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Case study

GTeC—A versatile MATLAB® tool for a detailed computation of the terrain correction and Bouguer gravity anomalies

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ABSTRACT

Gravity **Te**rrain **C**orrection (GTeC) is a versatile MATLAB® code for terrain correction aimed to this purpose and capable of going beyond the limits of other public domain codes targeted to this aim.

It runs with input gravity data (absolute measurements or free air anomalies) at the land/sea surface and with one or more DTMs (indifferently gridded or scattered) at different detail levels. Each of them can be used to calculate the gravity contribution of a concentric terrain zone around the point station with increasing resolution toward the center. The user can choose between two alternative algorithms for terrain modeling. The simplest one considers each grid point as the flat top of a squared prism. For areas closer to the point station a second algorithm can be chosen to better approximate the relief, with respect to others formulas, by means of a tessellation based network formed by triangular prisms. A more precise terrain correction is therefore achieved, especially in presence of high topographic gradients or just outside the sea/land boundaries. In the last case a suitable algorithm was expressly devised to fit the tessellation based network to the irregular trend of the coastline.

GTeC calculates also free air anomalies and both plate and curvature corrections, providing also a complete graphic output including topography, free air anomalies, plate correction, total terrain correction, Bouguer anomalies and the terrain effect due to each computational zone.

GTeC speeds up CPU times taking advantage from the parallel computing functions and from the vectorization code, both exploited in MATLAB®. Two code versions of GTeC (for normal or parallel computation), executable under MATLAB environment (pcode), are fully available as public domain software.

The results of a synthetic case, of a real case at the regional scale and of a microgravity survey carried out at a short scale, are here presented.

1. Introduction

The concept of gravity anomaly concerns the numerical difference between measured gravity and theoretical gravity expected. It needs a number of corrections to the theoretical value that are usually referred to the instrumental drift, the earth tides, the latitude of the point station and to its elevation above the reference level (e.g. the sea level).

After calculated the free air anomalies by means of a simplified formula (Lambert, 1930; Heiskanen and Moritz, 1967), the gravity effect due to masses not included in the reference spheroid has to be removed by adding to the free-air anomaly the Bouguer correction that is usually calculated in three steps. Firstly, the slab correction (Bullard A), approximates the relief to an horizontal infinite slab with thickness equal to the elevation of the station on the reference level.

The second step is the curvature correction (Bullard B), firstly applied by Bullard (1936). It takes into account the curvature of the Earth surface modifying the infinite slab modeled with the Bullard A to a spherical cap with the same thickness and extended up to a proper distance (usually ≈ 167 km) from the point measurement. Among the authors that developed approximations for Bullard B (LaFehr, 1991; Whitman 1991) suggested a simplified formula that speeds up the computation preserving the precision.

However, the reliefs placed above the elevation of the point station pull up on the instrument but they are not included within the slab. In addition, the lack of rock below the station, due to the sea bed terrain, decreases the observed value of gravity. Moreover, the slab correction erroneously assigns the reference density also to the cavities represented by the valleys within the slab.

The terrain correction (Bullard C) provides for such an overcompensation introduced in the previous cases by the slab correction. Hayford and Bowie (1912) firstly applied to gravity measurements a correction to take into account the effect of the

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topographic ondulations of the earth surface.

The idea of automatic computing was early proposed to overcome the well known problems related to the traditional methods (Hammer, 1939) in terms of both long time spent for calculations and precision depending on average heights estimated at a glance.

Bott (1959) and Kane (1962) firstly used gridded elevation data and formulas for the gravitational effect of regular solids to perform a computer-aided terrain correction but only for the distant zone, whereas Karlemo (1963) carried out the computations in two stages using two nets and including the near region as well.

Olivier and Simard (1981) developed a terrain correction based on the conic prism model. Ketalaar (1987) adopted the formula for a square vertical prism with a sloping surface to better approximate the real topographic surface. Cogbill (1990) approximated the innermost terrain surface using the rectangular integration rule of Renka and Cline (1984). Ma and Watts (1994) modeled the distant topography as distribution of masses along vertical lines and the near and inner zones as a set of, respectively, rectangular and triangular prisms with sloping upper face.

The terrain representation was also carried out by means of a set of Gaussian functions (Herrera-Barrientos and Fernandez, 1991) or of the Fourier methods to convert a power series for the topographic elevation into a series of convolutions (Parker, 1995, 1996). The method speeds up the CPU time consuming but Tsoulis (1998) reported problems with dense topographic grids causing divergence and Gomez et al. (2013) confirmed significant overestimation at high elevations with respect to the classical integration.

Other authors suggested techniques based on spherical harmonic of the terrain elevation developed to the third power (Nahavandchi and Sjoberg, 1998). Banerjee (1998) uses digital terrain data for the outer zone and station-dependent compartmentalized data for the inner zone by approximating the relief with equiangular sector of conic prism models.

Hwang et al. (2003) suggested to approximate the terrain by means of a point-wise algorithm based on the Gaussian quadrature. Fullea et al. (2008) calculate the gravitational effect due to a flat topped squared prism for the outer and intermediate zones using, respectively, the McMillan (1958) and that Nagy et al. (2000) formulas. Following Lopez (1990), they divide the innermost zone in four quadrants and approximate the relief falling inside each of them into one-fourth of conic prism with its vertex coinciding with the point station.

Some authors (Lopez, 1990; Hwang et al., 2003; Banerjee, 1998, Fullea et al., 2008), made available the code lists to run their programs. Nevertheless, they seem to manage the digital terrain models under too restrictive conditions, limiting their practical application.

As an example, only the program released by Fullea et al. (2008) seems to deal with the terrain correction also with offshore point stations. Moreover, it is not clear whether and how the other available codes make calculations with points station nearby the shorelines, perhaps with high slope gradients.

Lopez (1990) prescribes the use of a single DTM with a step grid fixed at 1 km and limited at a 40×40 km^2 wide zone around the station. Hwang et al. (2003) divide the terrain around each station only in two zones (outer and inner) making difficult in some cases a versatile management of the available data sets. Again, a more precise computation is set only in a small, fixed, area delimited by only the eight elevation points surrounding the station and divided into octants (Lopez, 1990) or conic prisms (Banerjee, 1998; Fullea et al., 2008). In addition, in both cases the chosen shape slopes from the apex, coinciding with the station, toward each outer edge placed to a given height. Since this edge is delimited by two adjacent DTM grid points at different eights, an unavoidable error affects a precise reproduction just where it should be needed. On the other hand, the program by Fullea et al. (2008) runs only if DTM data are both gridded and coinciding with the gravity (free air) data. This condition is strongly restrictive because it is satisfied only in some cases (i.e. satellite-derived data) but not when gravity measurements are taken on scattered point stations.

2.1. Gravity corrections

Among all the input data sets (gravity meter measurements, normal gravity, geodetic latitude, free air anomaly) GTeC checks which input data are available and individuates which output is computable and which not, showing a warning message, if needed. In fact GTeC provides the complete Bouguer anomaly calculating normal gravity, free air correction, free air anomaly, plate correction, curvature correction and, finally, terrain correction.

GTeC runs accepting, indifferently, both free air anomalies and instrumental measurements as input data. When geodetic latitudes and instrumental measurements are available (referred to the *International Gravity Standardization Net 1971*–IGSN71), the program calculates the normal gravity on the Geodetic Reference System 1980 (GRS80) ellipsoid using the Somigliana's formula, considered more accurate than those based on the first and second Chebyshev approximations.

In a second step, the free air correction is calculated by applying the reduction by Heiskanen and Moritz (1967) based on the GRS80 parameters.

The curvature correction (Bullard B) should be applied as a refinement of the plate correction because it minimizes the difference between the gravity effect of the horizontal slab and that of the real spherical cap due to the Earth curvature. If required, GTeC calculates the Bullard B basing on Whitman (1991) and decreasing the computation time as a counterweight to a quite small loss of precision (less than 1 μGal for Bouguer slabs of thickness up to 4 km).

The program can therefore calculate the simple Bouguer anomaly. Finally, the last and most crucial step of the procedure, namely the terrain correction, is carried out as described in the next section.

2.2. Terrain correction by GTeC: general features

GTeC accepts measurements points with regular or scattered distribution. Also the digital terrain models used as input data can consist in topographic elevations both equi-spaced and irregularly distributed above the surface. Like most terrain correction algorithms, also GTeC needs only gridded DTM. Therefore, in case of input scattered elevations, the program automatically interpolates the data with the most appropriate grid size chosen by the user.

GTeC uses from one to four topographic data sets to take advantage from an increasing accuracy toward the point station if more digital elevation models with different resolution are available. Therefore, the whole area considered for terrain correction is divided in five computational zones: distant zone (zone I), intermediate zone (zone II), internal zone (zone III), closest zone (zone IV) and near station zone (zone V).

However, all elevation points have to be positioned so that each grid is exactly nested inside the other, thus filling the blank volumes existing between prisms of adjoining data sets. This is an uncommon case and therefore, it is necessary to re-grid each DTM to meet such a requirement. GTeC can automatically perform this step. Data interpolation is a crucial task because output grids can strongly change depending on the chosen interpolating algorithm. In this case GTeC performs a Delaunay triangulation of the data creating a mesh of triangles with planar surfaces for each triangle (linear interpolation). However, DTMs are usually gridded and this makes easier the task, since the interpolation of data in a uniform