as the default vertical distance with optimal conversion provided to other vertical datums, e.g., NGVD29, CVGD28, and NAVD88. Additionally, orthometric height (elevation) relative to appropriate national geoid (sea level) should be provided. As a result two heights should be given for each station: the ellipsoid height relative to the ellipsoid and the elevation relative to the accepted geoid for the region.

- No one vertical datum is appropriate for all regions. To achieve consistency the recommendation is to use ellipsoidal height relative to the same ITRF (WGS84) datum suggested for the horizontal (latitude, longitude) coordinates.
- The geoid models GEOID99 in the U.S. and HTv2.0 in Canada, as well as the transformation VERTCON in the U.S., provide software for conversion from one datum to another.
- The recommended use of ITRF (WGS84) is contrary to the suggestion to use the NGVD29 datum for the U.S. Gravity Database (Hildenbrand et al., 2002b).

- Despite the common usage of NGVD29 in gravity studies, NAVD88 is preferable to it because the newer datum removes distortions found in NGVD29.
- Canada can only produce elevations relative to CGVD28, i.e., mean sea level, which is consistent with NGVD29 and Mexico is covered by NAVD88, but not by NGVD29 or CGVD 28.
- A more accurate vertical datum and geoid is imminent from new global gravity data observed during the Grace satellite mission. Accordingly, conversion of NGVD29 gravity-related heights to NAVD88 should be postponed until the GRACE-derived datums are available.
- An ellipsoid-based vertical datum is advantageous because gravity observation positioning is now commonly obtained by GPS that provides the height relative to the ellipsoid. Another advantage of the use of ellipsoid-referenced heights is that the 'indirect effect' of gravity can be eliminated in the calculation of gravity anomalies. This is particularly beneficial to the geophysical use of gravity (Li and Götze, 2001).
- Use of the ellipsoidal height relative to the ITRF (WGS84) datum rather than the height relative to the geoid will produce only very long-wavelength Bouguer and isostatic gravity anomaly differences with amplitudes of less than roughly 10 mGal. As a result the effect of using the ellipsoidal height will be negligible on geological studies and most geophysical investigations.

c. Observed Gravity

Observed gravity should be referenced to IGSN 71 without the Honkasalo term for tidal deformation.

- Observed gravity should be tied to the International Gravity Standardization Net 1971 (IGSN71) (Morelli et al., 1974).

- The IGSN71 values include the Honkasalo (1964) correction for tidal deformation. This correction should be removed (Moritz, 1980), i.e., no tidal correction should be included in IGSN71. Morelli et al. (1974) give the Honkasalo term as

  $$g = 0.0371(1 - 3\sin^2 \varphi) \text{ mGal},$$

  where φ is the latitude. The correction varies from +0.04 at the equator to –0.07 mGal at the poles.
- Standard procedures for reducing gravity measurements to observed gravity should be specified in the tutorial explanatory material accompanying the NAGDB. The use of IUGG recommended procedures is encouraged for tidal corrections, meter 'drift', local atmospheric effects, calibration of gravimeters, and ties to gravity benchmarks.

3. Gravity Corrections

a. *Theoretical (Ellipsoid) Gravity*

Theoretical gravity on the GRS80 ellipsoid should be determined using the Somigliana closed-form equation.

- The theoretical gravity accounting for the mass, shape, and rotation of the Earth is the gravity on the best-fitting ellipsoidal surface of the Earth. The latest ellipsoid recommended by the International Union of Geodesy and Geophysics (IUGG) is the GRS80 (Moritz, 1980). Conversion to more modern ellipsoids has a negligible effect on the theoretical gravity (in the range of thousandths of a milligal). However, this equation should be updated when recommended by the IUGG.
- The Somigliana closed-form formula to calculate the theoretical gravity, g_φ at latitude φ, is

  $$g_{\varphi} = g_e \frac{1 + k\sin^2\varphi}{\sqrt{1 - e^2 \sin^2 \phi}}.$$

where the GRS80 reference ellipsoid has the following values:

$g_e = 978032.67715$ mGal

k = 0.001931851353

e^2 = 0.00669438002290.

- Corrections made in older reference systems can be easily adjusted to the GRS80 system. Alternatively, corrections can be made to previously accepted reference systems when requested by the database user.

b. ***Height Correction***

The height correction should be calculated using the second-order approximation formula of Heiskanen and Moritz (1969) for the change in theoretical gravity based on the GRS80 ellipsoid with height relative to the ellipsoid.

- Historically, this height correction is called the 'free-air' correction and associated with the elevation (or orthometric height) above the geoid (sea level) and not the ellipsoid height.
- Heiskanen and Moritz (1969, p. 79) give the second-order approximation formula for this correction to the theoretical gravity for a height h in meters relative to the ellipsoid as:

$$g_h = -\frac{2g_e}{a}[1 + f + m + (-3f + \tfrac{5}{2}m)\sin^2\varphi]h + \frac{3g_e\, h^2}{a^2}$$

where the GRS80 ellipsoid has the following parameter values:

a = semimajor axis = 6,378.137 km

b = semiminor axis = 6,356.7523141 km

f = flattening = 0.003352810681

g_e = 978,032.67715 mGal

$m = \omega^2 a^2 b / GM$ = 0.00344978600308

ω = angular velocity = 7,292,115 x 10^{-11} radians s^{-1}

GM = geocentric gravitational constant = 3,986,005 x 10^8 m^3s^{-2}.

For the GRS80 ellipsoid the second-order formula is

$$g_h = -(0.3087691 - 0.0004398 \sin^2 \varphi)h + 7.2125 \times 10^{-8} h^2$$

where the ellipsoid height h is in meters and g_h is in milligals.

c. *Bouguer Correction*

The closed-form formula for the gravity effect of a spherical cap (LaFehr, 1991) of radius 166.7 km based on a spherical Earth with a radius of 6371 km, height relative to the ellipsoid, and a density of 2,670 kg/m^3 should be used in calculating the Bouguer correction.

- The Bouguer correction accounts for the gravitational attraction of a layer of the Earth with a thickness equal to the difference in height between the station and the vertical datum; in this case, the ellipsoid.
- This correction, g_{BC}, has traditionally been calculated assuming the Earth between the station and the vertical datum is an infinite horizontal slab, that is $g_{BC} = 2\pi G\sigma h$ where G = gravitational constant = 6.673 +/- 0.01 x 10^{-11} $m^3kg^{-1}s^{-2}$ (Mohr and Taylor, 2001) [Note: This is the most recently accepted value for G and differs from the value provided in GRS80], σ is the density of the horizontal slab in kg/m^3, and h is the height of the station in meters relative to the ellipsoid in the procedure recommended in this report rather than using the elevation H in meters above/below the geoid or sea level. In this formulation the correction is given in units of m/s^2 that is converted to milligals by multiplying by 10^5. To avoid the effect of the curvature of the Earth, the closed-form formula of LaFehr

(1991) for a spherical cap of radius 166.7 km is recommended. According to LaFehr (1991, p. 1181) the selection of the radius of 166.7 km for the spherical cap minimizes "…*the differences between the effect of the cap and that of an infinite horizontal slab for a significant range of elevations.*"

- The choice of a density of 2,670 kg/m^3 for solid-earth material above/below the ellipsoid is based upon an approximation to the average density of the Earth relative to the ellipsoid (Chapin, 1996; Hinze, 2003). In the future the average density of the earth material relative to the ellipsoid over the North American continent may be mapped using deterministic methods. These density data could be incorporated into the Bouguer and terrain corrections as an alternative in calculating Bouguer and isostatic anomalies in future revisions of the NAGDB.
- In the case of marine observations of gravity the density of sea water is assumed as 1,027 kg/m^3, for fresh-water observations of gravity the density of fresh water is 1,000 kg/m^3, and for observations of gravity on glaciers, the density of ice is 917 kg/m^3.

d. *Indirect Effect (Correction)*

The geophysical indirect effect correction is unnecessary if the default vertical datum recommended for the NAGDB (the ellipsoid height relative to the International Terrestrial Reference Frame) is used in calculating the height and Bouguer corrections. Nonetheless this correction should be provided for each station for the user employing the geoid as the vertical datum.

- The 'geophysical' indirect effect, which is applicable to all anomalies, is the gravitational effect produced by use of the elevation (orthometric height) relative to sea level (the geoid) rather than the height relative to the ellipsoid in height-related gravity corrections. The adjective ‘geophysical’ is used to differentiate it from the indirect effect in geodetic studies. The difference between ellipsoid height and elevation is the geoid height that attains maximum values of the order of +/-100 m. The indirect effect due to the use of elevation in the height and simple Bouguer (that assumes a horizontal layer) corrections has the same sign as the geoid height. The gravitational effect of this correction for land observations is 0.1967N mGal/m [(0.3086-2_G{2670})N] where N is the geoid height in meters assuming a density of 2,670 kg/m^3 for the layer between the ellipsoid and the geoid. A similar correction (0.2656N mGal/m) is needed for marine gravity observations assuming a density of 1,027 kg/m^3 for sea water (Chapman and Bodine, 1979).

- The indirect effect is spatially slowly varying because of the low horizontal gradient of the geoid. The amplitude of the geoid height for wavelengths shorter than 10 km is usually smaller than 10 cm, and the amplitude for wavelengths shorter than 100 km is considerably smaller than 1 m.
- The use of a vertical datum which is the ellipsoid height relative to the ITRF (WGS84) eliminates the need for consideration of the geophysical indirect effect. Ellipsoid height is given directly by modern positioning technologies, such as GPS. Thus, the traditional elevation or orthometric height is a derived quantity from the ellipsoidal height. For example, the conversion of the ellipsoidal height relative to the WGS84 ellipsoid to elevations can be accomplished using GEOID99 for the U.S. (see

http://www.ngs.noaa.gov/PUBS Lib/gislis96.html).

- Despite the lack of need for this correction in the preferred procedure it is recommended that it be calculated for each station and be made available to the user from the fields menu of the database.

e. *Terrain (Bathymetry) Effect*

A 3-part terrain effect procedure based on distance from the station should be employed as height data permits, using a density for solid earth material of 2,670 kg/m^3, 1,000 kg/m^3 for fresh water, 1,027 kg/m^3 for ocean water, and 917 kg/m^3 for ice:

1. **Utilize near-station topographic information collected in the field, either by instrumentation or visual estimation, to a distance of about 100 m from the station, to calculate terrain effects using the gravitational attraction of a form of segmented rings centered on the station (e.g., Hammer's (1939) method).**
2. **Use local high-resolution height data to calculate terrain effects to a distance of 895 m using a form of segmented rings centered on the station (e.g., Hammer's [1939] method).**
3. **Employ digital terrain model data to compute terrain effects from 895 m to 166.7 km based on vertical prisms centered on topographic grids using Plouff's (1966) algorithm on 15-sec, 1-min, and 3-min topographic grids and accounting for the Earth's curvature beyond 14 km.**

- The data collector is responsible for obtaining the heights and terrain corrections of Parts 1. and 2. The selection of the outer distance of Part 2. is consistent with the resolution of the 15-sec terrain grid ($\approx$450 m).
- The terrain correction to 895 m can be approximated with Plouff's (1966) program using the 15-sec terrain grid, but it should be stored separately from the corrections of Parts 1 and 3. and users advised of its potential error.
- It is understood that use of elevations (orthometric heights) for both heights of gravity stations and heights in digital terrain models in terrain corrections, rather than heights relative to the ellipsoid, will result in errors due to the indirect effect. The resulting errors are negligible for most geophysical purposes, but for consistency in procedures and to eliminate these errors the ellipsoid height should be used in terrain corrections as soon as practical. The change from digital elevation models to digital height models in the calculation of terrain effects should be implemented in future revisions of the North American Gravity Database.
- Long-term modifications to these procedures should extend the terrain and bathymetry to 500 km and beyond using 2- and 5-min elevation and bathymetry grids and an elliptical Earth. Eventually a global correction should be computed and made available in the NAGDB. Moreover, terrain corrections of improved accuracy especially in the inner zones will become possible as the higher-resolution digital terrain models become available.
- In the long-term, bathymetry corrections are necessary taking into account the density of sea and fresh water as appropriate.

- Improved estimates of the densities of earth materials should be used in future revisions of the NAGDB.
- Solid-earth material density should be modified when densities are available for grid points of digital terrain models.

f. *Atmospheric Effect*

The gravitational effect of the mass of the atmosphere should be determined by linear interpolation with respect to elevation above sea level using the table given in Moritz (1980).

- The mass of the atmosphere is included in the theoretical gravity given by IGF80. The mass of the atmosphere decreases with increasing elevation of a station, thus, decreasing the atmospheric gravity effect.
- The correction for the change in gravity due to the mass of the atmosphere is added to the observed gravity.
- An alternative analytical approach for the atmospheric effect should be incorporated into future revisions of the NAGDB.
- Correction of the observed gravity for local atmospheric mass variations is at the discretion of the data collector. Use of this correction should be noted in the NAGDB's metadata of the contributed survey.

g. *Isostatic Compensation Effect*

The isostatic compensation effect should be calculated with a modified version of Jachens and Roberts (1981) method that assumes local compensation. The isostatic correction for varying depth to a hypothetical crust-mantle boundary caused by differential topographic or bathymetric loads above or below the ellipsoid should be based on a crust-

mantle boundary density difference of __ = 300 kg/m^3 and a crustal thickness of 30 km for sea level surface elevation. Topography is modeled assuming a continental crustal density of 2,670 kg/m^3 using 3-min elements of topography to 166.7 km plus interpolated values to 180^o from Karki et al. (1961).

- The inverse correlation between regional elevations and Bouguer gravity anomalies is interpreted to reflect the gravimetric response to topographic loads by variations of the density of the crust/lithosphere or a change in the thickness of the crust/lithosphere. To remove these subsurface regional effects the response to topographic loads is calculated by making the simplifying assumption that the crust varies in thickness accordingly.
- The isostatic compensation effect is computed in a manner similar to the terrain model using the Airy-Heiskanen model. In the near term this will be done using a modified version of Jachens and Roberts (1981) method. However, in the long-term consideration should be given to performing these calculations using a method in the space domain consistent with the procedures for calculating the terrain and bathymetry with appropriate global digital terrain models and taking into account the ellipticity of the Earth. It is important to extend the calculation of the effect of isostatic compensation to the entire Earth.
- It is understood that use of (orthometric) elevations in isostatic corrections rather than heights relative to the ellipsoid will result in errors due to the indirect effect, as is the case for terrain corrections. The resulting errors are negligible for most geophysical purposes, but for consistency in procedures and to eliminate these errors the ellipsoid height should be used

in isostatic corrections as soon as practical. The change from digital elevation models to digital height models in the calculation of isostatic effects should be implemented in future revisions of the North American Gravity Database.

- The interpolated values from Karki et al. (1961) need to be replaced by an analytical form in future revisions of the NAGDB.
- The crust-mantle density differential is based on the average density of the lower 10 km of the average global continental crust and the density of the uppermost mantle. The density of the 10 km layer at the base of the crust is assumed to consist of 50% mafic granulite and 50% mafic garnet granulite that results in an average density of 3,040 kg/m^3 (Christensen and Mooney, 1995; Figure 18). The uppermost mantle is assumed to consist primarily of peridotite and has a compressional seismic wave velocity of 8.1 km/s. The corresponding density is 3,340 kg/m^3 (Christensen and Mooney, 1995; Figure 16).
- The average global continental crustal thickness weighted for crustal type is roughly 40 km (Christensen and Mooney, 1995; Figure 18). Based on the average continental elevation of 1 km and assuming isostasy, the sea level crustal thickness is approximately 30 km. Both the crust-mantle density contrast and the crustal thickness will vary not only from continental to oceanic crust, but also with geologic/tectonic/petrophysical conditions. However, isostatic effects obtained from different crustal models vary by only a small percentage of their overall effect (e.g., Simpson, Jachens, Blakely, and Saltus, 1986).
- In the long term consideration should be given to improving the computational techniques employed in computing the isostatic

compensation effect and the associated parameters.

4. Gravity Anomalies

a. *Free-Air Gravity Anomaly*

Calculate the Free-Air Gravity Anomaly by determining the difference between the observed gravity and the theoretical (predicted) gravity at the station taking into account the theoretical gravity on the GRS80 ellipsoid, the height of the station above the ellipsoid and the atmospheric effect.

b. *Complete Bouguer Gravity Anomaly*

Calculate the Bouguer Gravity Anomaly by determining the difference between the observed gravity and the theoretical (predicted) gravity at the station taking into account the theoretical gravity on the GRS80 ellipsoid, the height of the station above the ellipsoid, the Bouguer and terrain effects, and the atmospheric effect.

- Users should have the option of selecting the solid-earth material density used in the calculation of the Bouguer correction and terrain effects for the Bouguer Gravity Anomaly. This also applies to the Isostatic Gravity Anomaly.
- In the future it may be possible to request a variable density for the Bouguer correction and terrain effects based on estimates of the density of solid-earth materials over the North American continent. This also applies to Isostatic Gravity Anomaly.

c. *Isostatic Gravity Anomaly*

Calculate the Isostatic Gravity Anomaly by determining the difference between the observed gravity and the theoretical

(predicted) gravity at the station taking into account the theoretical gravity on the GRS80 ellipsoid, the height of the station above the ellipsoid, the Bouguer and terrain effects, the atmospheric effect, and the isostatic compensation effect.

d. *Gravity Anomalies for Geodesy*

Precedent is given to 'geophysical' gravity anomalies in the North American Gravity Database. However, consideration of geodetic gravity anomalies is facilitated by the availability of both height relative to the ellipsoid and elevation relative to the regionally accepted geoid in 2.b., the use of both elevation and height in the calculation of the terrain (3.e.) and the isostatic compensation effect (3.g.), and the geophysical indirect effect (3.d.) for each station.

5. Updating the Standards and Format of the North American Gravity Database

The preferred standards and formats recommended above are a useful starting point in preparing a NAGDB. They are achievable in the near term building upon existing software and procedures and will provide very useful gravity anomaly data for a wide range of geoscientists. However, as explained in the above recommendations, improvements are possible in these standards and formats that will serve the interests of the community of users. We suggest that the standards and format of the database be monitored for modifications that can be made to improve its accuracy, effectiveness, and efficiency using the suggestions provided herein as a starting point. For example, we anticipate that the GRACE satellite mission will lead to definition of

an improved global geoid that will improve the NAGDB. Potential contributors of gravity data to the NAGDB should be alerted to the desired metadata including error estimates that are desired for the database.

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