ERTH 4121
Gravity and Magnetic Exploration
Session 5
Gravity forward modelling
Lecture schedule (subject to change)

Minimum 10 x 3 hour lecture sessions: 1:30pm Tuesdays

Aug 2: 1. Introduction to gravity method 1
        2. Introduction to gravity method 2
        3. Introduction to magnetics method 1
        4. Introduction to magnetics method 2
          [1st assignment]
Sept 13: 5. Gravity forward modelling
        6. Magnetics forward modelling
          [Term break]
Oct 4: 7. Introduction to inversion 1
Oct 7?: 8. Introduction to inversion 2
Oct 18: 10. Magnetics inversion
ERTH4121 Assignment #1

Due next class: Sept 22nd

Any questions?
Topics – Gravity Fwd Modelling

- Introduction to Forward Modelling
- Principle of Superposition
- Gravity of spherical shell
- Gravity inside spherical shell
- Gravity inside homogeneous sphere
- Model parameterisation
- Terrain modelling
- VPmg gravity algorithm
- Some modelling considerations
- Introduction to VPmg files
- Introduction to VPview
The Forward Problem

**Given:** Estimates or values of the Earth System (model parameters)

**Determine:** The theoretical responses (data)

### The Forward Process

- **Input:** Model Parameters (size, shape, contrast)
- **Operator:** Physics of the System (Forward Theory)
- **Output:** Computed Response (magnetic, seismic or electrical data etc...)

**Physics of the System**
Forward modelling

Calculate the synthetic data for a given model

Prime considerations:

Model parameterisation: resolution/speed trade-off
range of shapes

Physical approximations: true TMI
remanence
self-demagnetisation (BV problem)
cavity correction (downhole magnetics)

Numerical approximations: accuracy/speed trade-off

Filtering: airborne gradient data
Forward Modelling

2D/2.5D polygonal models

3D laminae models

3D polyhedral models

3D block models
**Principle of superposition**

Gravity due to several masses is the sum of their individual gravity. Therefore, total potential from a density distribution throughout volume \( V \) is the sum of the individual point mass potentials:

\[
U(\vec{r}) = G \int_{V} \frac{dm}{|\vec{r} - \vec{r}'|} = G \int_{V} \frac{\rho(\vec{r}')dV}{|\vec{r} - \vec{r}'|}
\]
Gravity due to spherical shell: external point

Blakely, 1995, pp49-51

\[ U_P = G \int_V \frac{dm}{r} = G \int_S \frac{\sigma ds}{r} = 2\pi G \sigma a^2 \int_0^\pi \frac{\sin \theta}{r} d\theta \]

where \( \sigma \) is the surface density (mass/unit area).

Using the Cosine Rule,

\[ r^2 = R^2 + a^2 - 2aR \cos \theta \]

Hence,

\[ \sin \theta d\theta = \frac{rdr}{aR} \]

Substituting, and converting to an integral w.r.t. \( r \),

\[ U_P = \frac{2\pi G \sigma a}{R} \int_{R-a}^{R+a} dr = 4\pi a^2 \sigma \frac{G}{R} = \frac{mG}{R} \]

where \( m \) is the total mass of the spherical shell.

Spherical shell gravity is identical to that for point mass at its centre
2.4 The gravity anomalies of simple shapes

- The sphere
- The horizontal cylinder
- The horizontal truncated thin sheet
- The horizontal cylinder of arbitrary cross section

The gravity anomalies of several bodies of simple shape serve to illustrate the form and size of anomalies expected in typical field surveys.

http://appliedgeophysics.lbl.gov/gravity/index.html
Gravity response of a sphere
Gravity due to spherical shell: internal point

(Blakely, 1995, pp49-51)

\[ U_P = G \int \frac{dm}{r} = G \int \frac{\sigma ds}{r} = 2\pi G \sigma a^2 \int_0^\pi \frac{\sin \theta d\theta}{r} \]

\[ r^2 = R^2 + a^2 - 2aR \cos \theta \]

\[ \sin \theta d\theta = \frac{r dr}{aR} \]

\[ U_P = \frac{2\pi G \sigma a}{R} \int_{a-R}^{a+R} dr = 4\pi G \sigma a \]

Potential inside spherical shell is constant, therefore gravity is?
Gravity due to spherical shell: internal point

Consider a tight cone, solid angle $d\Omega$, with apex at $P$.

Gravity from cap subtended at the top of the sphere:

$$g_{\text{top}} \approx -\frac{G(\sigma b^2 d\Omega)}{b^2}$$

Gravity from cap subtended at the bottom of the sphere:

$$g_{\text{bot}} \approx \frac{G\sigma(2a-b)^2 d\Omega}{(2a-b)^2}$$
Gravity inside a homogeneous sphere

(Blakely, 1995, pp51-53)

Contribution from material at radii > R

Integrate concentric spherical shells:

\[
U_{r>R} = 4\pi G \int_R^a (\rho dr)r = 2\pi G \rho \left( a^2 - R^2 \right)
\]

where areal density \( \sigma \) has been replaced by \( \rho dr \)
Gravity inside a homogeneous sphere (cont’d)

Contribution from material at radii \( r < R \) is

\[
U_{r<R} = \frac{GM}{R}
\]

Mass of sphere with radius \( R \) is ?

Combining contributions from \( r > R \) and \( r < R \):

\[
U_p = \frac{2\pi G \rho}{3} \left( 3a^2 - R^2 \right)
\]

Therefore gravity varies in ?? fashion with depth
Earth model parameterisation

Geometry, geology, rock properties

- “Reduces” non-uniqueness - exclude certain model types
- Imposes desired/achievable resolution.
- Defines model volume: 3D spatial extent, relevant data coverage
- Implications for separation of local and regional effects.

Prismatic body inversion:
cast interpretation in terms of simple geometrical shapes, small number of params
=> over-determined
"Traditional" quantitative interpretation

For example, use a simple dipping slab model to site an exploration drill hole. Define 7 parameters: dip, strike, density, depth-to-top, strike extent, dip extent, true thickness.

Various formulae:
Telford et al., 1990, pp35-46
http://appliedgeophysics.lbl.gov/gravity/index.html

Survey Parameters

Number of Stations

51

Scale

0.1 km

Model Parameters

Density Contrast

1.0 grams per cubic centimeter (Body Density - Host Density)
2D Earth model parameterisation: Bosch

Joint inversion of gravity & magnetics

triangular cells, variable in size
stratigraphic => reduce number of property parameters, retain topological significance of contacts
allows heterogeneity within each lithology
finite lateral & vertical extent
parameters are physically different: properties of cells, positions of nodes
geo-statistical characterisation of rock properties for each lithology

Impose geological & petrophysical constraints (as well as geophysical data constraints)
2D parameterisation (Bosch)

(magnetic data (100 x nT))

Depth (km)

susceptibility

gravity data (mGal)

Depth (km)

density

lithotype

(property)

(property)

lithology

(after Bosch & McGaughey, 2001)
Physical Property Considerations

- Models should honour all geological control (outcrop positions, drillhole intersections) and petrophysical control (core measurements, borehole logs).

- Physical properties should preferably be measured (on core, or downhole) but in many cases starting values must be inferred from published tabulations.

- Ideally, define the statistical distribution of physical property for each geological unit.

- Honour physical property measurements, i.e. assign measured values in their true 3D locations. In practice, the model cells are usually much larger in volume than the hand sample (or downhole ‘excitation volume’). Therefore, assignment of an appropriate value to the model cell enclosing the measurement is not always straightforward.

- If spatial density of physical property measurements is adequate, the physical property distribution can be modelled. Options range from simple 3D interpolation to sophisticated geostatistical modelling. The measured gravity or other data can serve as constraints on the geostatistical modelling.
The gravitational attraction of a prism at the origin is:

\[
F_z = G \rho \left[ x \ln (y + r) + y \ln (x + r) - z \arcsin \frac{z^2 + y^2 + yr}{(y + r) \sqrt{y^2 + z^2}} \right],
\]

There is a linear relationship between \( F_z \) and \( \rho \).
Lateral Discretisation

Illustration of a rectangular mesh used to discretise a model
(mesh is ‘floating’ above the model in this illustration)
3D Earth model parameterisation
quantitative property models

University of British Columbia and some other software developers use a rectangular mesh, regular over sub-volumes if not the entire model volume.

UBC-GIF GRAV3D & MAG3D parameterisation:

• uniform 3D cell size (over sub-volumes)
• limited ("quantised") vertical resolution
• finite model extents, laterally & vertically
• padding cells to reduce edge effects
• non-stratigraphic
• active parameters are all physically identical: properties of (fixed-size) cells
• numerical inverse problem under-determined
3D Earth model parameterisation: VPmg

government models: rock type + property

VPmg parameterisation

• uniform cell size in plan
• arbitrary size vertically
• extends to infinity laterally
• extends to arbitrarily large depth
• stratigraphic => reduce number of property parameters, retain topological significance of contacts

• different styles of inversion: homog. property, heterogeneous property, & geometry
• parameters can be different: properties of units & of basement cells, elevations of contacts
• numerical inverse problem over- or under-determined or “well-posed”
Original rationale for VPmg

- Allow geometry of contacts to adjust in response to the data, but explicitly honour drill hole “pierce points” during inversion
- Generate a model acceptable to both geologists and geophysicists
Distinguishing characteristics of “VP suite”

- Cell boundaries can have geological significance, as contacts, alteration fronts, or structures - no longer arbitrary and artificial
- Cells belong to geological entities
- Therefore, the VP inversion model is a geological model
Geological models

• Geologically constrained inversion comes naturally when inversion models are … geological

• Geological models are comprised of rock type domains, their properties, and the boundaries which enclose them
Characteristics of geological models

- categorical and quantitative

Each ‘cell’ of the model is assigned to a ‘rock type’

The properties of the cells belonging to a rock type are statistically linked
**VPmg model parameterisation**

- Vertical rectangular prisms with internal boundaries
- Cells have arbitrary vertical dimension
- Topography incorporated implicitly in model
- Cell boundaries fixed, free, or bounded
- Homogeneous or heterogeneous geological units
- Property bounds assigned to each geological unit
- Heterogeneous basement (extending to great depth)
VP models – Additional Features

- Cell thickness arbitrary
- The absence of vertical quantisation permits efficient representation of thick and thin units and subtle changes in elevation from prism to prism (left).
- Further sub-division of vertical prisms can occur for detailed property modelling (right).
Individual vertical prism in a VPmg model

Simple layered model. Green surface represents topography and the pink-brown surface represents a geological interface between two units.

Illustration of all prisms constituting the model.

Close up view of a single vertical prism; a single elevation and physical property are stored for each interface that cuts the prism.
VPmg representation of a model surface

The individual VPmg prism interfaces represent the exact elevation of the surface at the centre of the prism – there is no vertical discretisation.
VP model structure supports full 3D complexity

…. and permits a variety of model options

Cross section through a simple 3D example
Accounting for Regional Effects

- VPmg models are incised into a half space (model does not abruptly terminate => reduced edge effects)
- VPmg models can be incised into a regional model which is in turn incised into the half space
- Regional model may be pure basement (apparent density/susc)
- VPmg permits inversion of \( \text{measured} = \text{regional} + \text{local} \) (not limited to \( \text{local} = \text{measured} - \text{regional} \))
Terrain effects

The accuracy with which the terrain is modelled can be important for gravity interpretation and critical for gravity gradient interpretation.

Terrain correction versus terrain modelling.

Terrain models can involve more than one density.

**VPmg is well suited to terrain modelling & correction:**

- vertical dimension of cells arbitrary: “unlimited” vertical resolution
- no independent topographic surface: model DTM grid files directly
- no restriction to positive density or susceptibility
- fewer cells in model: faster computation
Regional Terrain
Local Terrain

Regional terrain using same colour scheme as adjacent image
Local Free Air Gravity Data

Regional (surrounding) terrain dominates the survey gravity response
Gravity response of alluvium

A layer of alluvium also exists beneath the terrain in the valley with a density significantly less than other material.

Colour depicts the alluvium thickness (m) in both graphics.

3D perspective representation of the terrain. Alluvium thickness is illustrated as a coloured property on the topography surface.

Colour depicts the alluvium thickness (m) in both graphics.
Computed gravity response of alluvium + terrain model

As expected, the regional terrain dominates the computed gravity response
Terrain-corrected local gravity data

Corrected gravity data reveals anomalies that relate to known geology
Detailed terrain modelling

If $\lambda < 2*DX$ and relief appreciable, perform detailed terrain correction prior to inversion.

- $\lambda$ = topographic wavelength
- $DX$ = model cell dimension
- = actual measurement station
Constrained 3D Potential Fields Inversion

**SOG Environs Infrastructure**

- **SOG Pit**: ~ 800m x 600m x 270m
- **Tower Hill Pit**: ~ 500m x 150m x 70m
- **Main waste Dumps**: Up to 1000m x 700m x 50m
- **Tailing Dams**: up to 1000m x 1000m x 20m

Looking to the North

(Jackson et al., 2004)
Waste/Tails corrected data
VPmg forward algorithm for gravity

Volume integral

Surface integral

Line integral

Gauss’ Theorem

Green’s Theorem
Gravity of a homogeneous rectangular prism

The gravity vector outside an arbitrary body of uniform density, $\rho$, can be written as an integral over the body volume (Coggon, 1976)

$$\ddot{g} = G\rho \nabla_0 \int \frac{dv}{|\vec{r}|}$$  \hspace{1cm} (1)

where $G$ is the universal constant of gravitation, $\nabla_0$ represents the gradient with respect to the observation point, and $|\vec{r}|$ is the distance between the observation point and a point within the body. The component, $g_z$, in the z-direction is then given by

$$g_z = G\rho \hat{z} \cdot \nabla_0 \int \frac{dv}{|\vec{r}|}$$  \hspace{1cm} (2)

where $\hat{z}$ is the unit vector in that (arbitrary) direction.
Gravity of a homogeneous rectangular prism: cont’d

The volume integral can be converted to a surface integral by noting that

\[ \hat{z} \cdot \nabla \left( \frac{1}{|\vec{r}|} \right) = -\nabla \cdot \left( \frac{\hat{z}}{|\vec{r}|} \right) \]  

(3)

where \( \nabla \) represents the gradient with respect to the internal (body) point. Substituting from (3) into (2) and invoking Gauss’ Theorem,

\[ g_z = -G \rho \int \frac{\hat{z} \cdot \hat{n}}{|\vec{r}|} \, ds \]  

(4)

where \( \hat{n} \) denotes the outward unit normal vector to the body surface.

The expression in (4) is completely general. However, if \( \hat{z} \) represents the vertical direction vector, it follows that the vertical gravity due to any vertically-sided generalised cylinder can be computed as surface integrals over its top and bottom.

If, furthermore, the top and bottom are planar, the surface integrals can be reduced to line integrals around the edges.
Gravity of a homogeneous rectangular prism: cont’d

According to Green’s Theorem in the plane (e.g. Kreyszig, 1967, p313),

\[ \iint_S \frac{\partial f}{\partial x} \, dx \, dy = \oint_C f \, dy \]  \hspace{1cm} (5)

for a differentiable function \( f(x,y) \). Therefore, (4) can be evaluated as a contour integral if a function \( f \) can be found with \( x \)-derivative

\[ \frac{\partial f}{\partial x} = \frac{1}{|\vec{r}|} = \frac{1}{\sqrt{(x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2}} \]  \hspace{1cm} (6)

The required function is

\[ f(x,y) = \ln \left( x - x_0 + \sqrt{(x-x_0)^2 + (y-y_0)^2 + (z-z_0)} \right) \]  \hspace{1cm} (7)
Gravity of a homogeneous rectangular prism: cont’d

If we limit attention to a vertical rectangular prism, with sides oriented parallel to the x- and y-axes, its vertical gravity anomaly reduces to a summation of four definite integrals of the form

\[ G\rho \int_{y_1}^{y_2} \ln(x + r) dy = F(x, z, y_2) - F(x, z, y_1) \]  \hspace{1cm} (8)

where (for an observation point at the origin)

\[ r = \sqrt{x^2 + y^2 + z^2} \]  \hspace{1cm} (9)

An analytic expression for \( F \) was derived by Fullagar (1975), viz.

\[ F(x, z, y) = G\rho \left( y\ln(x + r) - y + x\ln(y + r) - 2z\tan^{-1}\left(\frac{x + r - y}{z}\right) \right) \]  \hspace{1cm} (10)

where the branch of the arctangent function must be chosen to ensure that

\[ \text{sgn}\left(\left[-2z\tan^{-1}...\right]_{y_1}^{y_2}\right) = \text{sgn}(y_2 - y_1) \]  \hspace{1cm} (11)
Thus, calculation of gravity for homogeneous rectangular prism reduces to eight evaluations of function $F$ at the vertices.

For the rectangular cells comprising a “vertical prism” in a VPmg model, only 4 evaluations of function $F$ are required for each additional cell.

The function evaluations for a particular horizontal face are “weighted” by the density contrast across the face.
Some modelling considerations

1. Effect of prism size
2. Relationship between prism size and data spacing
3. Effect of data placement: collinear with prism edges; near prism corners
4. Effect of data height
Discretisation effects in forward modelling

Small computational errors can arise, depending on exact placement of data points on stepped model surface.

Minimised by gridding to cell centres (and by detailed terrain correction)
VPmg forward algorithm for gravity

Volume integral

Useful approximation at large distances: approximate as point mass at cell centre

Gauss’ Theorem

Surface integral

Useful approximation at medium distances: combine contributions from face centres

Green’s Theorem

Line integral

Exact calculation

Fullagar Geophysics Pty Ltd
Volume integral approximation at far offset

If a cell is far from the observation point, then

\[ g_z(\vec{r}_0) = -G\rho \int \frac{(z - z_0)dv}{|\vec{r} - r_0|^3} \approx -G\rho V \frac{(z_c - z_0)}{|\vec{r}_c - r_0|^3} \]

where \( V \) is the volume of the cell and where \( \vec{r}_c \) is the position vector of the cell centre.

Surface integral approximation at intermediate offset

If a cell is a moderate distance from the observation point, then

\[ g_z = -G\rho \int \frac{\hat{z} \cdot \hat{n}}{|\vec{r}|} ds \approx -G\rho A \frac{\vec{r}_s - \vec{r}_0}{|\vec{r}_s - \vec{r}_0|} \]

where \( A \) is the area of the cell top or bottom, and where \( \vec{r}_s \) is the position vector of the cell face.
Introduction to VPmg Files
VPmg  File Types

3 or 4 Files required:

1. Control file: define model files and inversion parameters

2. Data file: column ASCII (X,Y,Z,value)

3. Model file: starting model
   inverted model + calculated responses

4. Par file: define data file and its format
   specify components for multi-channel cases
VPmg control file

1 -3 -58 50000 0  !IGRAV, DEC, INC, AMB, IDH
0 1 2    !IREGNL, ILOCAL, IDL
DUMMY    !Local model file
P_rev_6.den   !Regional model file
8 0.1    !ITMAX, ERR
0.025 0.02   !PERT, DELD
grav_200.dat  !Data file
P_rev_6.008   !Output model file

PERT = maximum fractional change in contact depths per iteration
DELD = maximum absolute change in unit properties per iteration
VPmg model file structure

Model parameters:
cell size, areal extent, unit properties & bounds, etc.

Geological unit geometry & elevation constraints:
east, north, topo_RL, flag, {contact_RL, flag}

Basement topography & properties:
east, north, basement_RL, property

Heterogeneous unit properties & constraints
east, north, ncell, {unit, property, flag}

Observed data & calculated responses:
data_east, data_north, data_RL, observed, calculated, background
Start of VPmg model file

```
#MOD_3D#
Pillara 3-layer model
92750.00 105650.00 67550.00 73950.00
100.00 100.00
3
2.5000 2.49000 2.5100 Clastics
2.5500 2.5500 2.9000 Limestone
2.7000 2.6900 2.7100 Basement
154.86 2.670 1
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Introduction to VPview
(VPmg user interface)
Define inversion files & parameters
Create simple layered models

Define model parameters
Defining rock properties for geological units

### Magnetic model

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### Density model

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VPview display options:

Vertical section
VPview display options:

Horizontal fliche
References


