*Paper 105*

# A Program to Model and Interpret Borehole Gravity Data

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## ABSTRACT

*The development of a borehole gravimeter for the mining industry allows unique applications such as remote detection of ore bodies, excess mass determination, verification of surface and airborne gravity anomalies, and quantitative bulk density information about the formations intersected by the hole. The combination of surface and borehole gravity data also improves depth and geometry resolution of 3D gravity modelling. We have developed an interactive 3D modelling software based on the surface integral approach. Geological structures are meshed using polyhedrons and the gravity response along boreholes and at ground surface is computed using a surface integral over the facets delimiting the bodies. The vertical component of the gravity response* $g_z$ *and its vertical gradient* $g_z / z$ *are modelled, assuming free-air corrected data. The software is programmed in Java. It includes a graphical user interface to import or generate as well as to visualize the model, borehole trajectories and surface stations in 3D, to perform the calculations, and to view the synthetic gravity responses along with measured data. Hence, the software can be used to estimate the gravity anomaly from generic or complex models, or to interpret survey data.*

## INTRODUCTION

Borehole gravity measurements reflect the distribution of rock densities at depth with greater target sensitivity and spatial resolution than surface measurements. In conjunction with geological information and other geophysical parameters, continuously logged borehole gravity data provide input for 3D quantitative modelling of subsurface environments. In addition to the usual exploration applications, borehole gravity measurements have the unique ability to provide quantitative, bulk-density information about the formations being traversed by the hole. In several stages of mining activity, including deposit evaluation, mine planning and grade control, it is important to have an accurate measure of the bulk density of the ore.

Scintrex is now developing a gravity sensor based on its well proven quartz element technology which is small enough in diameter to enter the exploratory boreholes commonly drilled in mining programs, while retaining the same sensitivity as current surface gravimeters. As part of the project, the applied geophysics group of École Polytechnique de Montréal is working with Scintrex to develop a software package to interpret logging results and to predict the subsurface gravity from modelled geology. In this contribution, this software package is presented along with a case example.

## THEORETICAL BACKGROUND

There are two general approaches to three-dimensional discretization of solid volumes: regular grids composed of cells of cuboidal shapes, and irregular grids built with polyhedrons of arbitrary shapes. The former is also a particular case of the latter. Sharp topographic relief and geological bodies of complex shapes are usually more accurately described by polyhedrons with arbitrary number of faces than with regular grids. The topology of arbitrary polyhedrons is however more challenging to handle. Nevertheless, the ability to compute the gravity response of arbitrary polyhedron is favoured because specialized computer libraries facilitate their creation and processing. Numerous authors proposed algorithms allowing this computation. (Barnett 1976; Götze and Lahmeyer 1988; Coggon 1976). We retained the approach of Singh and Guptasarma (2001) for its simplicity and efficiency.

In the approach of Singh and Guptasarma (2001), a fictitious distribution of surface mass-density on the envelop of a solid body is defined to compute efficiently the gravity field due to the body. This surface mass-density is derived from the surface integral expression of the gravity field vector F

$$\mathbf{F} = G\rho \iint (1/r)(\mathbf{r}/r)\cdot\mathbf{u}_{\mathbf{n}}\,ds = G\iint (\rho\mathbf{r}\cdot\mathbf{u}_{\mathbf{n}})/r^2 ds\,,$$

where G is the universal gravitational constant, ρ is the uniform volume density of the body, un is the unit outward normal vector at the surface element ds and r is the vector pointing from the observation point to the element of surface ds. The term

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$(\rho \mathbf{r} \cdot \mathbf{u_n})$ has units of mass per squared area, and is coined surface mass density. For one of the plane facets bounding the body, each component of vector F can be obtained (Guptasarma and Singh 1999)

$$F_x = G\rho \iint \mathbf{r} \cdot \mathbf{u_n} (x/r^3) ds,$$
$$F_y = G\rho \iint \mathbf{r} \cdot \mathbf{u_n} (y/r^3) ds,$$
$$F_z = G\rho \iint \mathbf{r} \cdot \mathbf{u_n} (z/r^3) ds.$$

The originality of the approach is in the evaluation of the surface integrals. Guptasarma and Singh (1999) developed expressions to transform this surface integral into a function of the solid angle $\Omega$ subtended by ds at the origin and three line integrals over the edges of the facets, denoted P, Q and R respectively. The components of vector F become

$$F_x = -G\rho d(l\Omega + nQ - mR),$$
$$F_y = -G\rho d(m\Omega + lR - nP),$$
$$F_z = -G\rho d(n\Omega + mP - lQ),$$

where $d = r \cdot u_n$ and (l,m,n) are the components of $u_n$. The computation of the coefficients $\Omega$, P, Q and R is fairly straightforward, as shown in Guptasarma and Singh (1999).

## SOFTWARE DESCRIPTION

The software is programmed in Java (http://java.sun.com). A graphical user interface was developed to generate or import the model, to visualize the model, borehole trajectories and surface stations in 3D, to perform the calculations, and to view and compare modeled and measured gravity data. The 3D visualization components of the software are programmed using the open source VTK library (Visualization toolkit, http://www.vtk.org). The software relies extensively on the capabilities of the VTK library to optimize the creation and management of the polyhedrons used in the calculation of the gravity response.

### Geological model management

The geological models can be built entirely by the user inside the software, or created outside in a third party application such as GoCAD and subsequently imported. Both types of model are managed differently; with a "simple" mode for user defined models and a "complex" mode for imported models.

In the simple mode, four primitive shapes are available to build model components: cone, cuboid, cylinder and ellipsoid. Topography is not considered in this mode, and to optimize the calculations the background is set to null. As a consequence, a density contrast value is assigned to each earth body constituting the model. Figure 1 shows the graphical user interface for the construction of simple models, with an example of a cylinder and ellipsoid.

In the complex mode, models with complex geological bodies, heterogeneous background or severe topographic relief can be considered. In the program, the user is allowed to change the density of any cell of the model, but cannot change their shape or position.

### Survey data

Borehole and surface survey data can be incorporated into a modelling project. The survey gravity data need to be corrected for regional, free air, latitude, and drift before input to the program. If field data are not available, the user can define synthetic boreholes and surface profiles in order to compute the anticipated response over the selected geological model.

### Visualization of the results

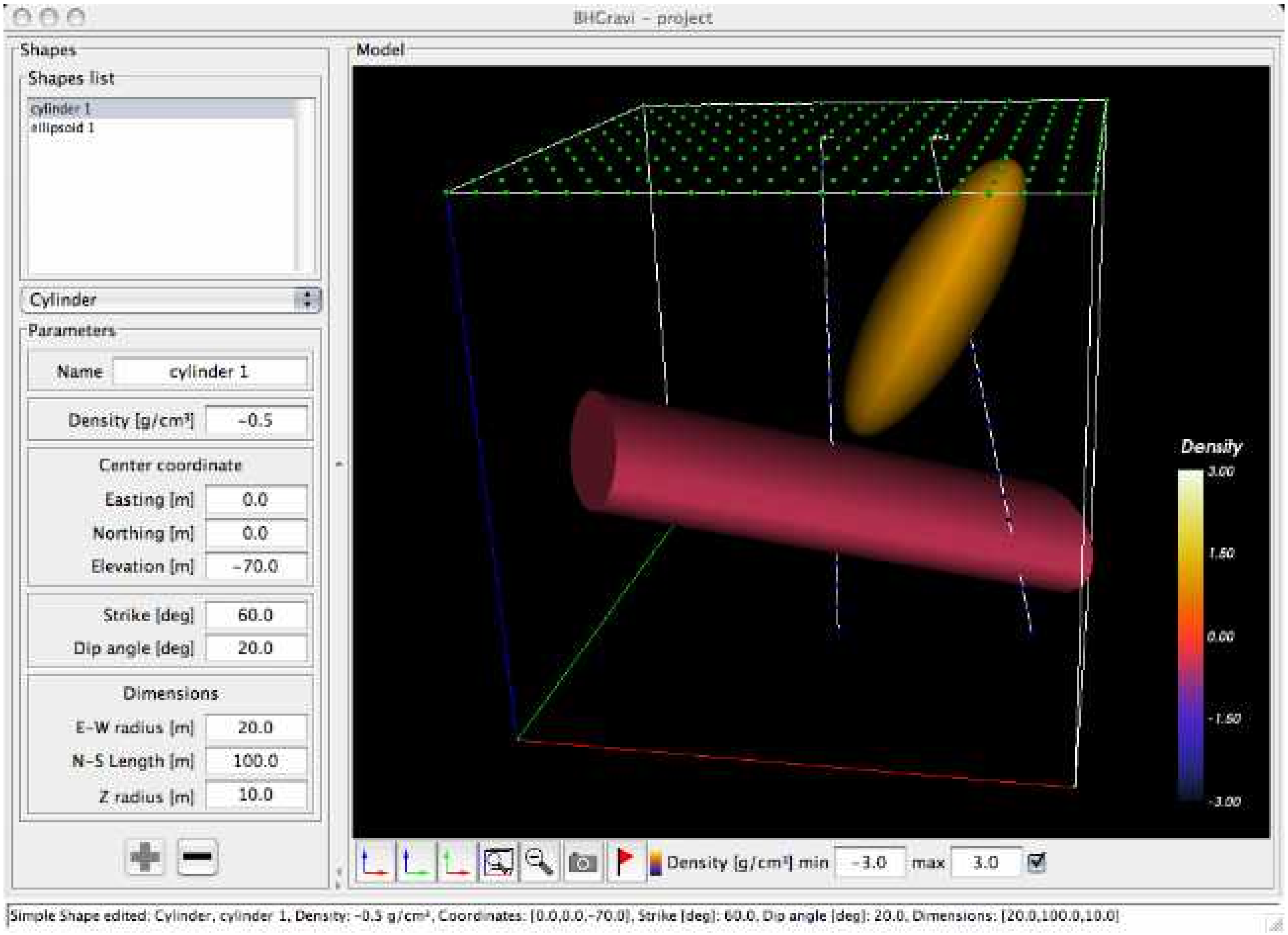
Computed borehole $g_z$ and $g_z/ z$ profiles and surface $g_z$ values can be plotted along with field data for direct comparison. The plots can be saved as images, and the computed responses can be exported in ASCII format for further processing in third party applications.

## CASE EXAMPLE

The borehole gravity response of Inco's well documented Kelly Lake Ni/Cu sulphide ore body, located in the Sudbury mining camp has been modelled to illustrate some of the possibilities offered by the software. At Kelly Lake, the ore body consists of three distinct zones. The two smaller zones are between 100 and 600 m depth. The main zone is 700 to 1600 m deep. Depths are measured from the surface, which is between 200 to 300 m ASL. The bodies have been delineated by intensive drilling and densities within the zones have been estimated for blocks of 5m x 5m x 5m from cores and density (gamma-gamma) logging. The igneous host rock density is about 2.8 g/cm$^3$, and the density contrast of the ore body zones with the host rock varies from zero to about 1.3 g/cm$^3$.

The structural complexity of the Kelly Lake ore body is evident in the figures below. The borehole gravity response will be complex, with anomalies indicating pockets of excess mass (high density) within the zones. We have used this real-world ore body to model four distinct scenarios that could occur in borehole gravity surveys. The vertical component of the gravity response $g_z$ and the vertical gradient $g_z/ z$ are modelled for the effect of the excess mass, assuming that all corrections summarized above have been applied.

Figure 2 shows the case of a vertical hole that would have missed the Kelly Lake bodies. The vertical gravity anomaly, $g_z$, and the vertical gravity gradient anomaly, $g_z/ z$, are represented on the right side of Figure 2 by solid and dashed lines respectively. The vertical gravity anomaly, $g_z$, will be positive when the gravity meter is above a high density pocket and negative below, with a cross-over opposite the pocket, due to excess mass at this location in the ore body. There are two recognizable $g_z$ anomalies on this profile. The shallower anomaly shows a peak to peak response of about 200 µGal with a cross-over at about 300m depth (surface at 250m ASL) and a separation between peaks of about 250m. The vertical gravity gradient anomaly, $g_z/ z$, has a positive peak at about 310m depth, coincident with the $g_z$ cross-over. These results indicate the presence of excess mass at a distance of about 250m from



Cylinder

Parameters

Name: cylinder 1

Density [g/cm³]: -0.5

Center coordinate

Easting [m]: 0.0

Northing [m]: 0.0

Elevation [m]: -70.0

Strike [deg]: 60.0

Dip angle [deg]: 20.0

Dimensions

E-W radius [m]: 20.0

N-S Length [m]: 100.0

Z radius [m]: 10.0

Density [g/cm³] min -3.0 max 3.0 ☑

Simple Shape edited: Cylinder, cylinder 1, Density: -0.5 g/cm³, Coordinates: [0.0,0.0,-70.0], Strike [deg]: 60.0, Dip angle [deg]: 20.0, Dimensions: [20.0,100.0,10.0]

**Figure 1:** Illustration of the graphical user interface of the software in the “simple” model mode. The borehole stations and trajectories are represented by the blue dots and white lines respectively, and the surface stations are indicated by the green dots. Two bodies are included: a large low density cylinder and a smaller high density ellipsoid.

the borehole at a depth of about 300m. The borehole passes between the two shallower zones of the ore body at this location, as indicated in Figure 2. A second $g_z$ anomaly is evident in Figure 2, with a cross-over at about 900m depth, a peak-to-peak response of about 150 µGal and a peak-to-peak separation of about 400m. There is a $g_z$/ z peak at about 850m depth. These results indicate the presence of excess mass at a distance of about 400m from the borehole at a depth of 850-900m. Referring to Figure 2, the borehole gravity response is indicating a pocket of high density near the top of the deeper zone of the Kelly Lake ore body. This is consistent with the density model of the ore body. The borehole gravity data in Figure 2 clearly indicate the presence of shallow zone of excess mass remote from the borehole. The deeper zone is somewhat visible in $g_z$ data and difficult to visualize in $g_z$ / z at the present scale of display.

Figure 3 shows the case of a dipping hole that intersects one of the shallow zones of the ore body. The $g_z$ cross-over in the vicinity of the intersection at a depth of 375 m shows a peak-to-peak response of about 150 µGal. The $g_z$ / z peak coincides with the $g_z$ cross-over. The responses from 375 m to 500 m depth are complex, indicating that the intersection is not a simple one and may actually be a number of individual lenses of varying densities within this depth range. There is a clear indication of another massive body at depth at the bottom of both $g_z$ and $g_z$/ z logs, suggesting that the hole should be extended.

## CONCLUSION

An interactive 3D modelling software was developed to interpret borehole gravity data and to predict the subsurface gravity from modelled geology. The core computing routines are based on an efficient surface integral approach, and the software relies on an optimized visualization library to generate and manage the polyhedrons that build the geological model. Near-future developments include 3D stochastic gravity inversion using cokriging and cosimulation. The inversion method will allow inclusion of density constraints and geological boundaries.

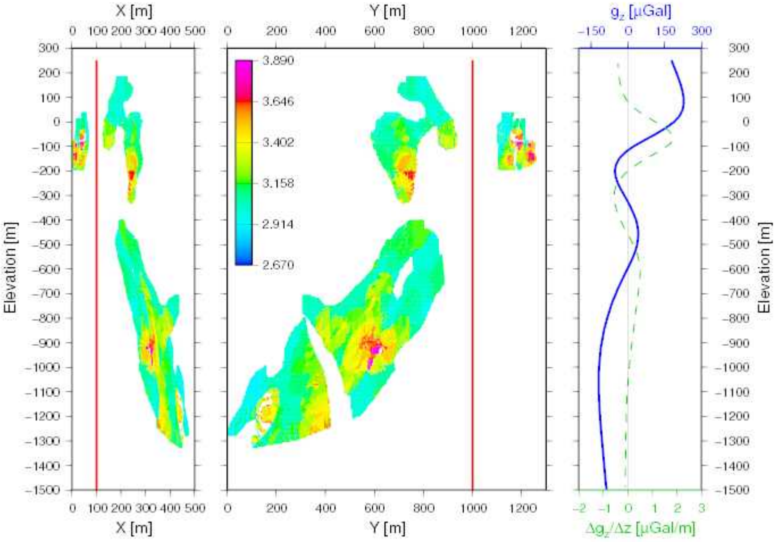


**Figure 2:** The borehole has missed the Kelly Lake ore body. The density model of the three zones in the ore body is shown projected into the xz (left) and yz (middle) planes along with the trace of the borehole. The panel on the right displays computed profiles of the vertical component of gravity, $g_z$,, (solid line) and the vertical gradient of gravity, $g_z$ / z, (dashed line). The colour bar shows the density distribution in gm/cm3. The host rock density is 2.8 g/cm3. The borehole gravity profiles show $g_z$ cross-overs and $g_z$ / z peaks corresponding to off-hole excess masses, indicating both shallow and deep zones remote from the borehole.

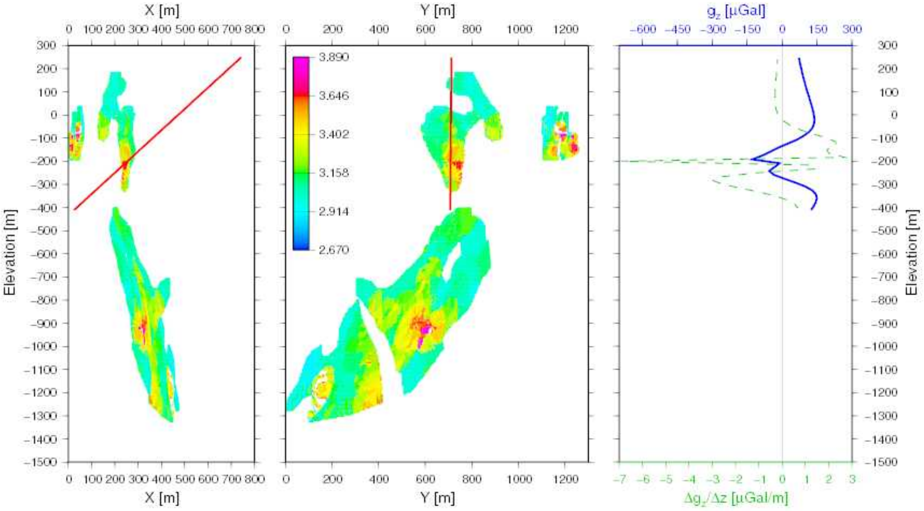


**Figure 3:** The borehole has intersected one of the shallow zones in the Kelly Lake ore body. The gravity responses display abrupt and complex changes in the vicinity of the intersection. There is evidence of a deeper zone below the bottom of the borehole.

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