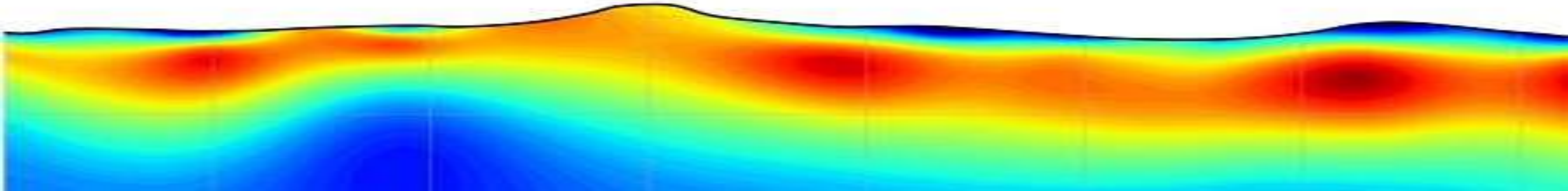
SUSTech Southern University of Science and Technology
南方科技大学 SOUTHERN UNIVERSITY OF SCIENCE AND TECHNOLOGY
地球与空间科学系 DEPARTMENT OF EARTH AND SPACE SCIENCES

ESS302 Applied Geophysics II

Gravity, Magnetic, Electrical, Electromagnetic and Well Logging

Gravity Wrap-up

Instructor: Dikun Yang Feb – May, 2020



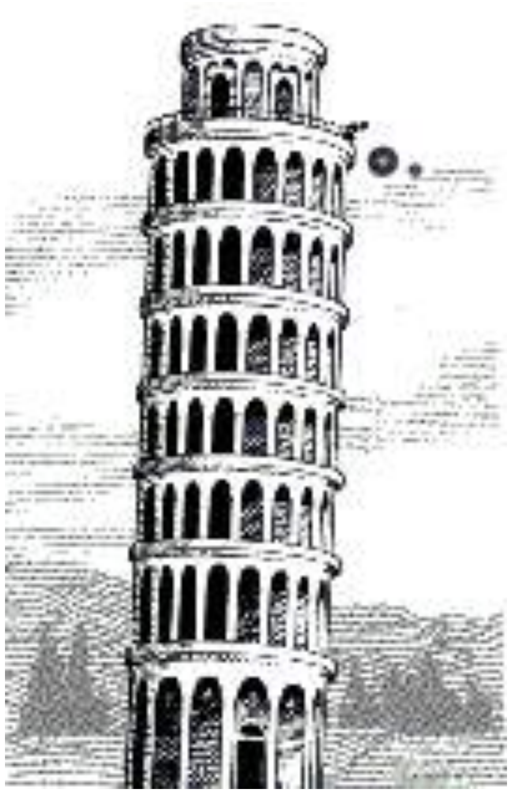
The Amazing World of Gravity

Learn from YouTube https://youtu.be/2_p2ELD7npw

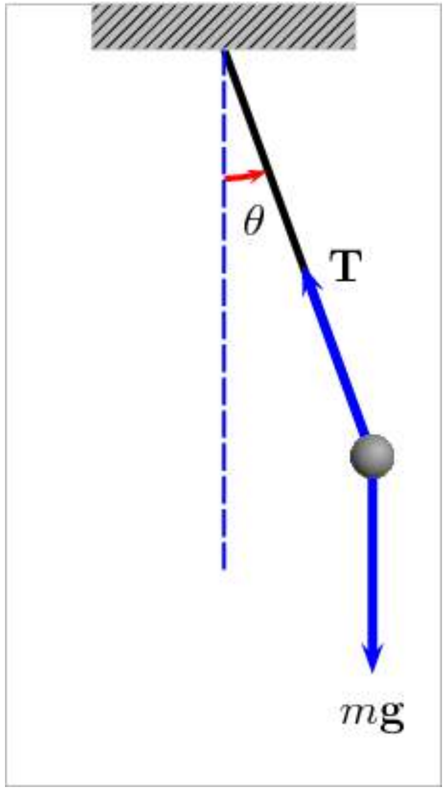
How to Measure the Gravity Field



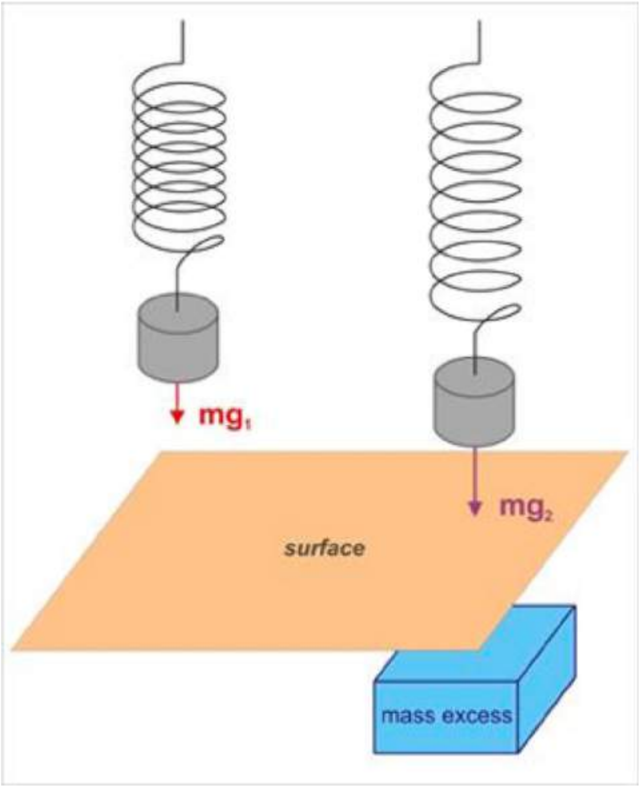
Measurement of Gravity Field



Free fall
(absolute)

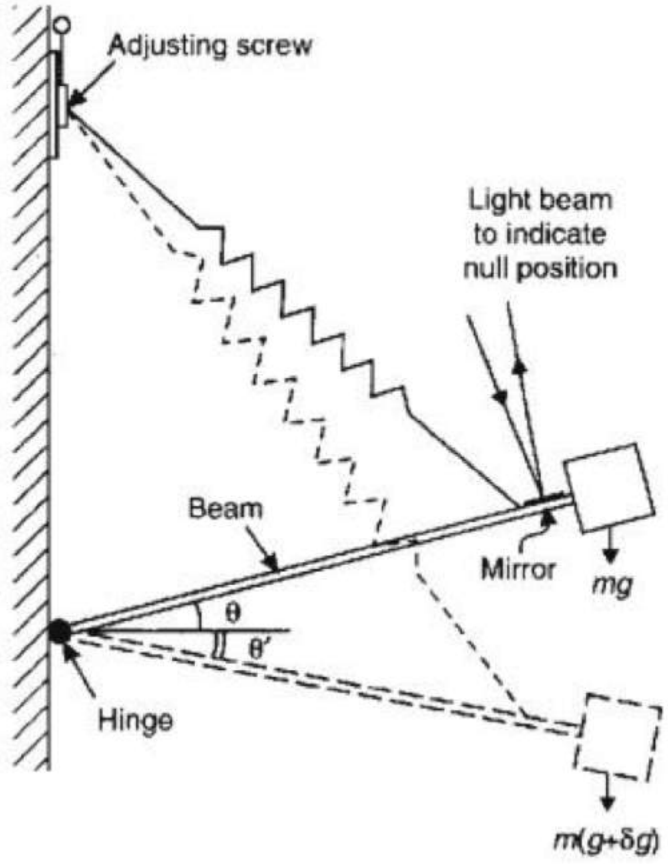


Pendulum
(absolute)



Spring
(relative)

LaCoste-Romberg Gravimeter



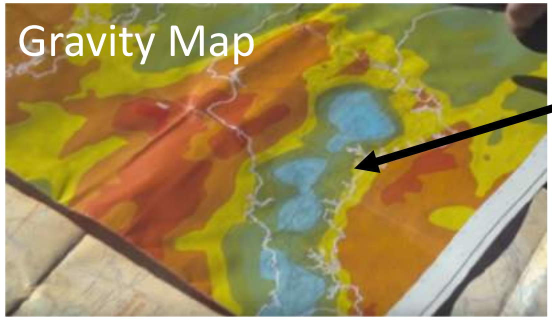
The Amazing World of Gravity

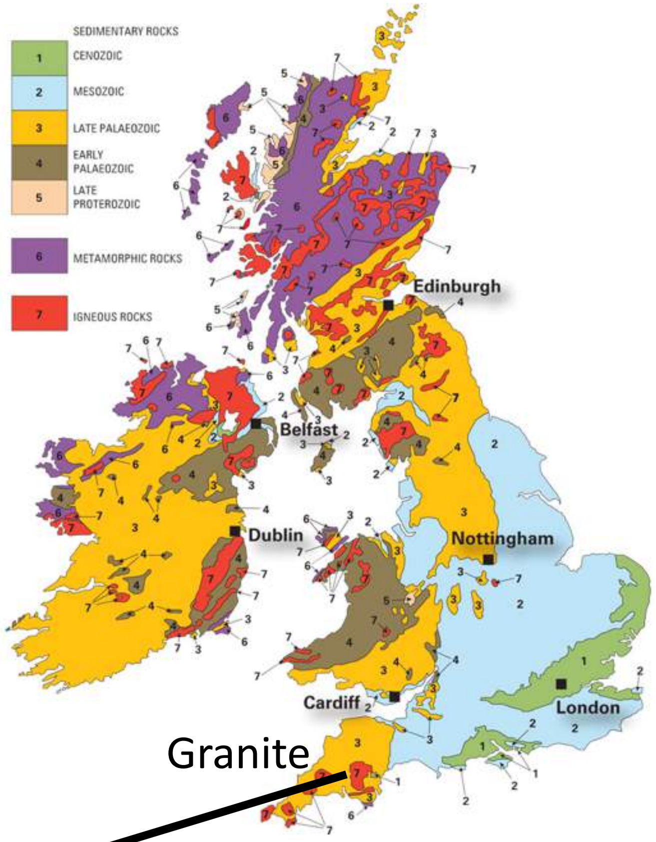
Learn from YouTube

https://youtu.be/2_p2ELD7npw

According to the video, what are the factors that affect the gravitational force exerted on us?

The Amazing World of Gravity

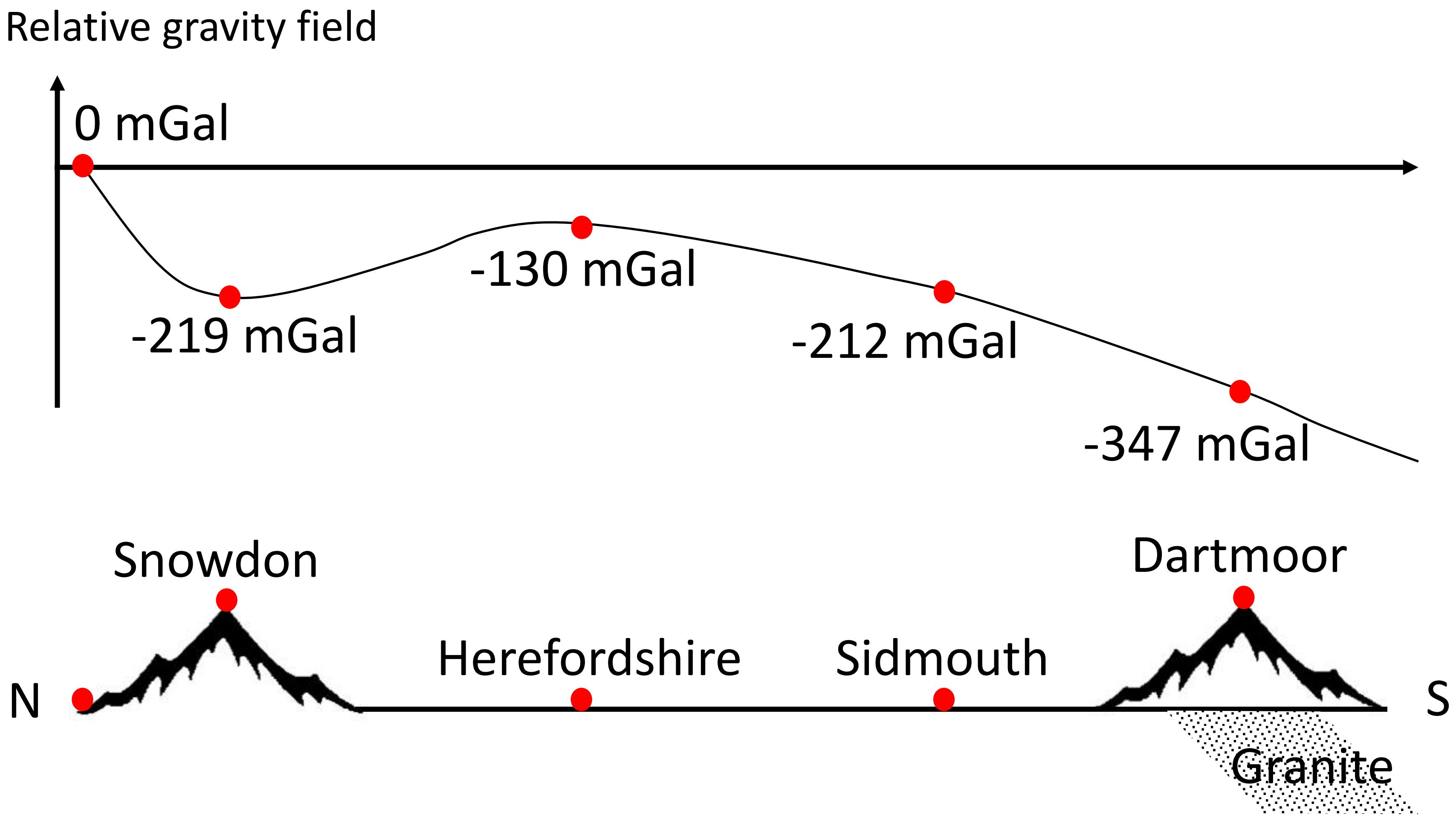




Granite

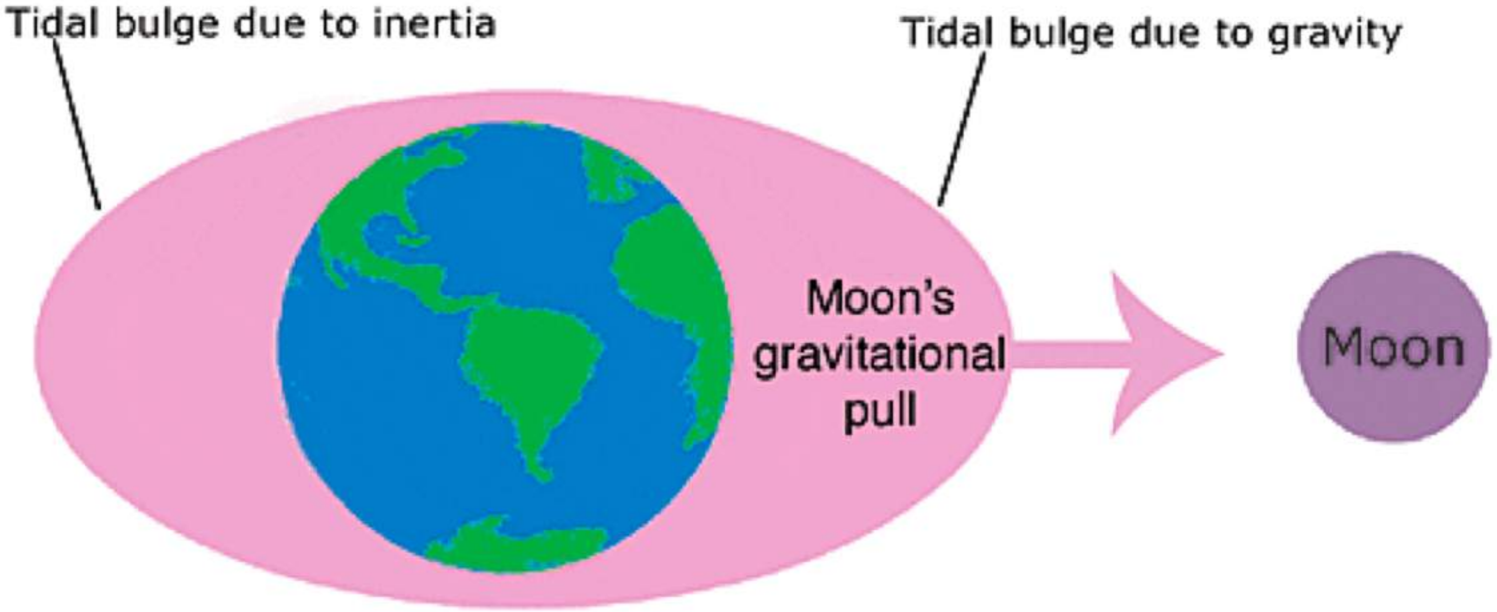
Applied geophysicist:
Maybe we can use the gravity field to find something that is not as apparent as altitude and latitude?

The Amazing World of Gravity



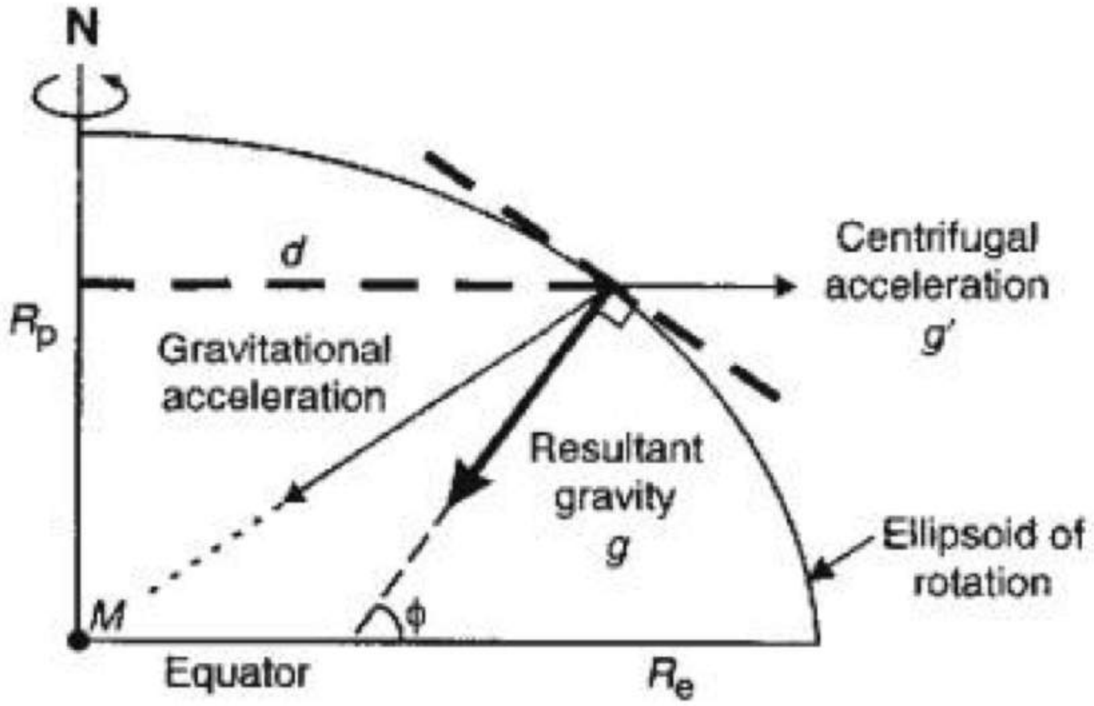
Gravity Data Correction

- Tidal correction



Gravity Data Correction

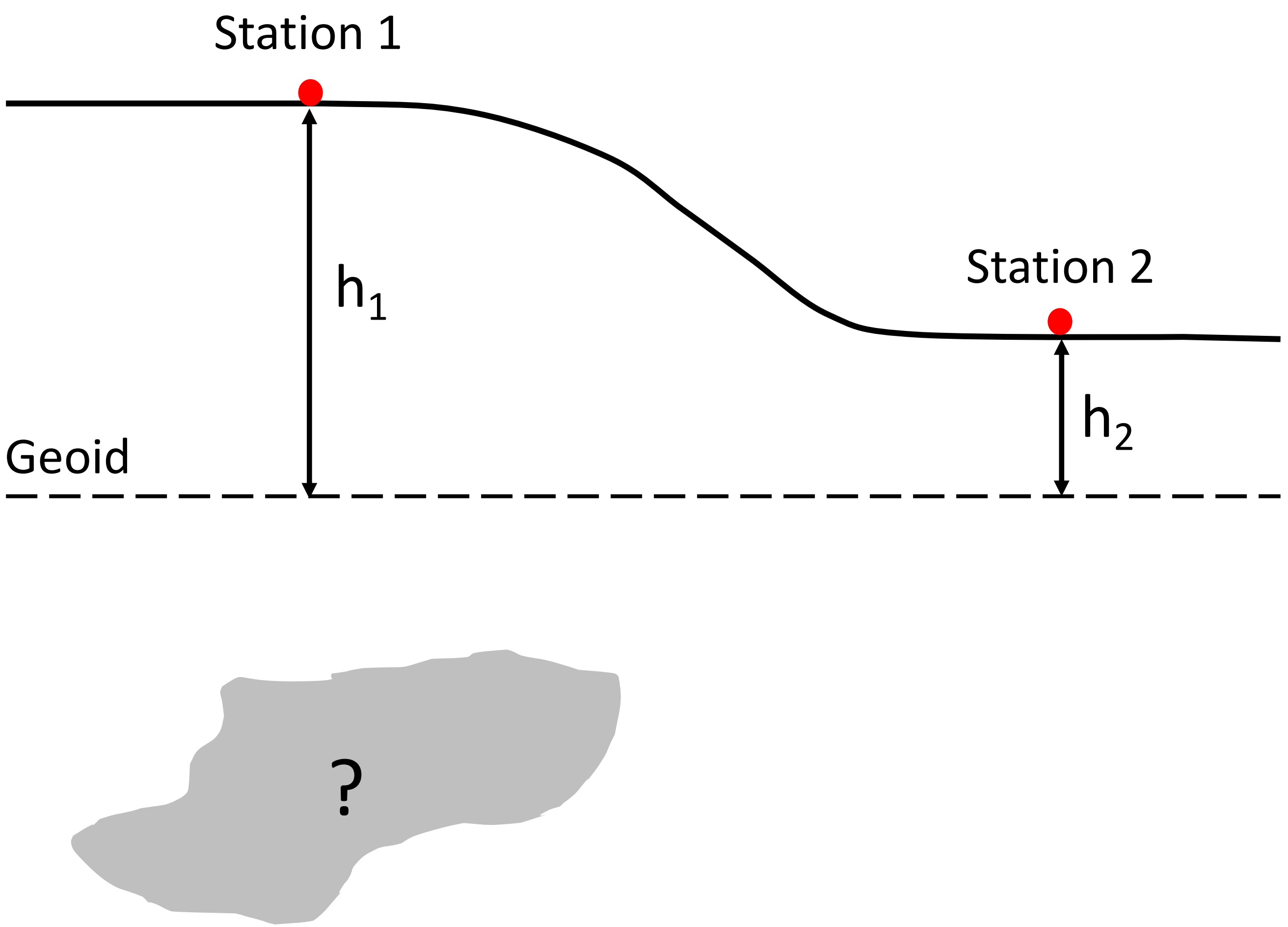
- Tidal correction
- Latitude correction



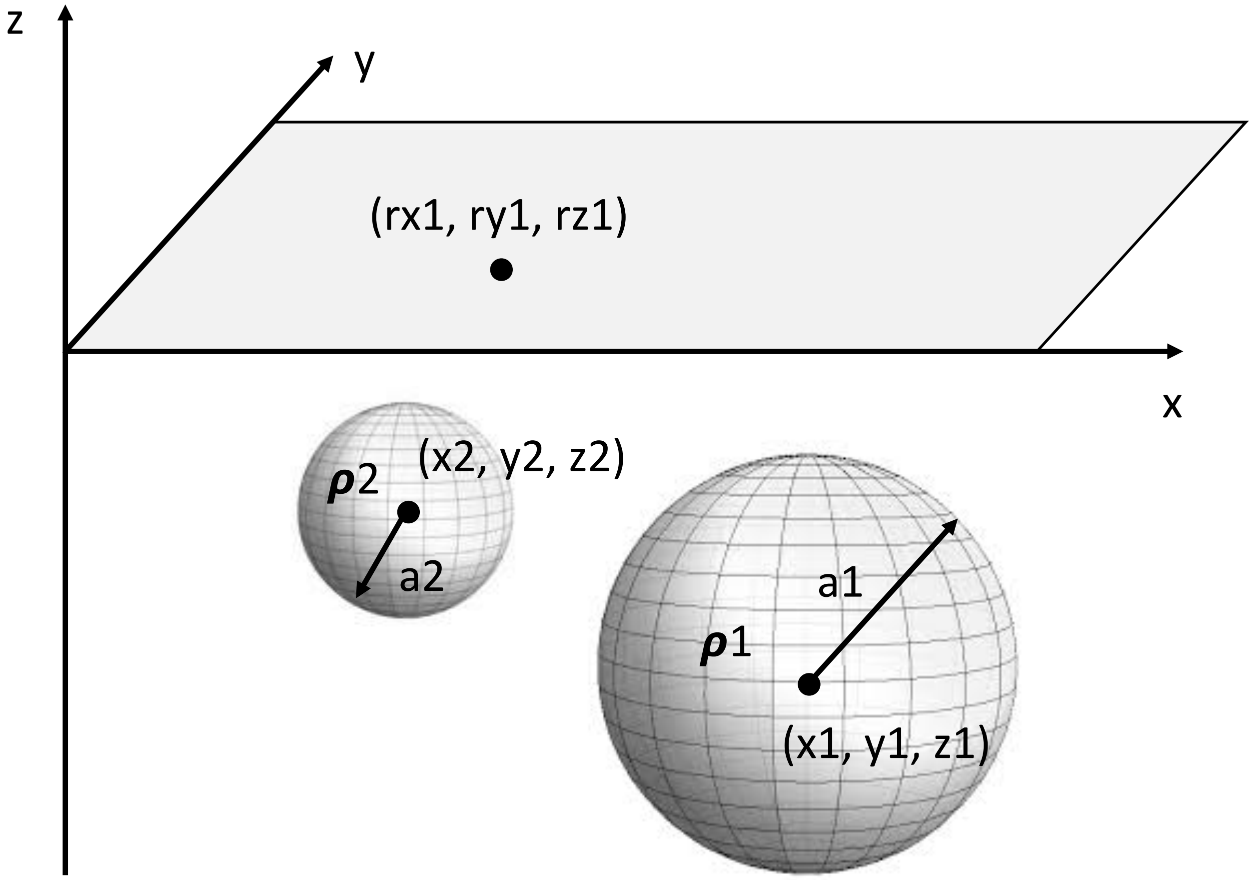
Earth: A spinning ellipsoid

Gravity Data Correction

- Tidal correction
- Latitude correction
- Elevation correction (get only the effect of density)
  a) Free-air (back to geoid)
  b) Bouguer (remove rock slab)
  c) Terrain (remove pull-up of mountains on side)



Gravity of Two (or N) Spheres



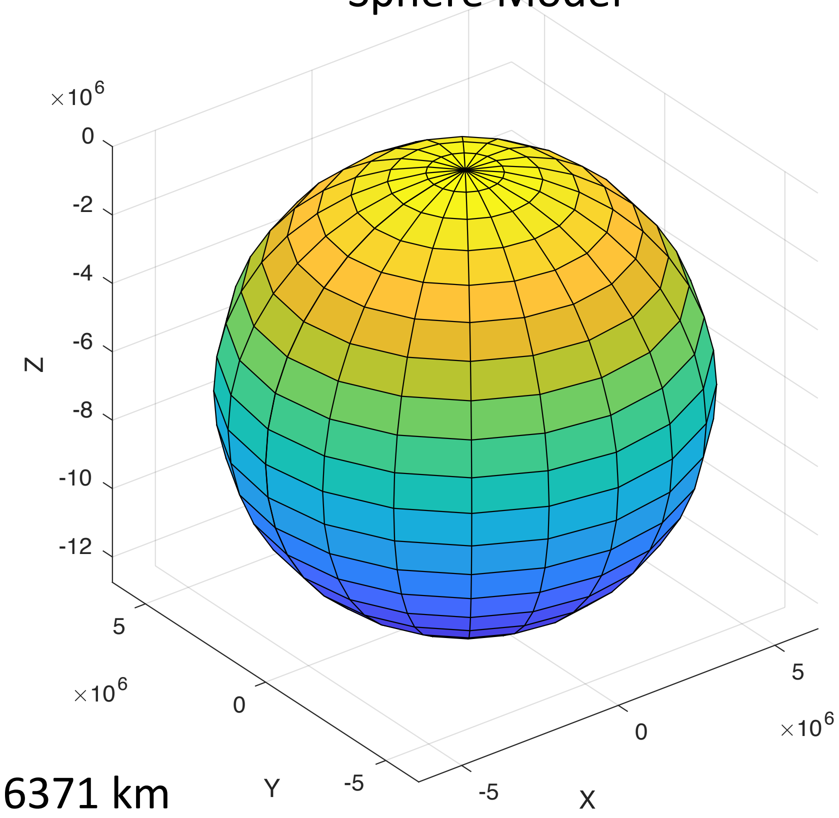
N uniform spheres of different densities located in the 3D space

Be able to calculate the gravitational field F anywhere in the 3D space outside of the spheres

Bury the two spheres underground and compute g_z over a data grid on the surface and make the plot

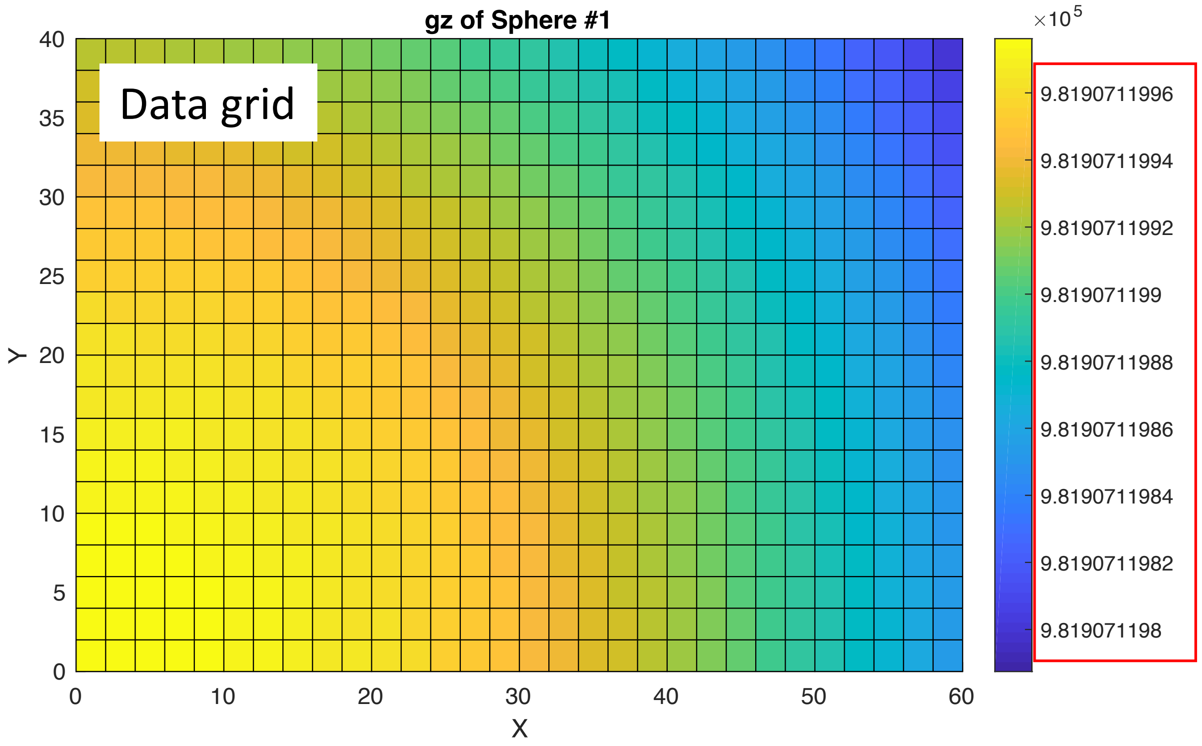
Experiment 1: One Really Big Sphere

Sphere Model



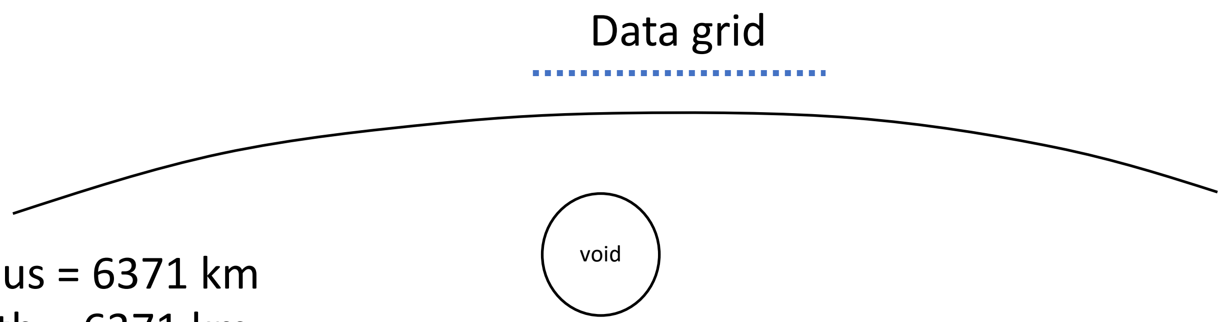
Radius = 6371 km
Depth = 6371 km
Density = 5.513 g/cm^3

Gravity Data (mGal)



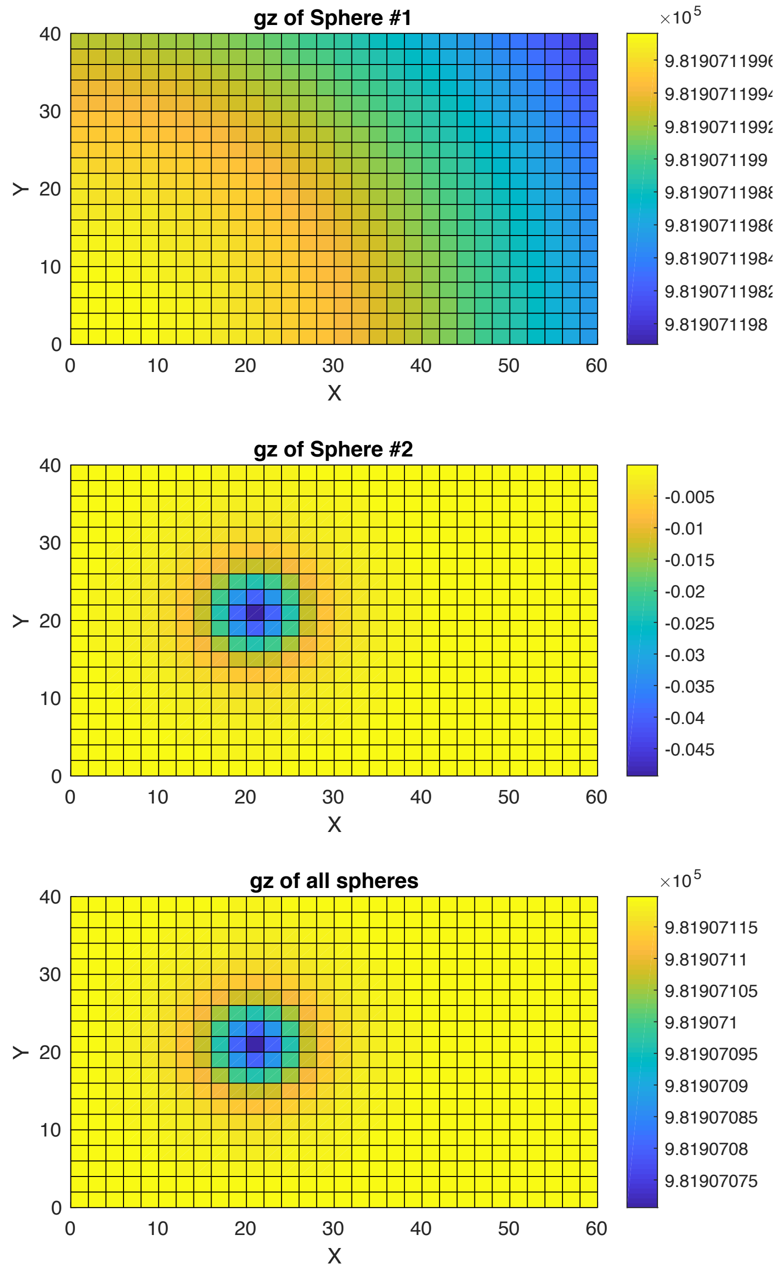
Conclusion: Big numbers but almost constant

Experiment 2: A Small Cavity in a Large Sphere



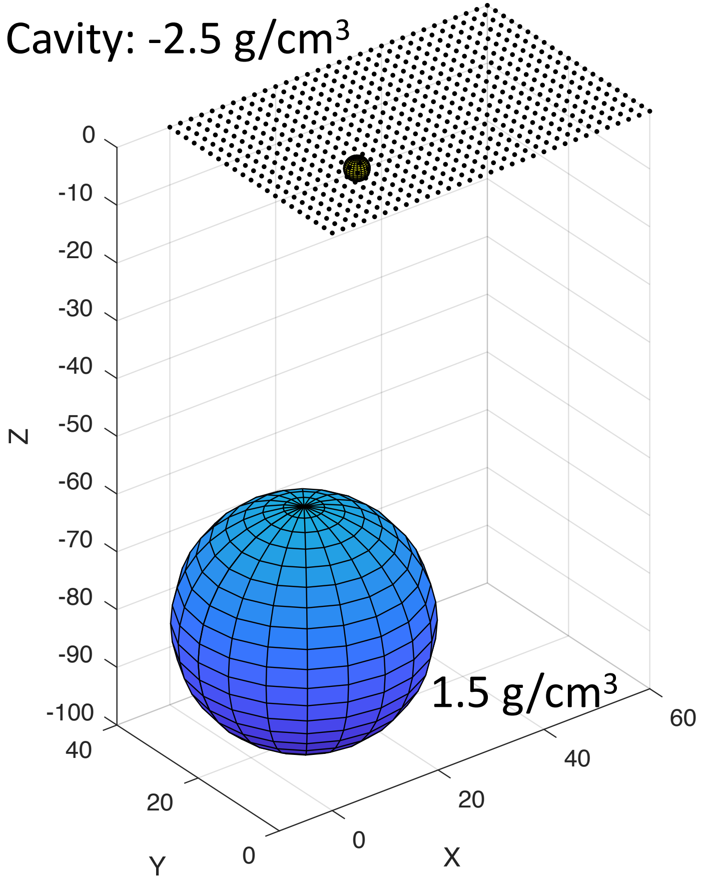
Radius = 6371 km
Depth = 6371 km
Density = 5.513 g/cm^3

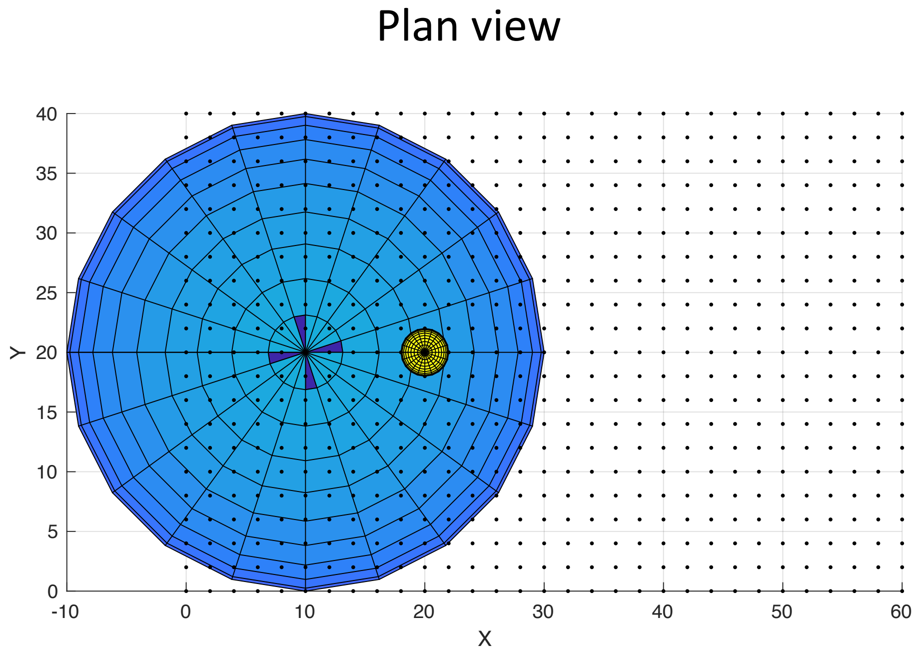
Radius = 2 m
Depth = 5 m
Density = -5.513 g/cm^3

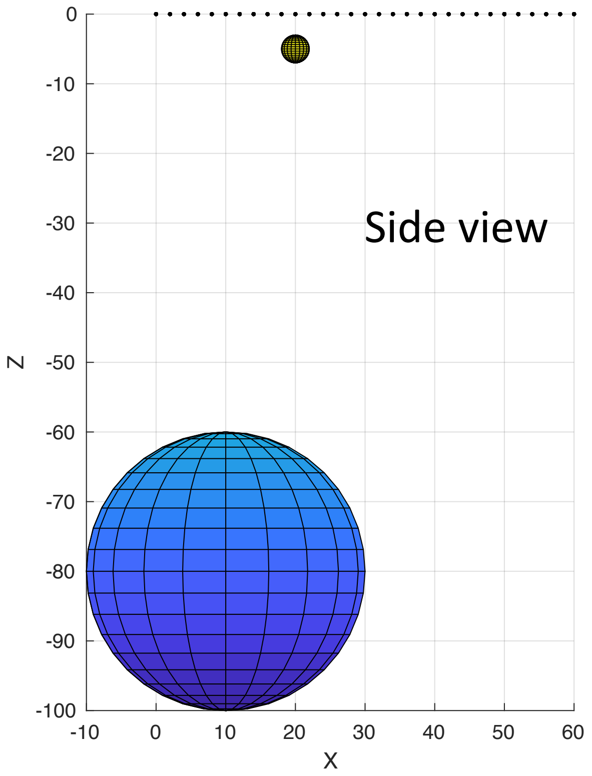


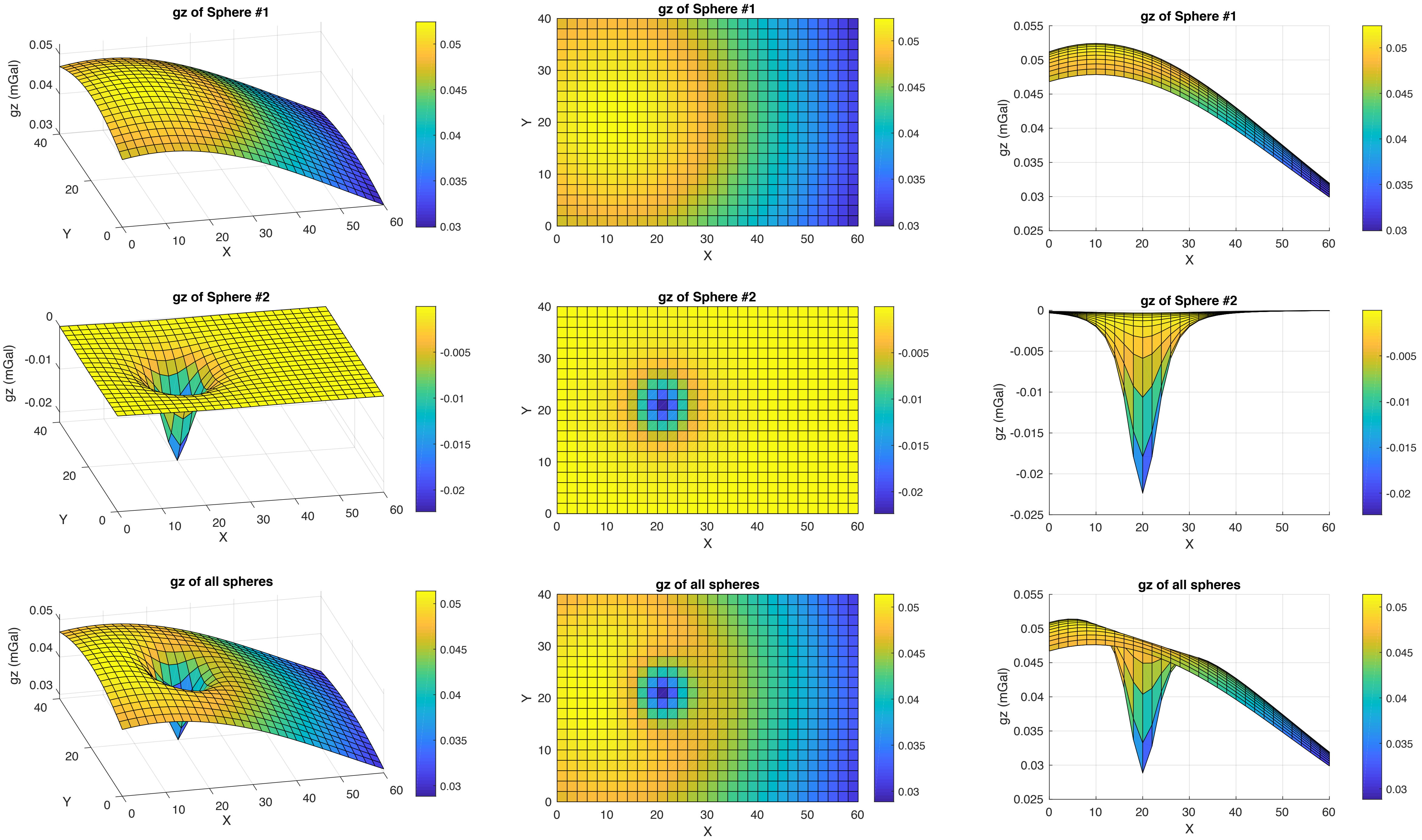
Conclusion: The field from the entire earth does not help us in finding buried objects

Experiment 3: Two Spheres in Different Sizes








gz of Sphere #1
gz (mGal)
X
Y
gz of Sphere #2
gz (mGal)
X
Y
gz of all spheres
gz (mGal)
X
Y

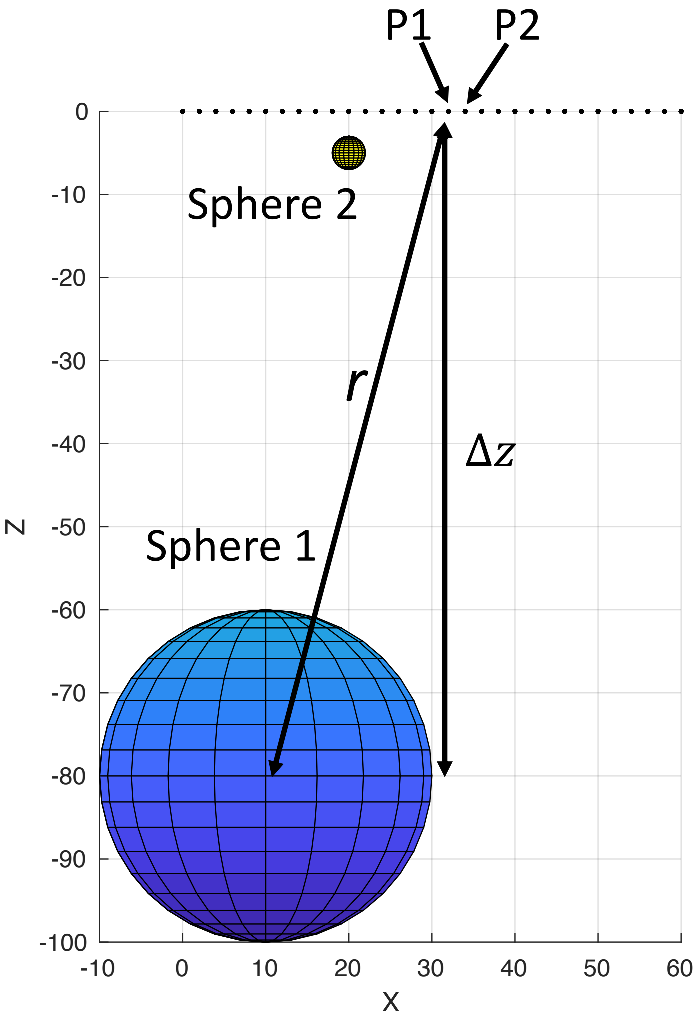
Gravity Signal Decays as $1/r^2$

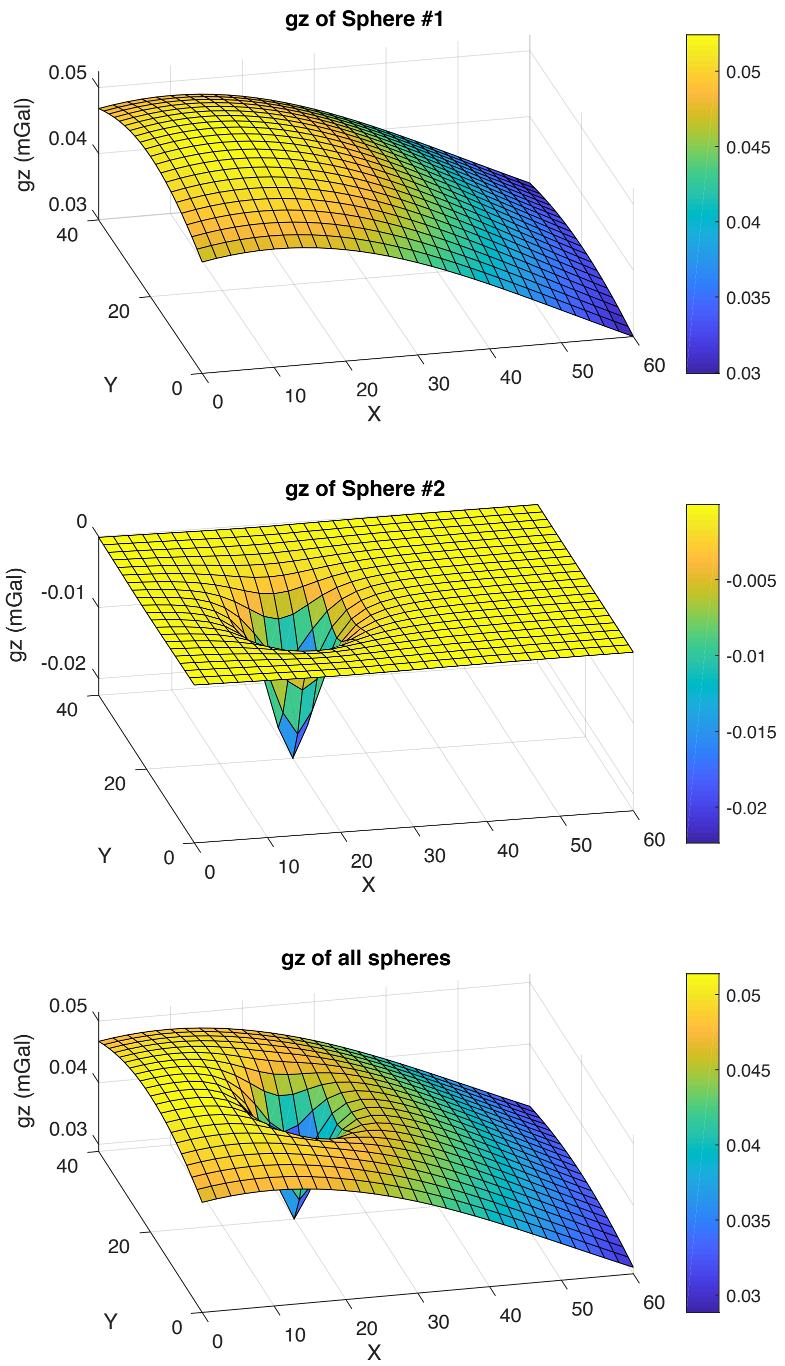
We measure the vertical component of *g* on the surface

$$g_z = \frac{GM\,\Delta z}{r^3}$$

Large distance: long-wavelength

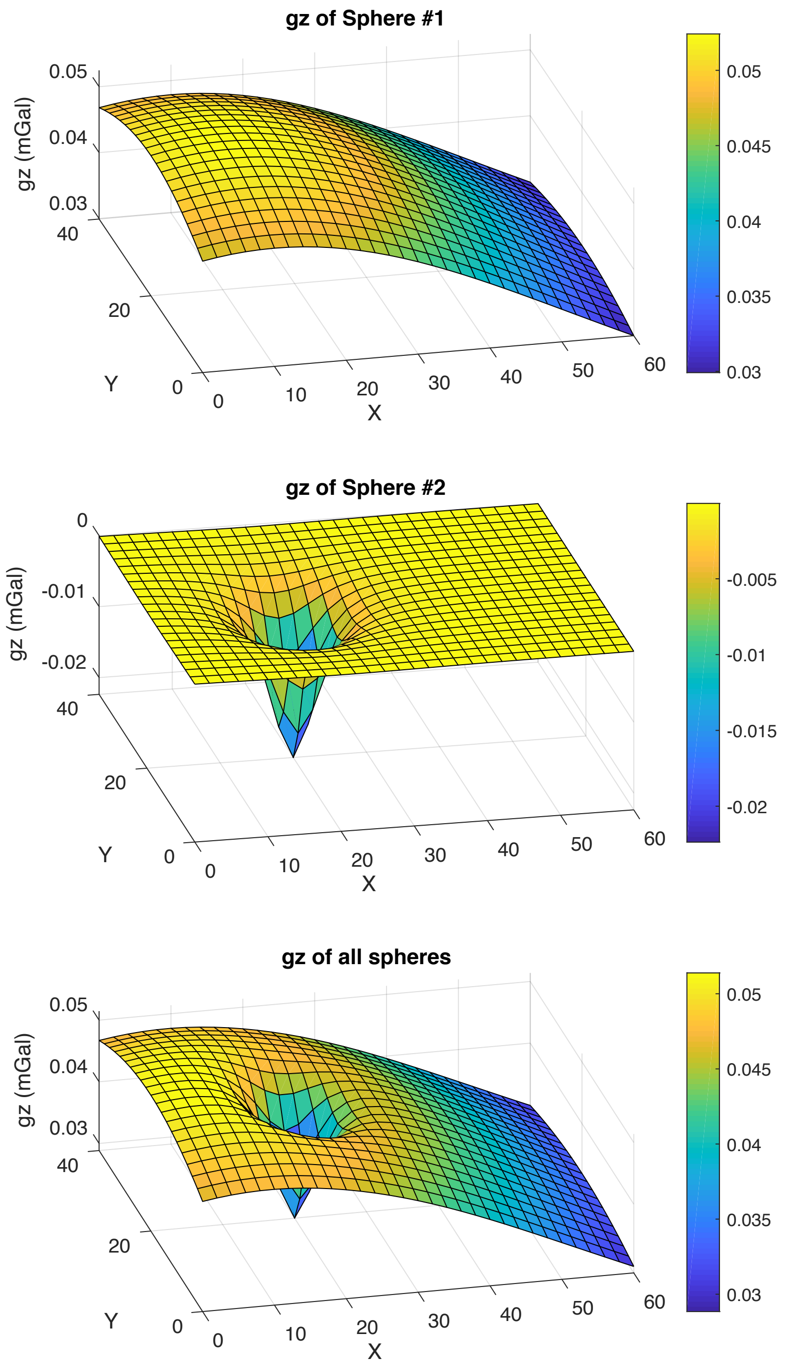
Small distance: short-wavelength



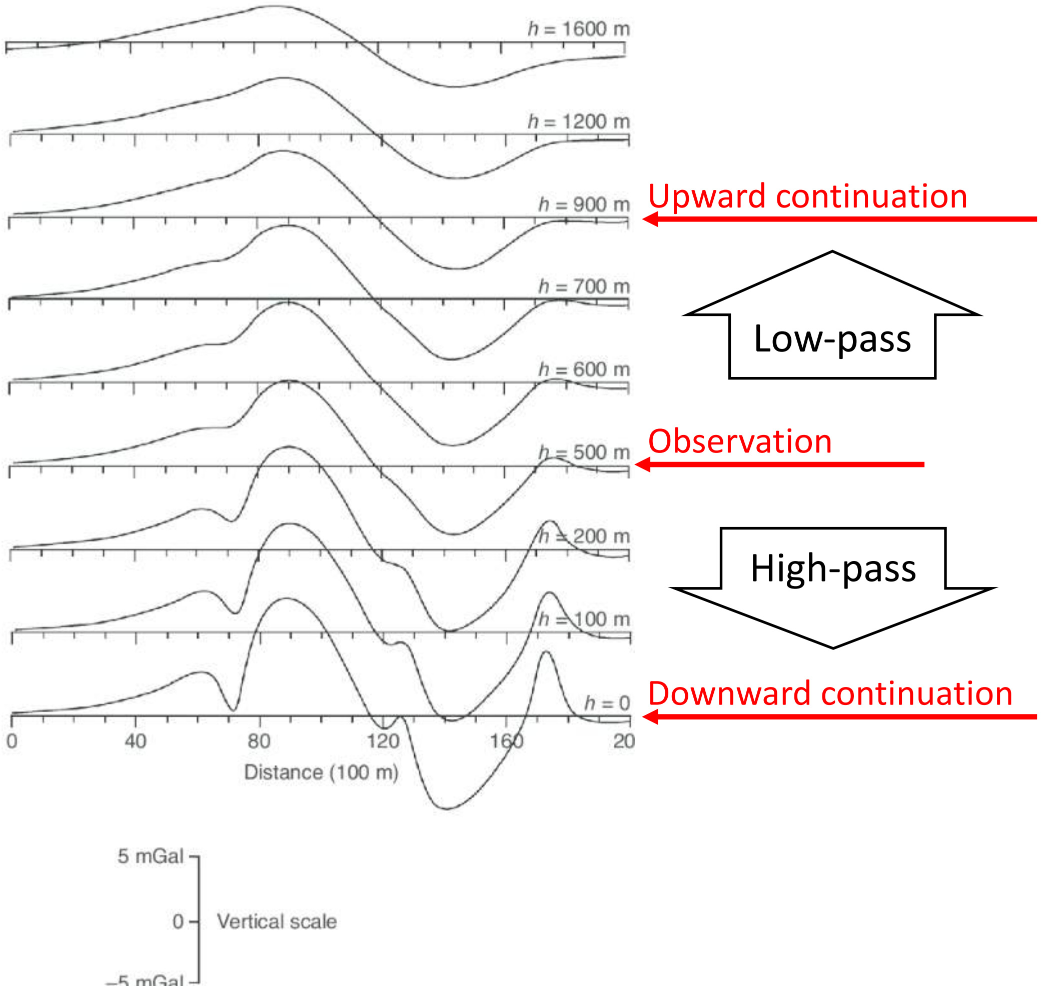


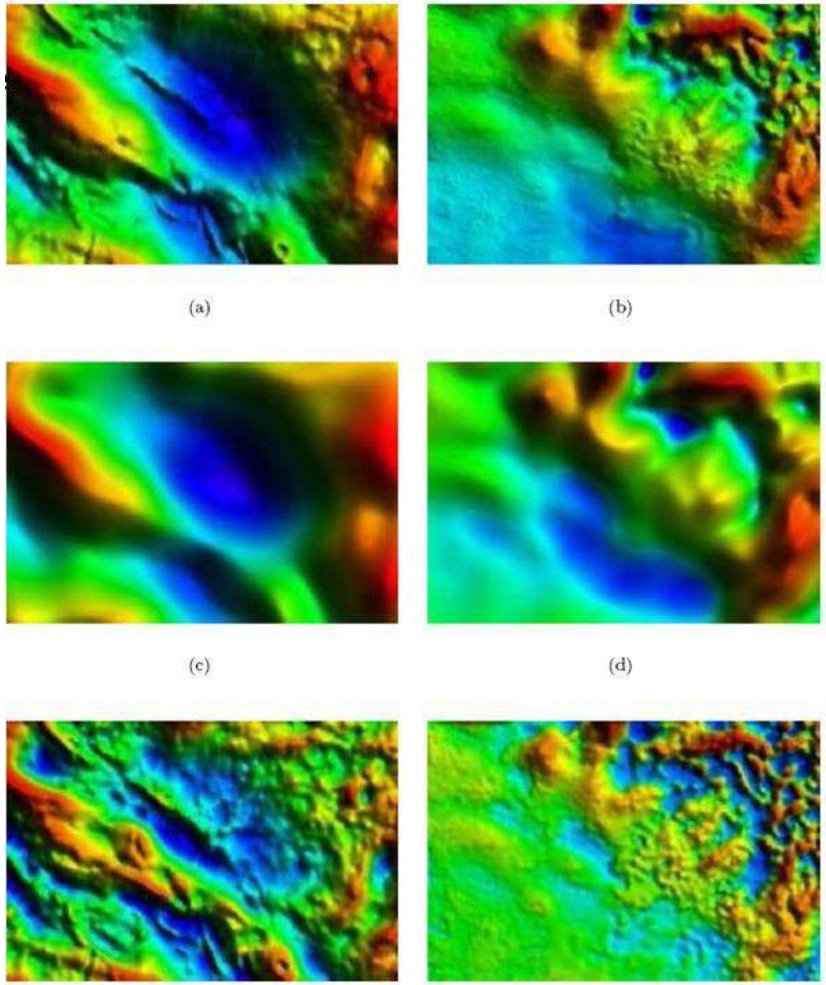
Regional Removal

- Separate signals with different wavelengths
- Isolate anomalies at the scales of our interest
  - Small and shallow: Near-surface cavity
  - Large and deep: Basin basement
- What are the approaches that can be used to carry out regional removal?
  - Moving window averaging
  - Wavenumber domain filtering
  - Best-fitting large sphere
  - Surface fitting – low-order polynomials



Upward and Downward Continuation



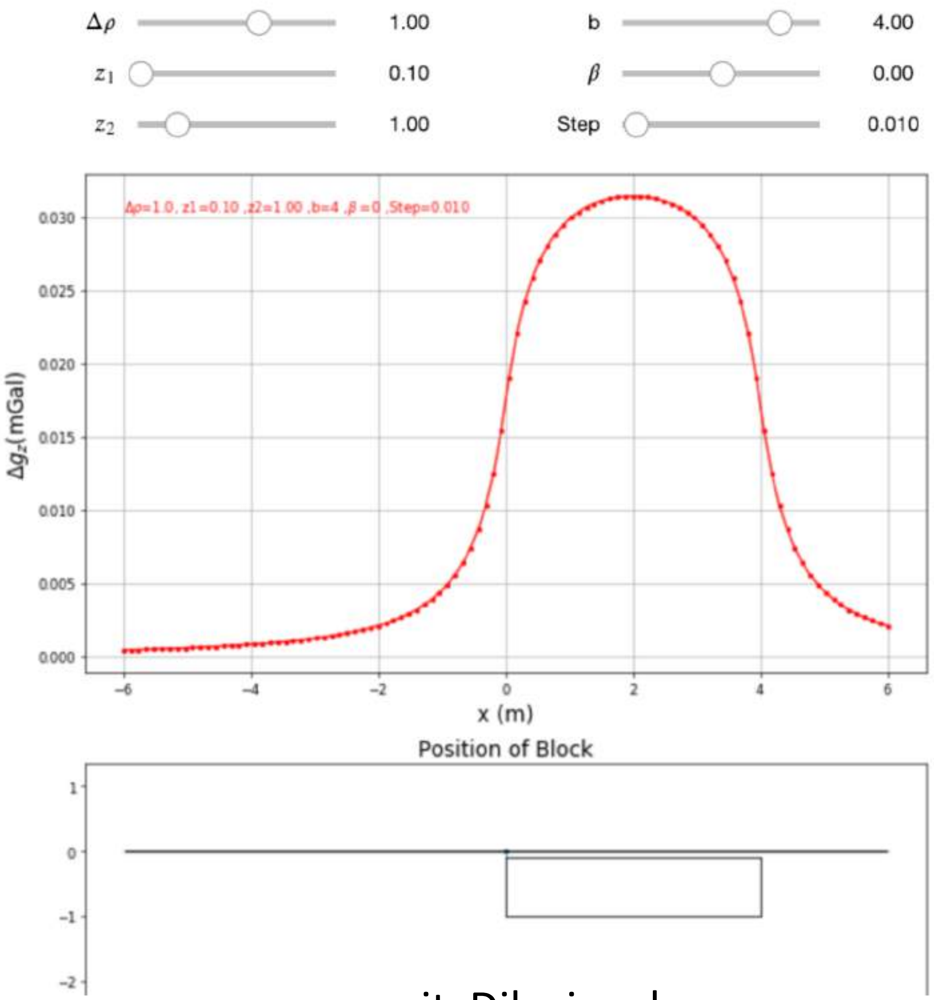


Original

Upward continued

Residual

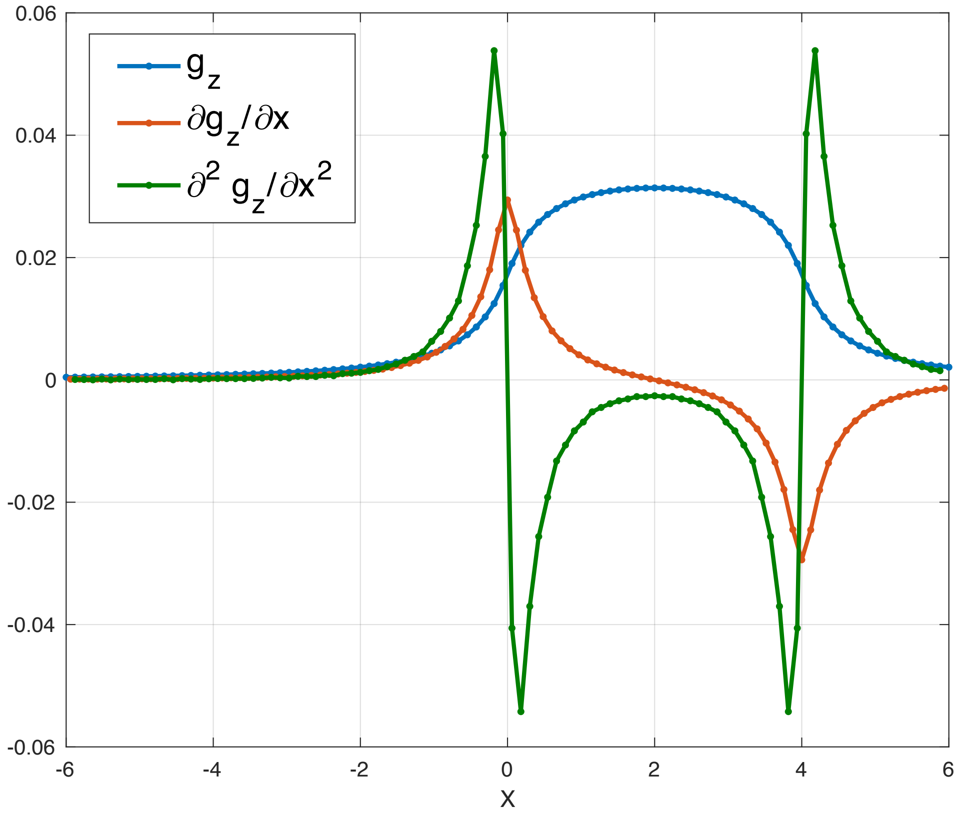
Horizontal Derivative



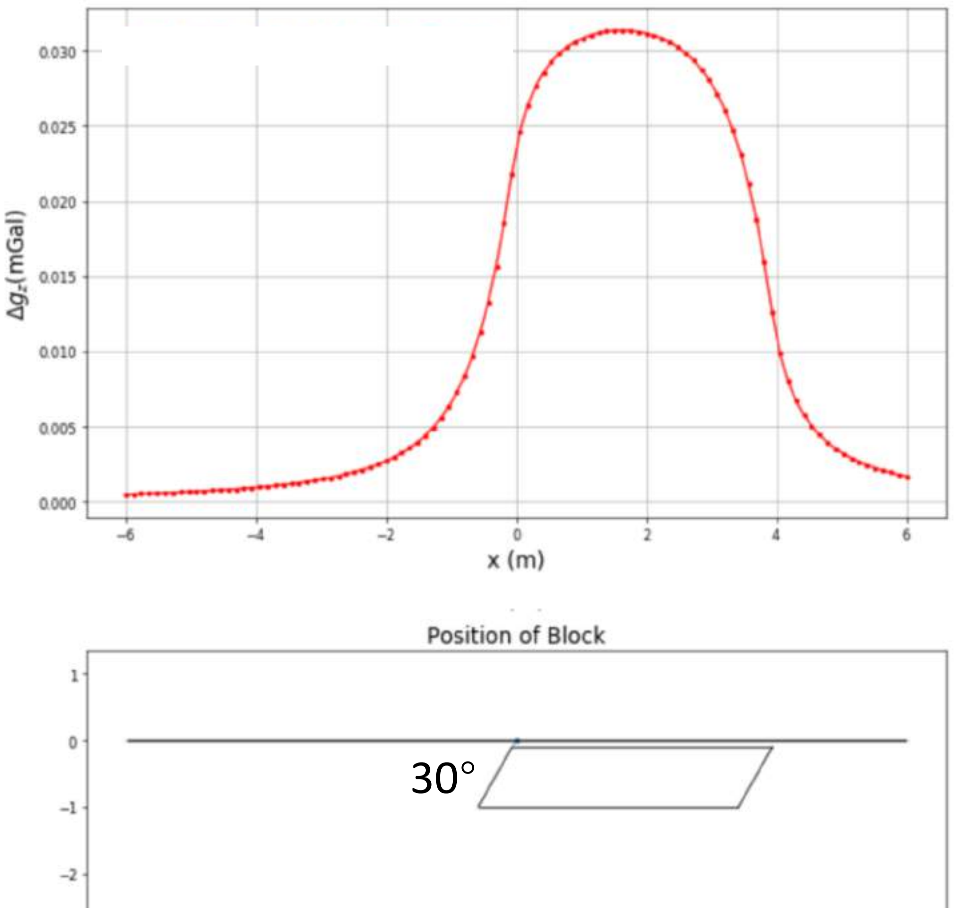
gravityDike.ipynb

Draw the first and second horizontal derivatives

Which derivative is more useful in defining the edges?

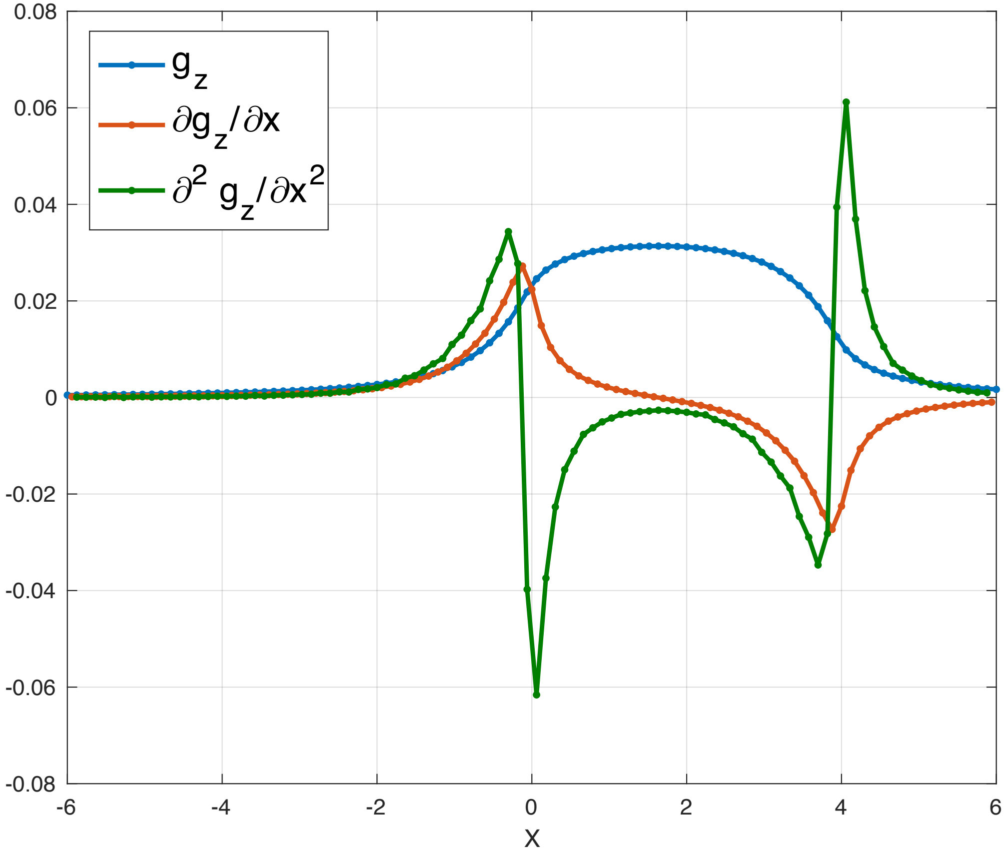


Horizontal Derivative

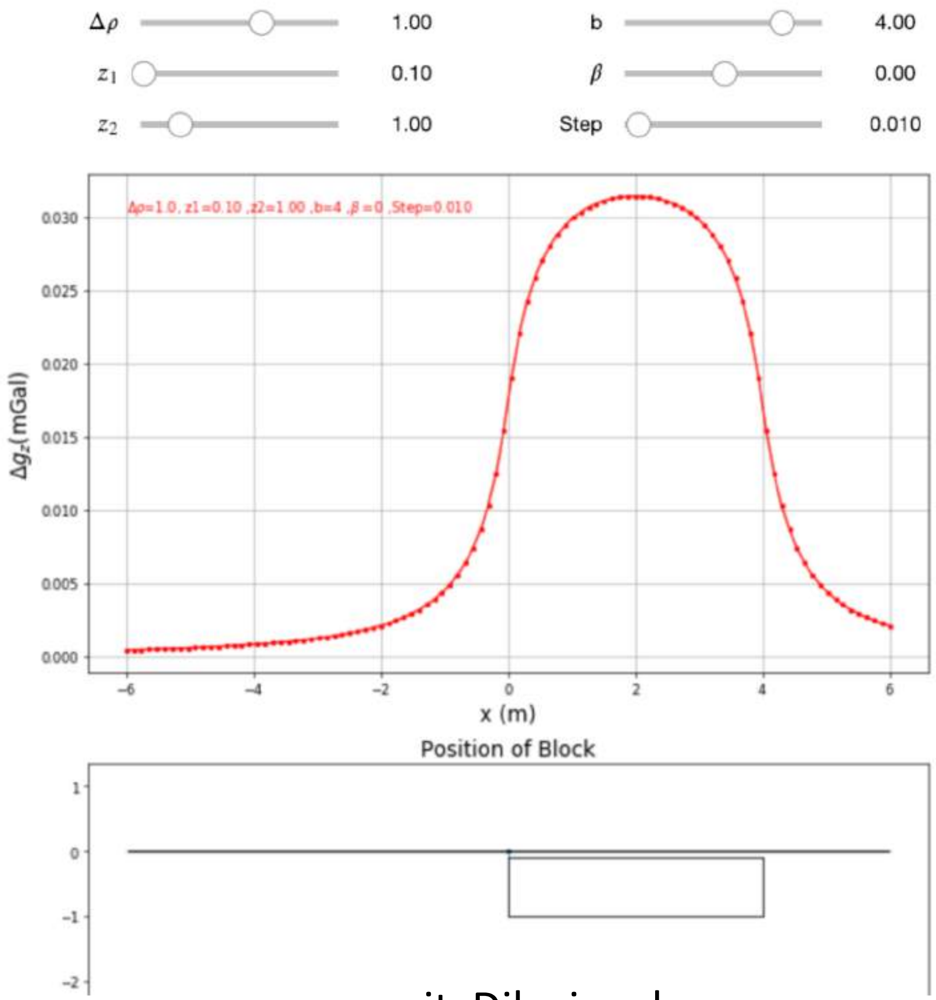


Can you tell the dipping direction from g_z?

Which derivative is more useful in finding the dip?

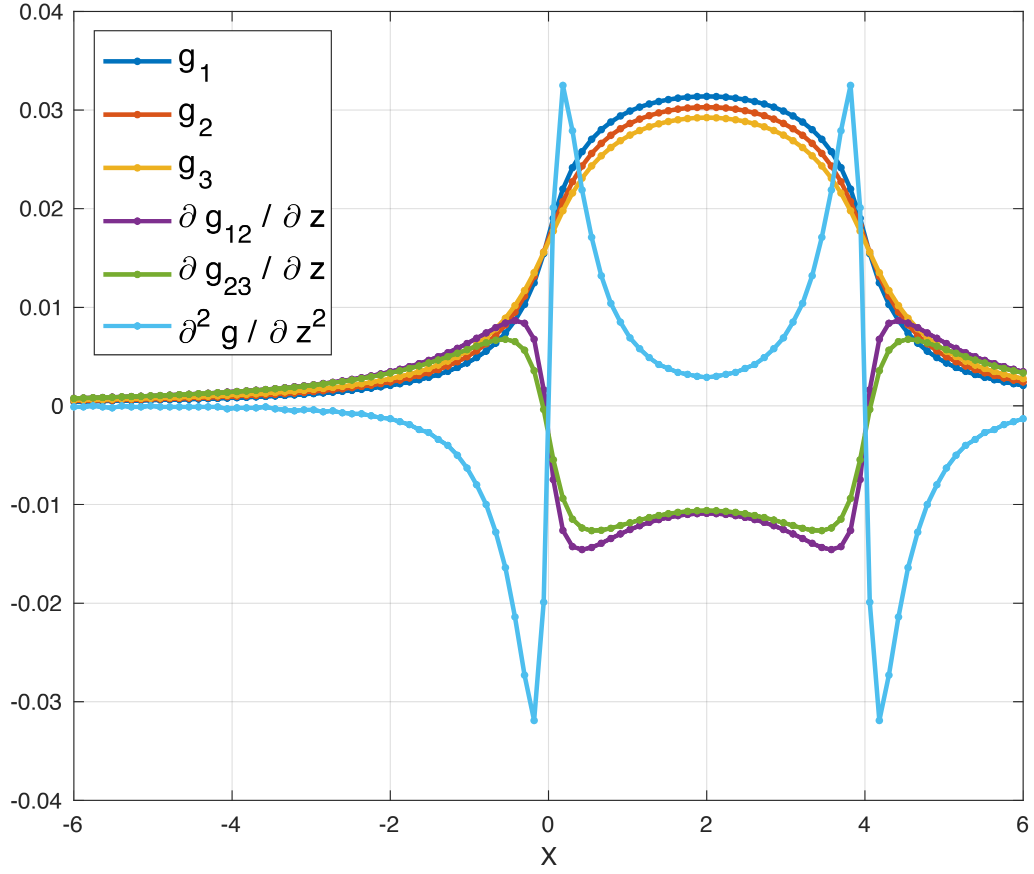


Vertical Derivatives

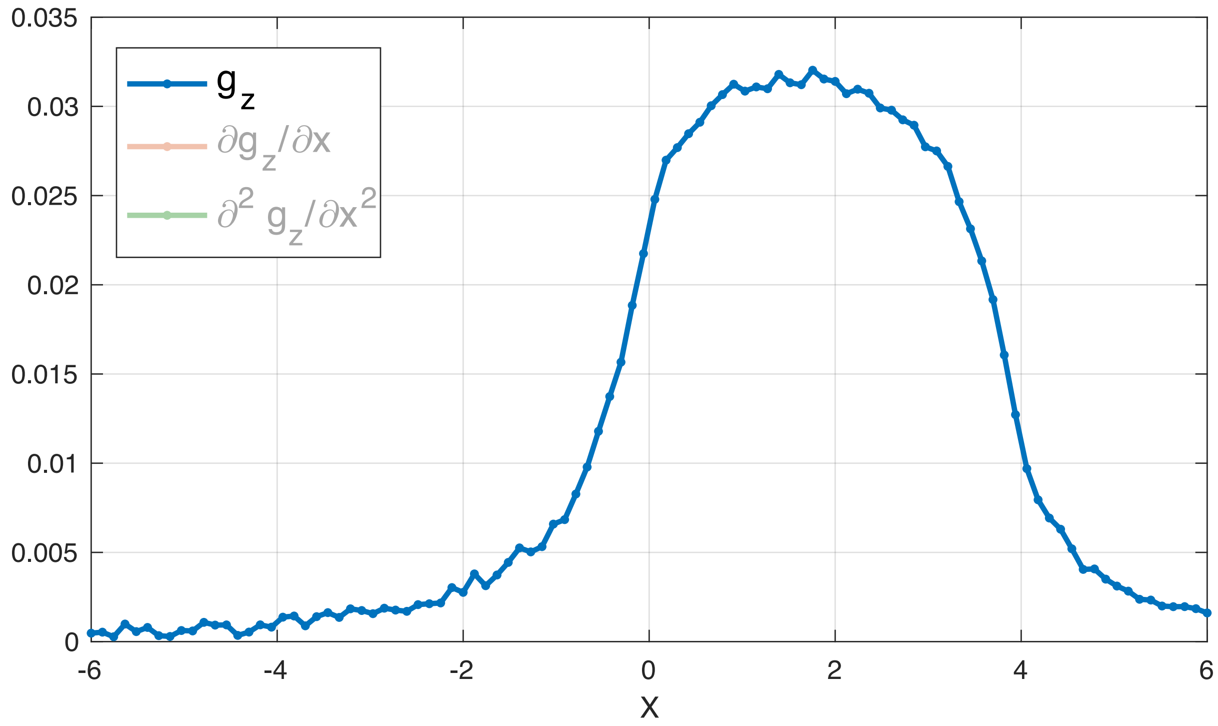


gravityDike.ipynb

g_1: 0 m above surface
g_2: 0.1 m above surface
g_3: 0.2 m above surface

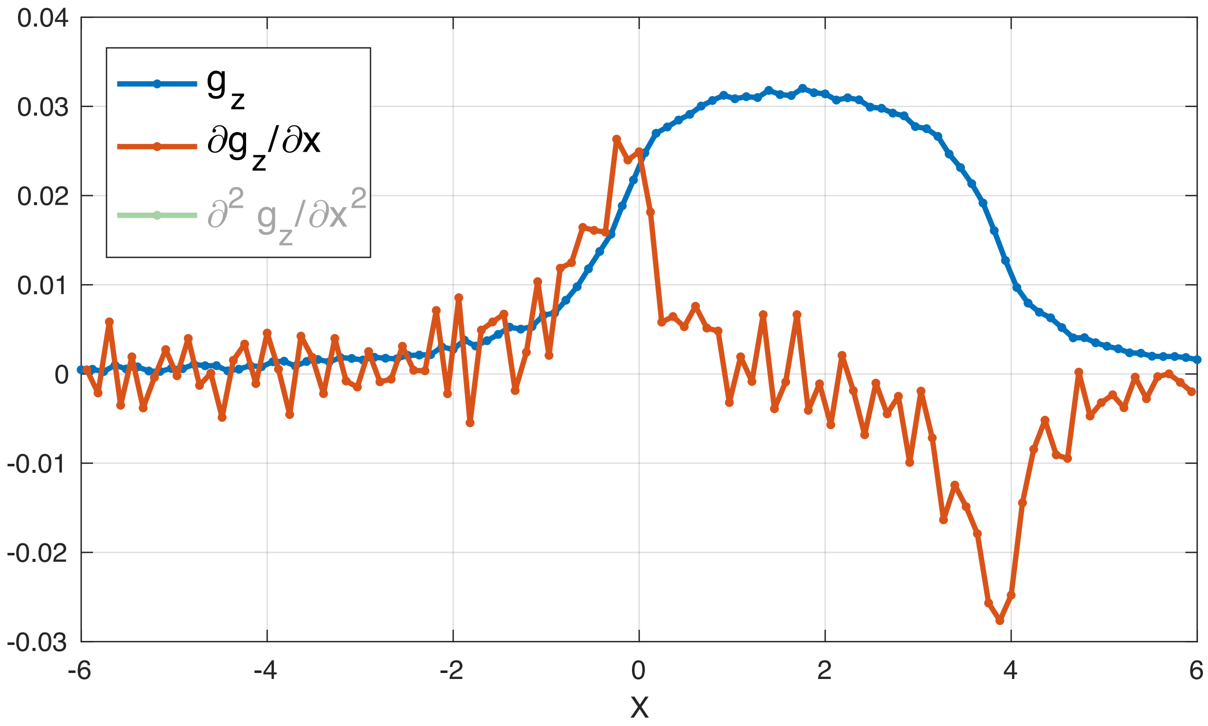


High Order Derivative?



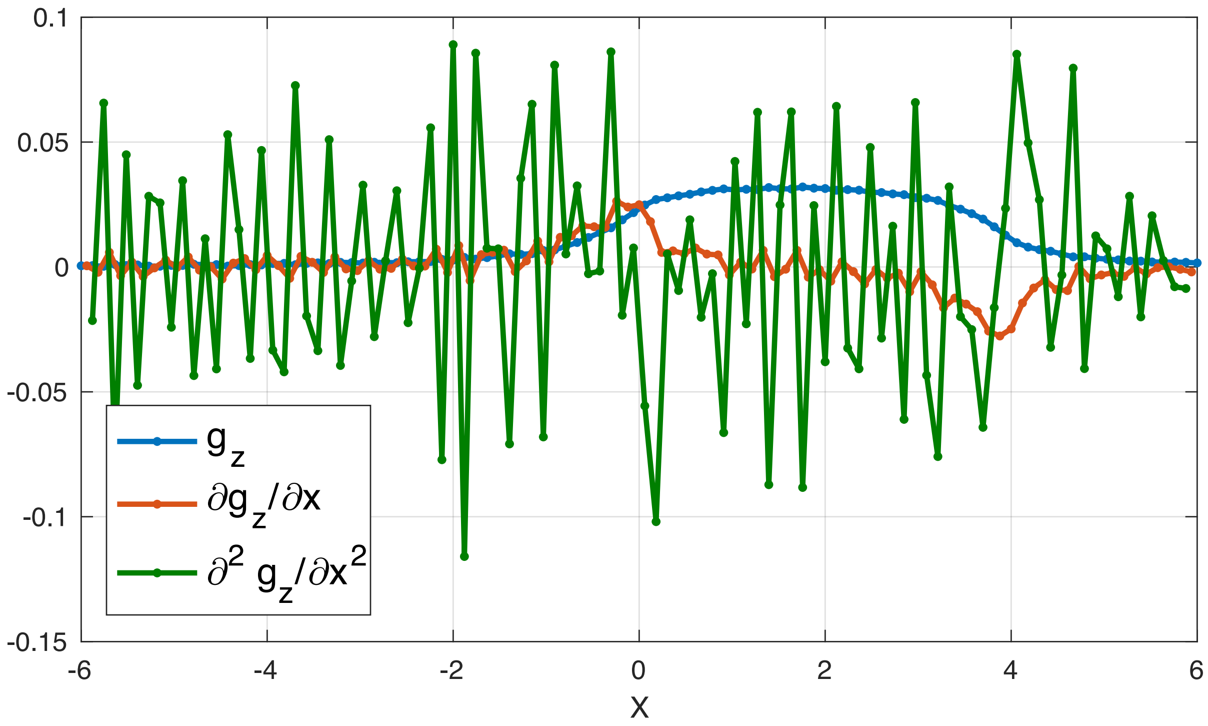
1% Gaussian noise in data

High Order Derivative?



Horizontal 1st derivative: Not too bad

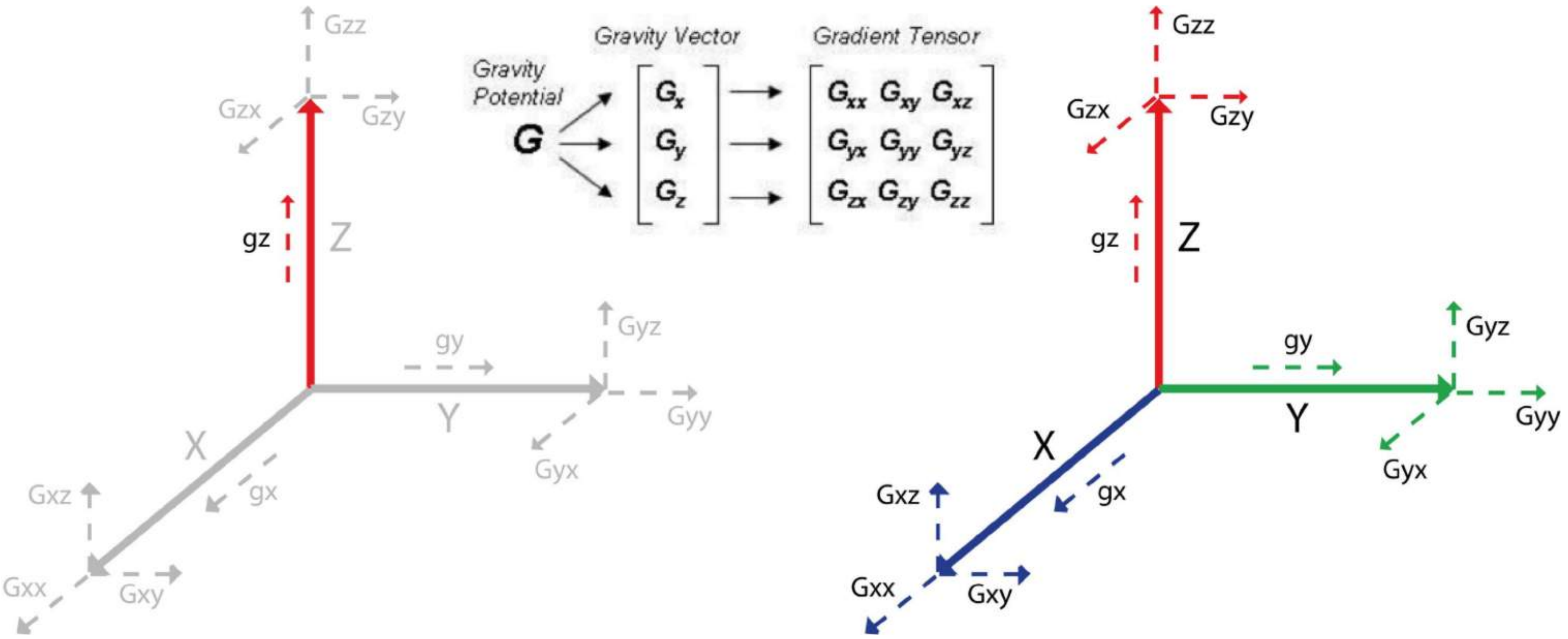
High Order Derivative?



Horizontal 2nd derivative: Caution!

Derivative magnifies noise in data

Full Tensor Gradient: More from g_x and g_y



3D-FTG

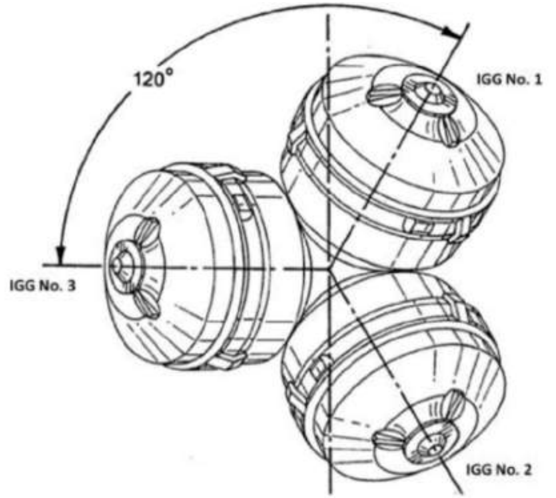


Figure 3 – Umbrella-like arrangement of Gravity Gradient Instruments (GGI) according to Brett & Brewster (2010).

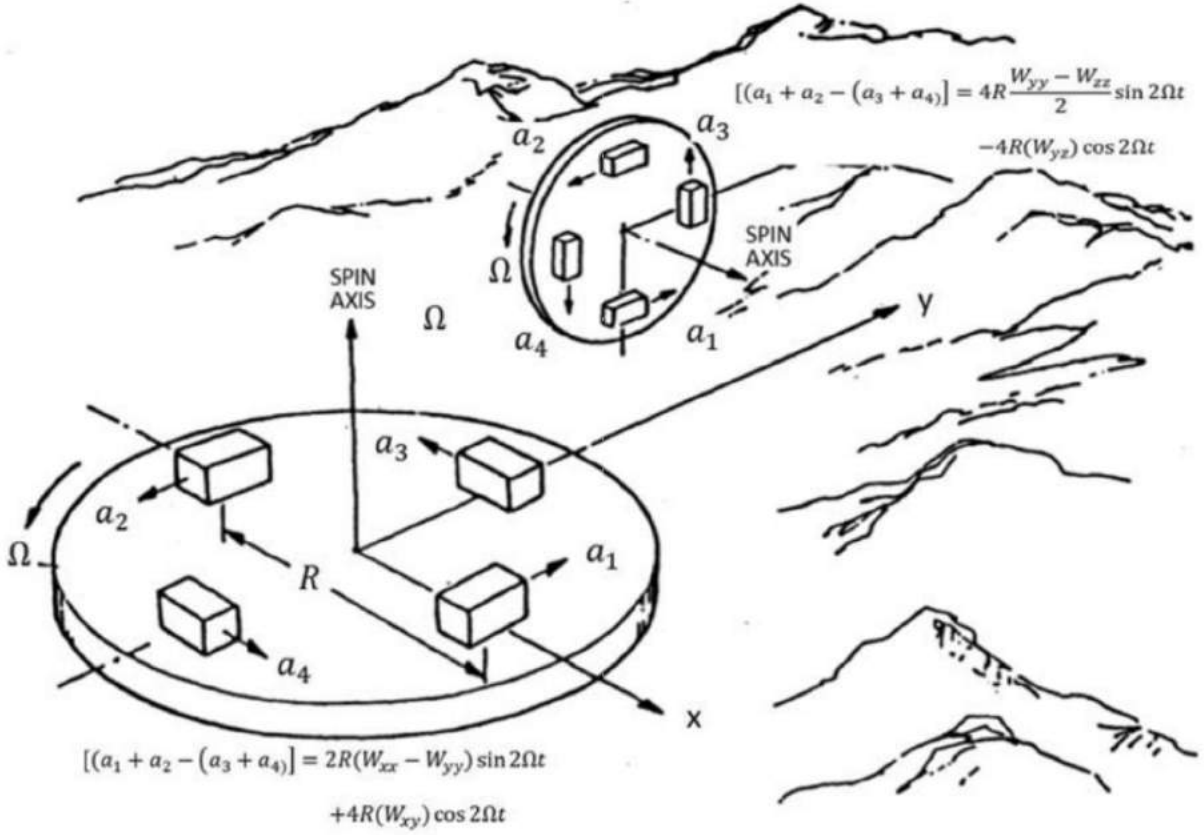
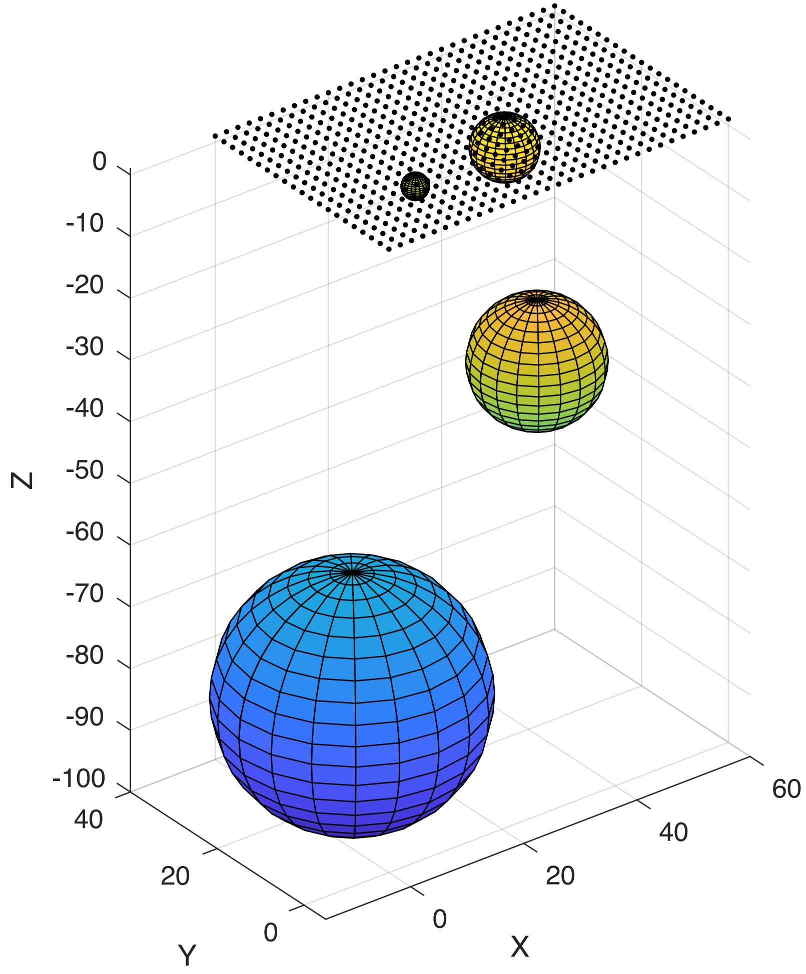
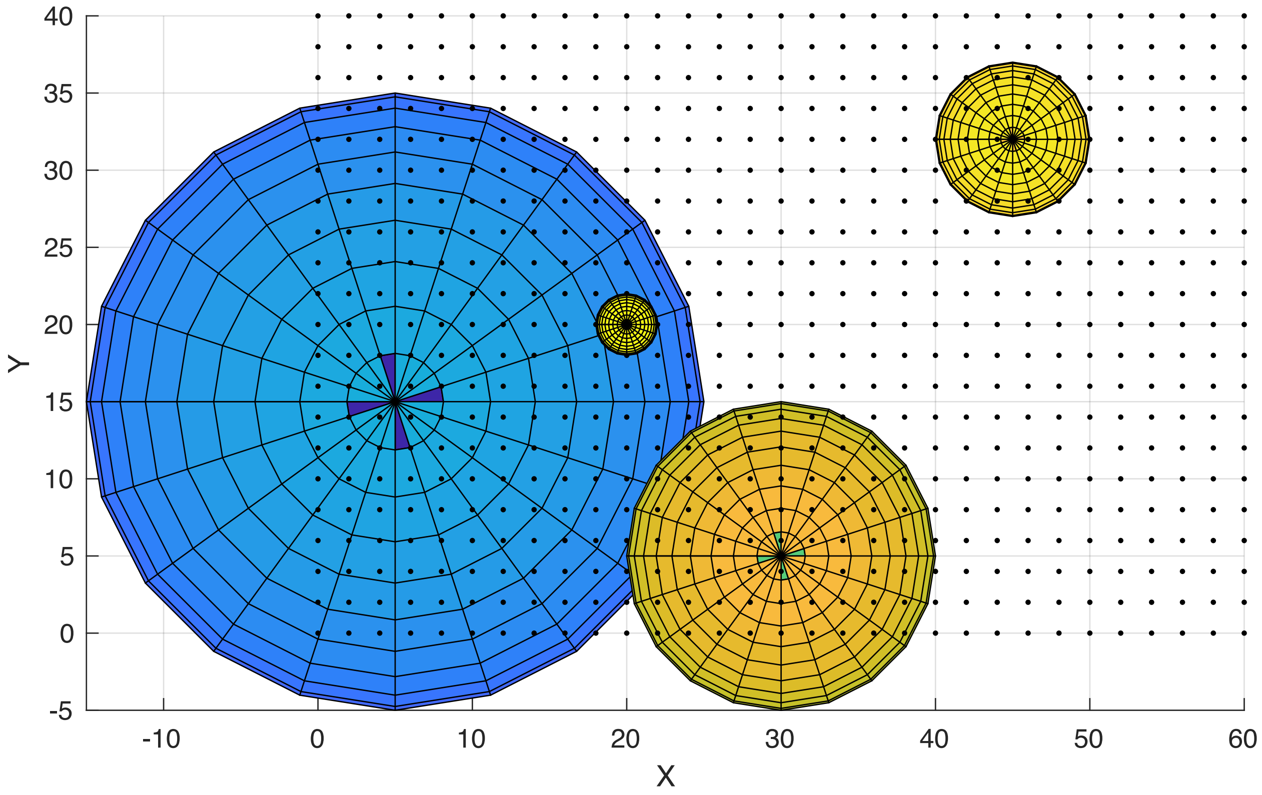


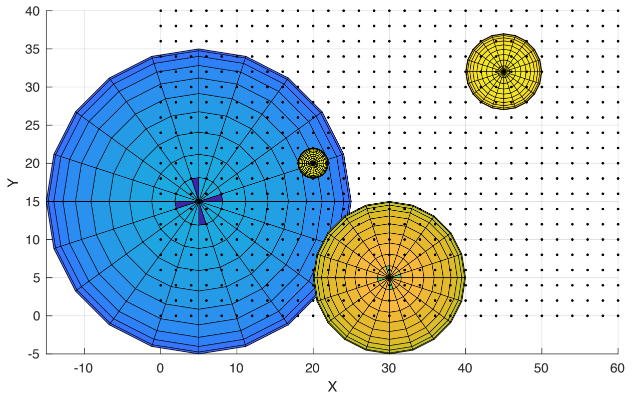
Figure 2 – Representation of rotational accelerometers gravity gradient according to Metzger (1986).

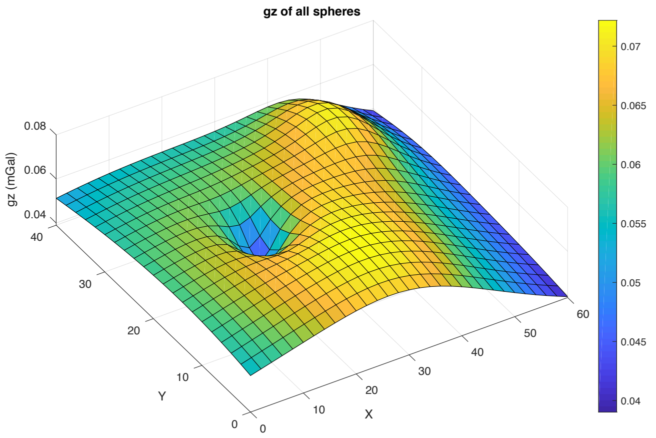
The Four-Sphere Model

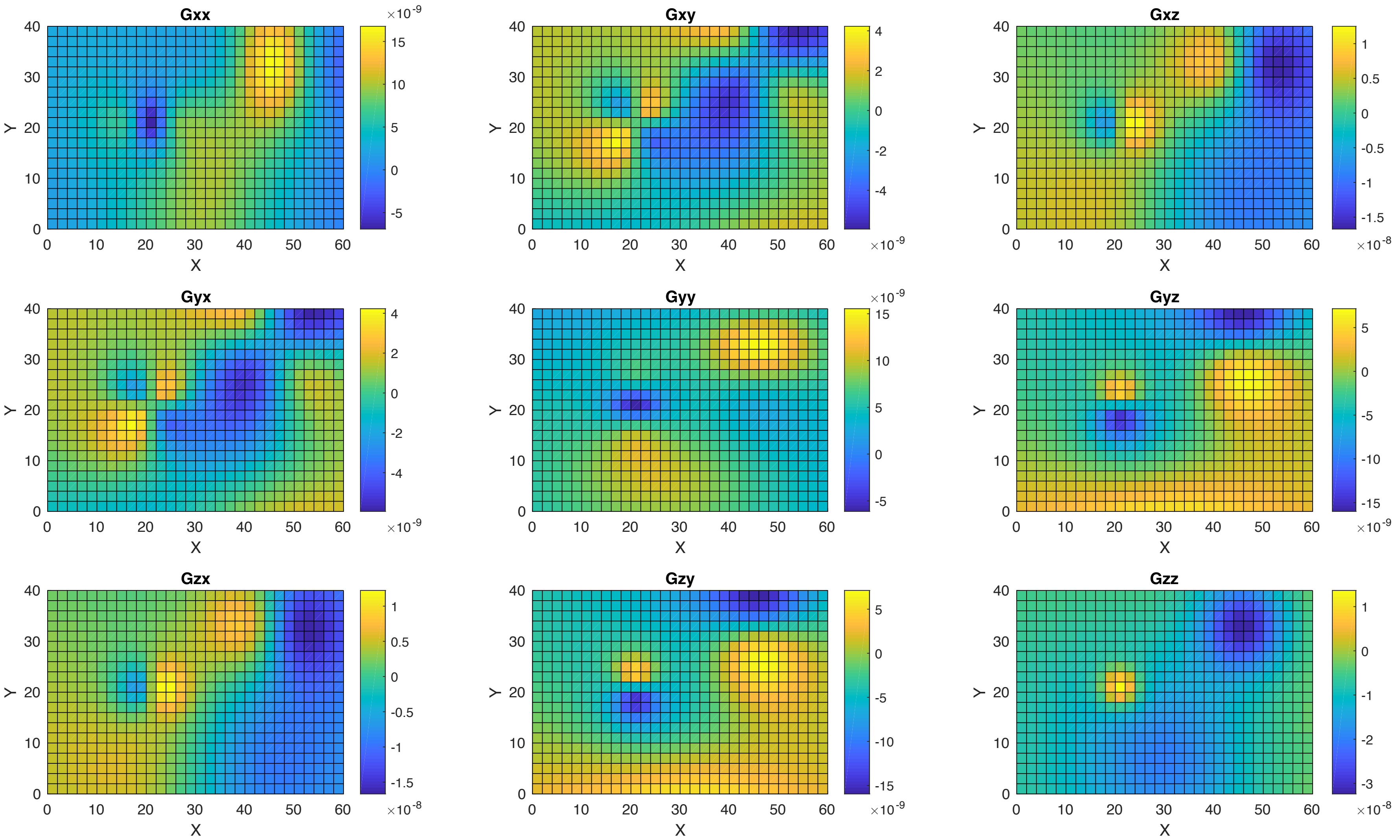




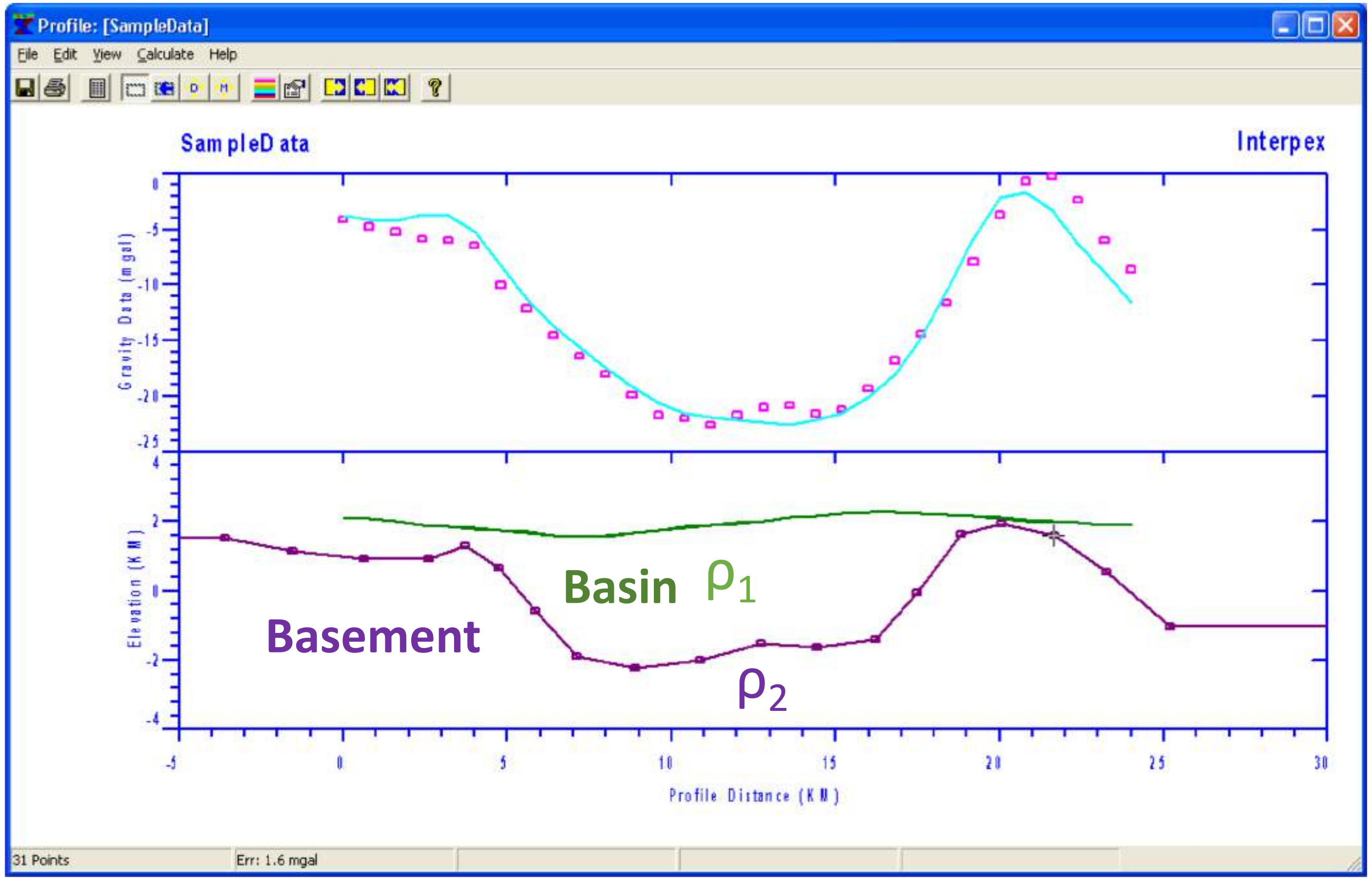
Full Tensor Gravity Gradient



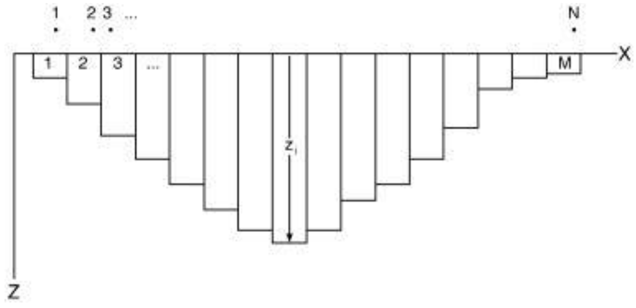


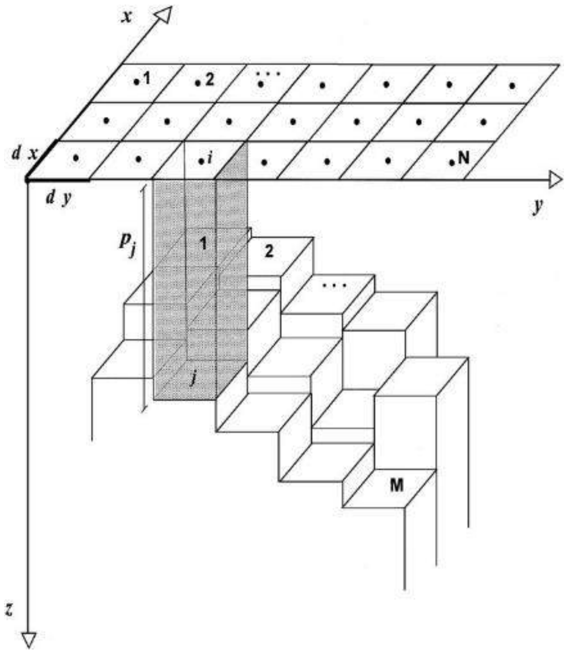


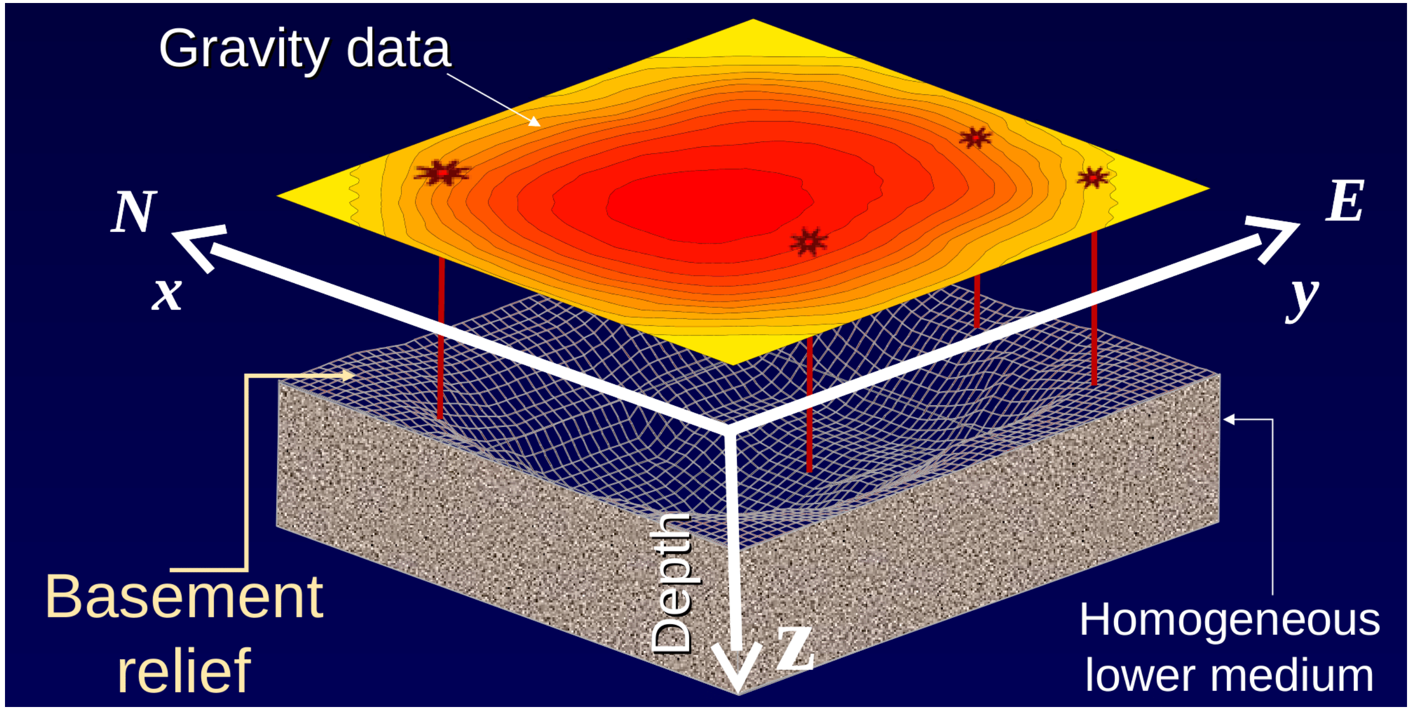
Geometric Inversion - Interactive



Geometric Inversion - Basement Relief



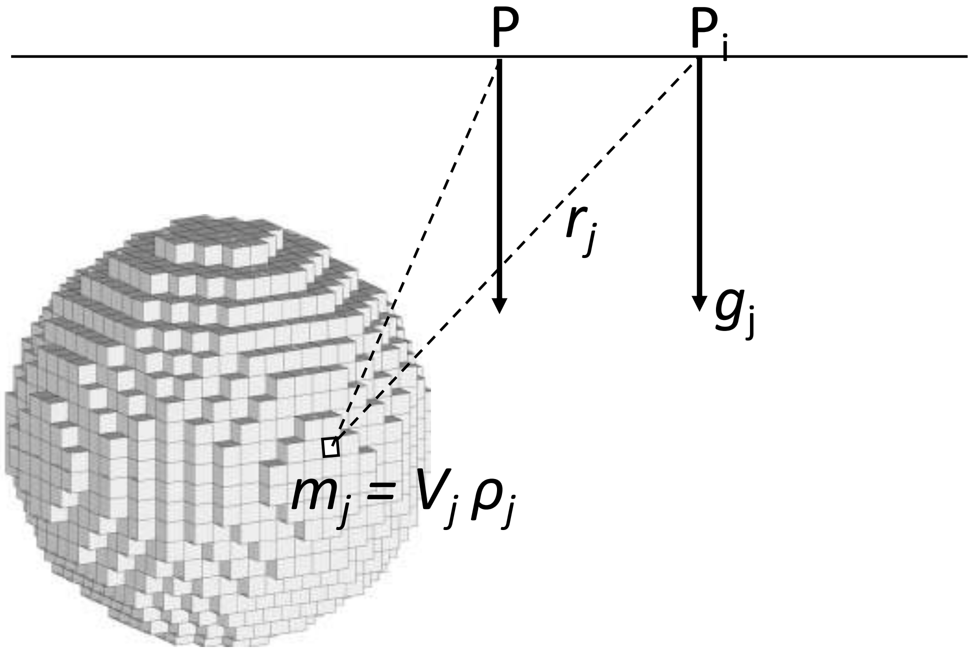




Pixel/Voxel Inversion

Superposition

$$g = \sum_j g_j$$



Data = Integration over a volume:
Not enough information to fully recover the true model

$$\begin{pmatrix} & & \\ & A & \\ & & \end{pmatrix} \begin{pmatrix} \\ \boldsymbol{\rho} \\ \\ \end{pmatrix} = \begin{pmatrix} \\ \boldsymbol{d} \\ \\ \end{pmatrix}$$

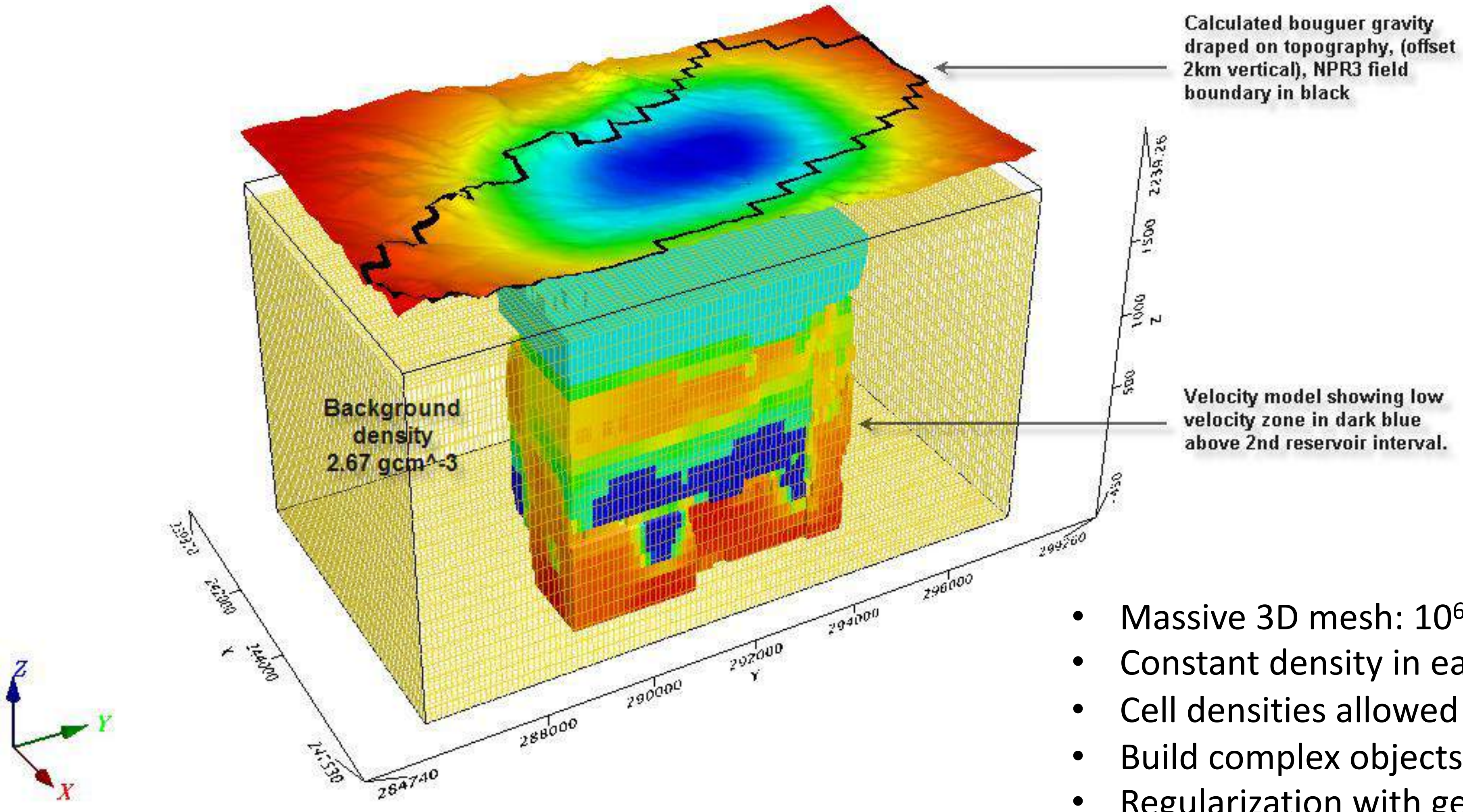
A_{ij}: Contribution of the j^{th} element to the i^{th} datum

Linear problem but the **inverse problem is ill-posed**!

So the piece-wise constant density model $\boldsymbol{\rho}$ is

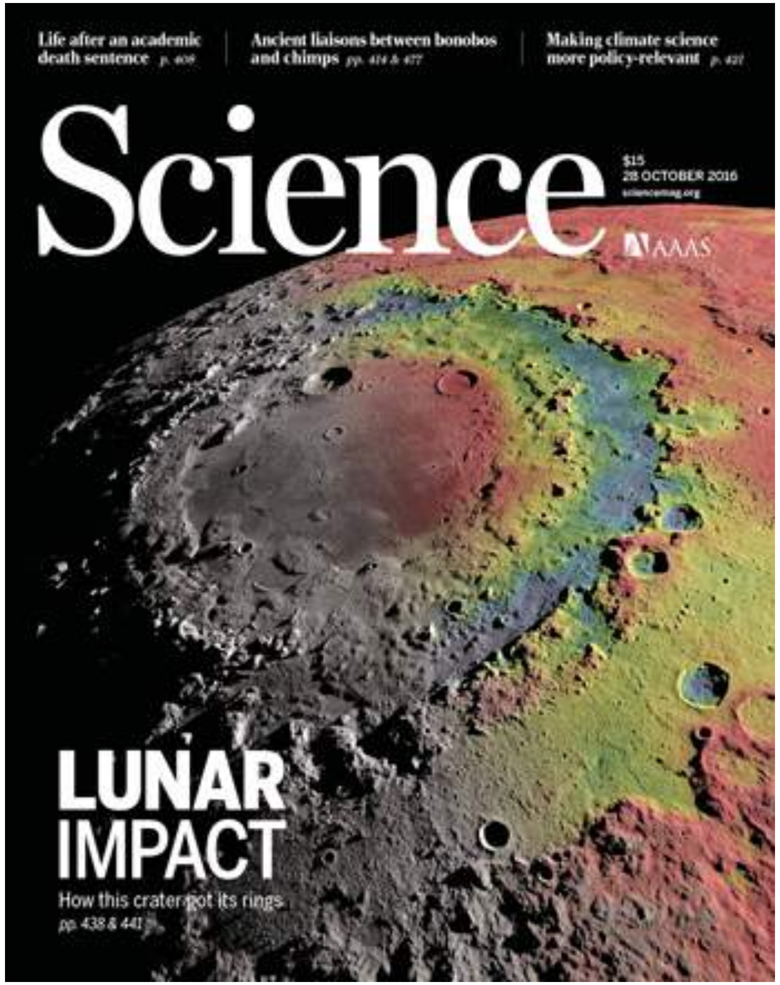
$$\begin{pmatrix} \\ \boldsymbol{\rho} \\ \\ \end{pmatrix} = \begin{pmatrix} & & \\ & A & \\ & & \end{pmatrix}^{-1} \begin{pmatrix} \\ \boldsymbol{d} \\ \\ \end{pmatrix}$$

3D Voxel Inversion



- Massive 3D mesh: 10^6 cells
- Constant density in each cell
- Cell densities allowed to vary
- Build complex objects: like Lego
- Regularization with geological a prior information

Planetary Science – Crater on Moon



Gravity field of the Orientale basin from the Gravity Recovery and Interior Laboratory Mission

Maria T. Zuber[1,*], David E. Smith[1], Gregory A. Neumann[2], Sander Goossens[3], Jeffrey C. Andrews-Hanna[4,5], James W. Head[6], Walter S. Kiefer[7], Sami W. Asmar[8], Alexander S. Konopliv[8], Frank G. Lemoine[2], Isamu Matsuyama[9], H. Jay Melosh[10], Patrick J. McGovern[7], Francis Nimmo[11], Roger J. Phillips[5], Sean C. Solomon[12,13], G. Jeffrey Taylor[14], Michael M. Watkins[8,15], Mark A. Wieczorek[16], James G. Williams[8], Johanna C. Jansen[4], Brandon C. Johnson[1,6], James T. Keane[9], Erwan Mazarico[2], Katarina Miljković[1,17], Ryan S. Park[8], Jason M. Soderblom[1], Dah-Ning Yuan[8]

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[13]*Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA.*
[14]*Hawaii Institute of Geophysics and Planetology, University of Hawaii, Honolulu, HI 96822, USA.*
[15]*Center for Space Research, University of Texas, Austin, TX 78712 USA.*
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[17]*Department of Applied Geology, Curtin University, Perth, Western Australia 6845, Australia.*
↵*Corresponding author. Email: zuber@mit.edu
– Hide authors and affiliations

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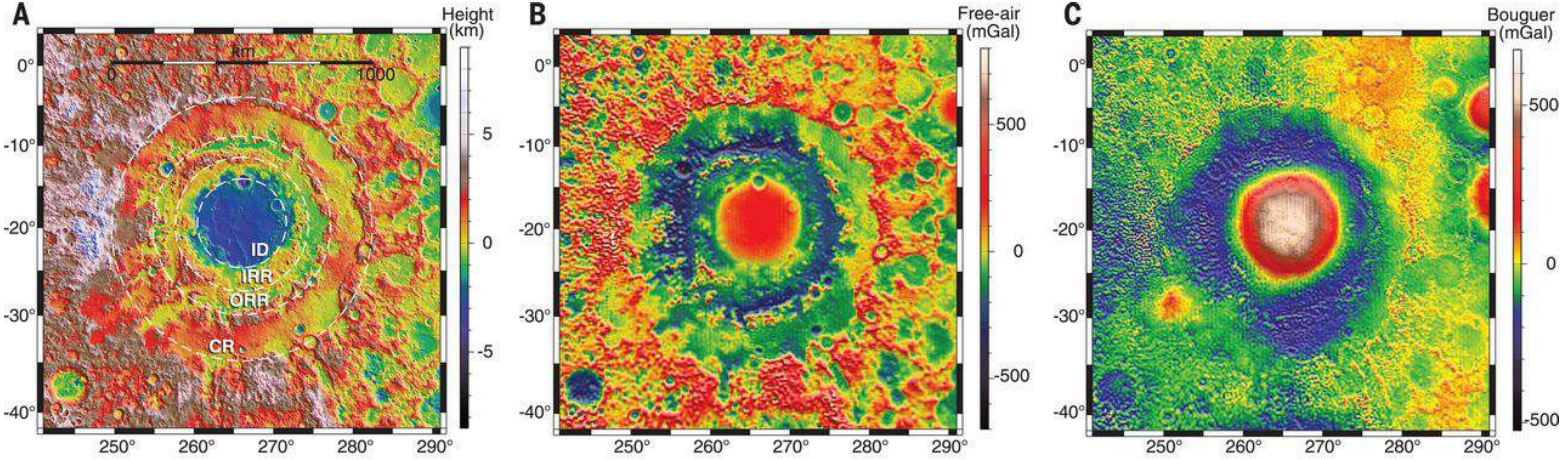
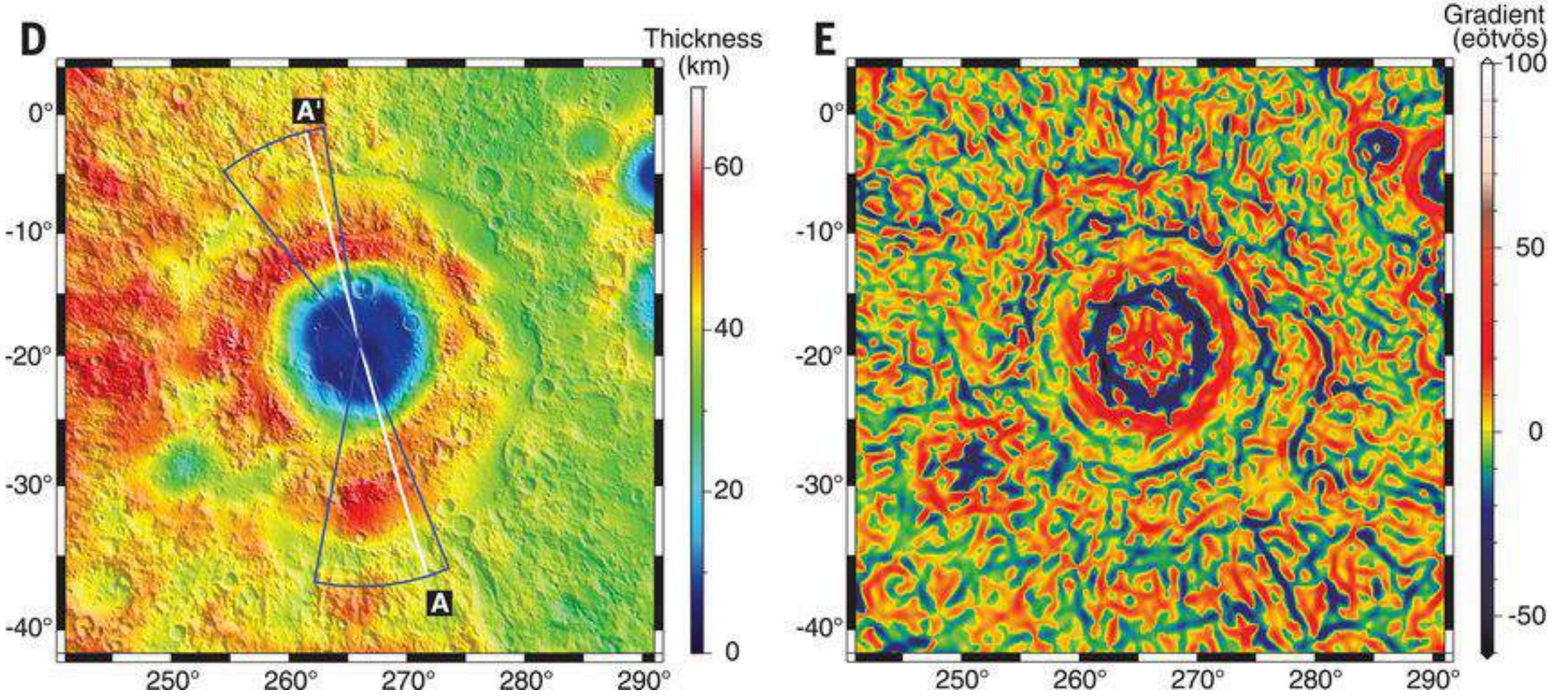
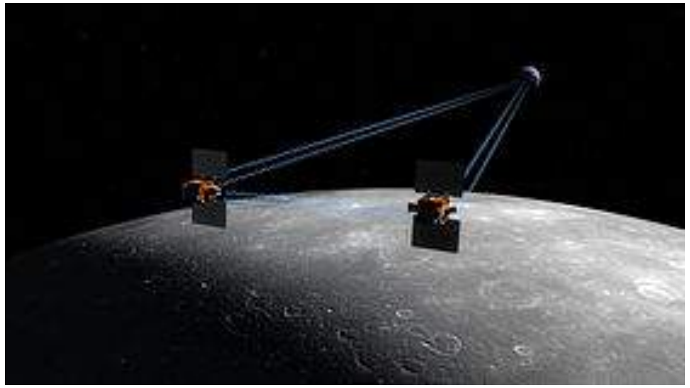
http://science.sciencemag.org/content/354/6311/438



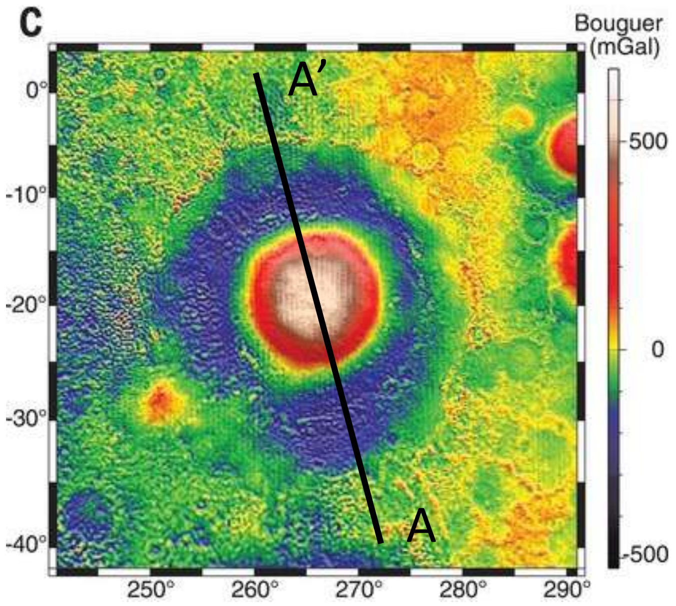


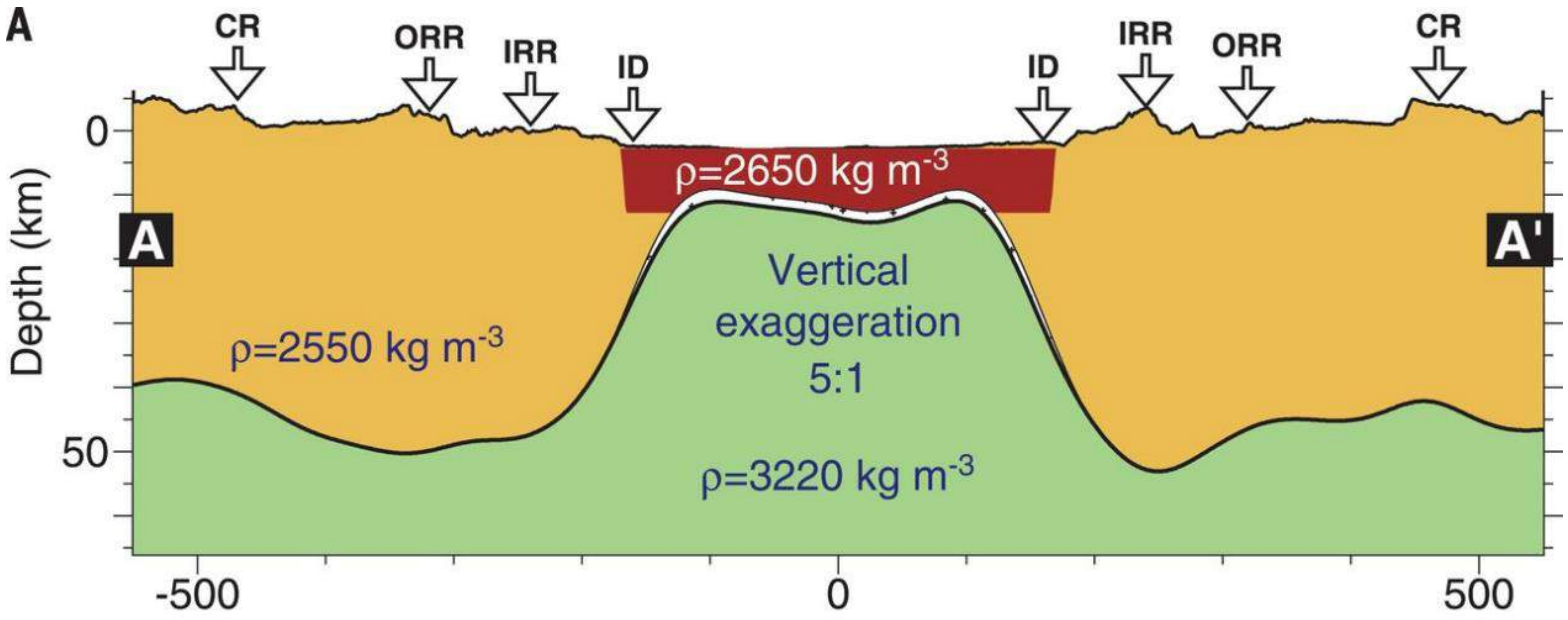


GRAIL

https://youtu.be/_hknIsPNsl8

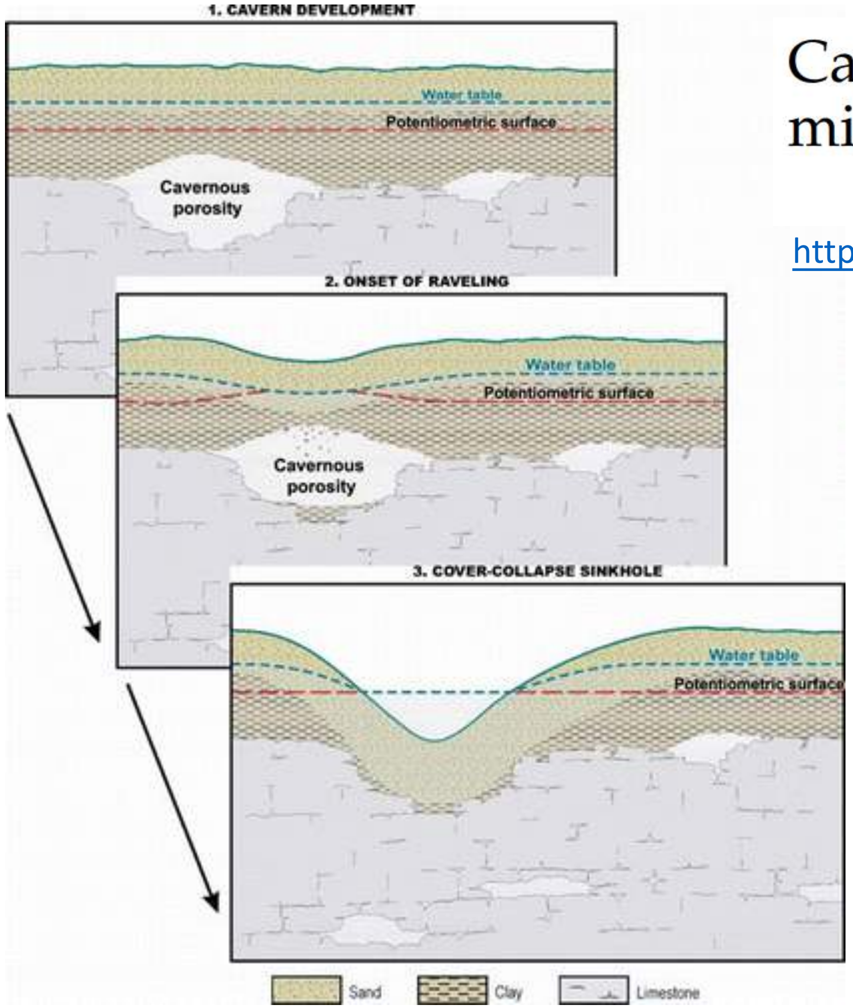
Density of the Moon’s Interior





Can you sketch a density structure along the cross section A-A’?

Environmental – Sinkholes

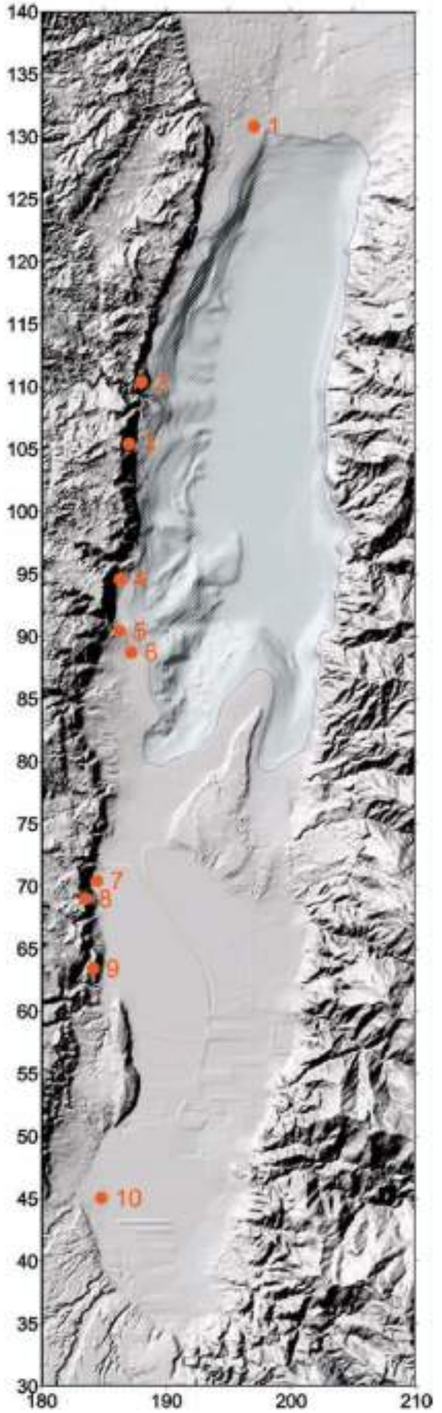


Cave detection and 4-D monitoring: A microgravity case history near the Dead Sea

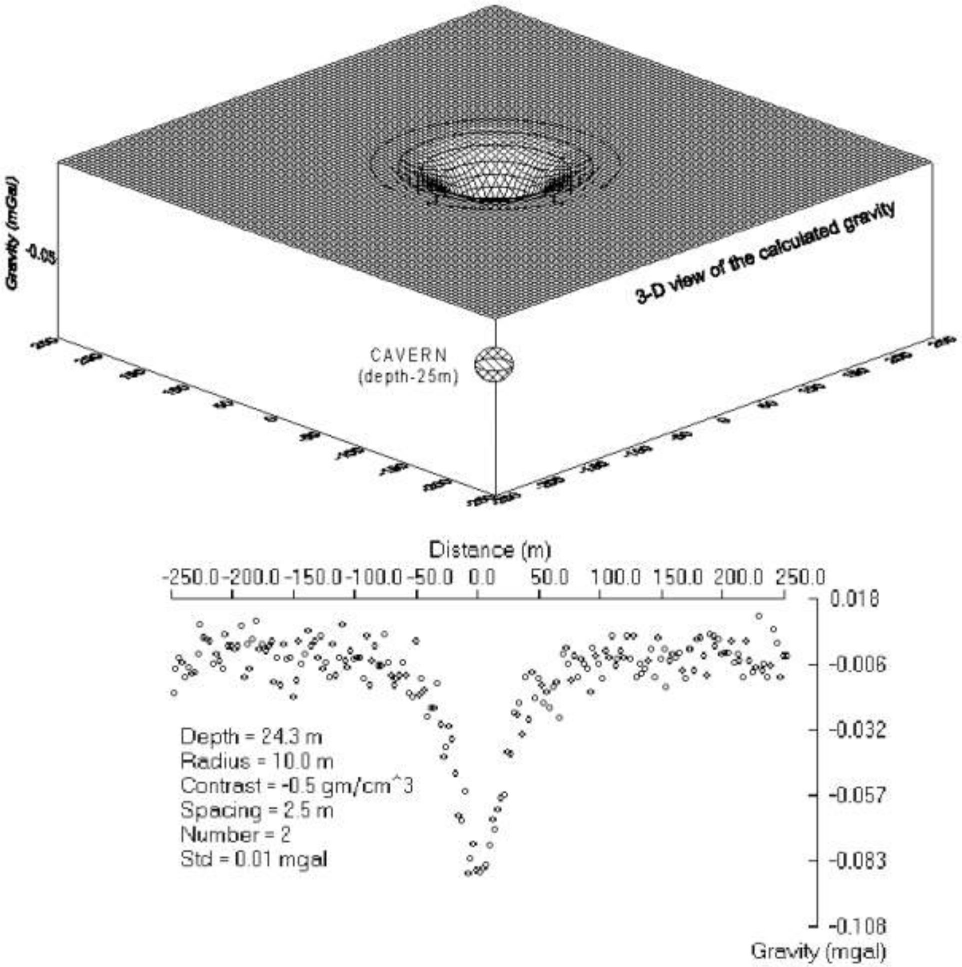
M. RYBAKOV, V. GOLDSHMIDT, L. FLEISCHER, and Y. ROTSTEIN, The Geophysical Institute of Israel

https://library.seg.org/doi/pdf/10.1190/1.1487303n

Figure 2. One of largest sinkholes in the Dead Sea area (after Gilat, 1999).



Forward Modeling: Feasibility Study



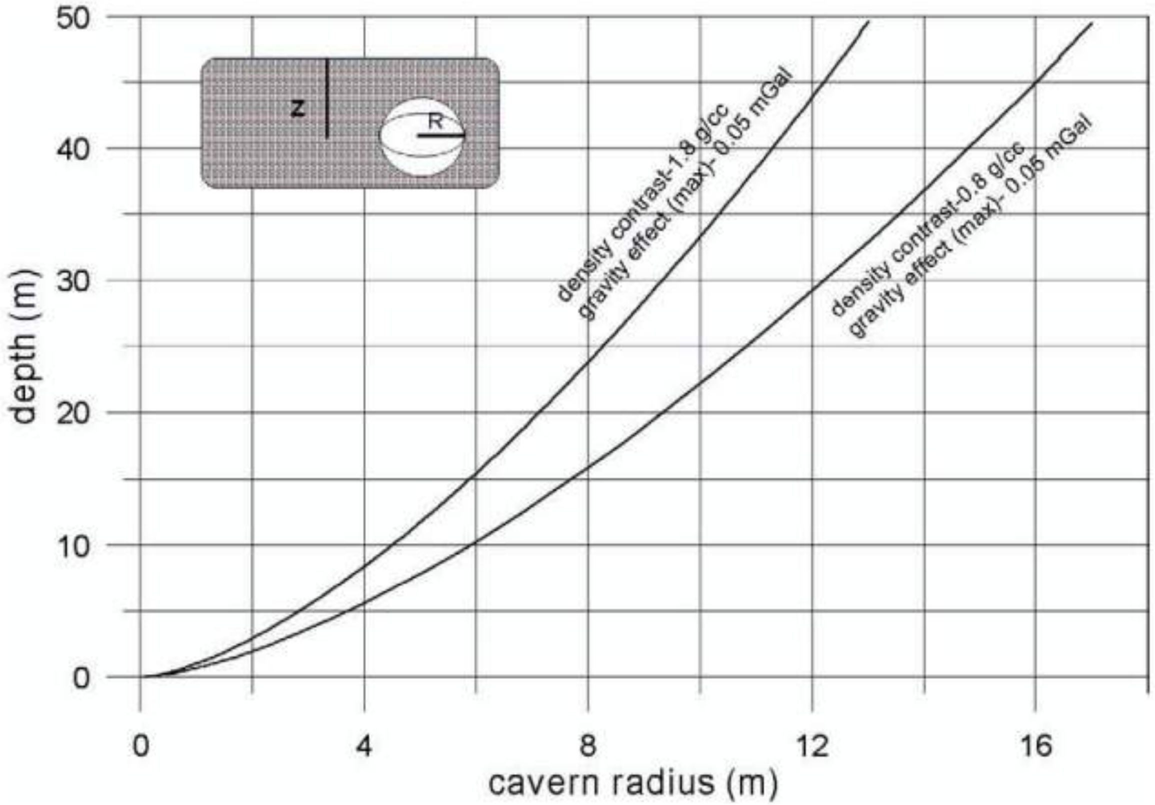
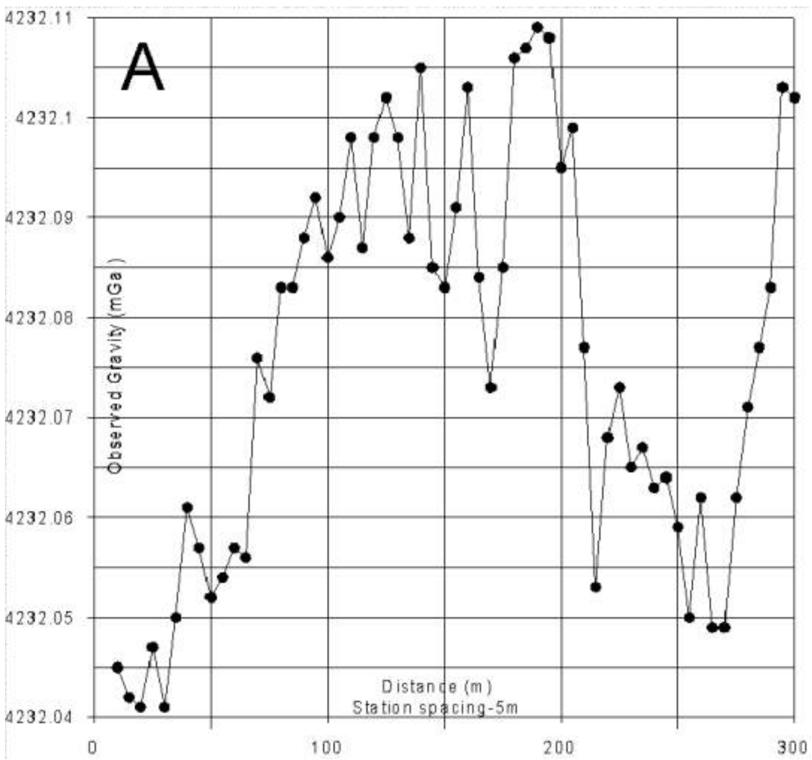


Figure 6. Effect of detectability threshold level and density contrast—maximum depth for detection of spherical concealed cavern. Large density contrast corresponds to air-filled cavern and small density contrast to saltwater-filled cavern.

Cavern Mapping Result



Raw gravity data along a line

- Gravimeter accuracy 0.005 mGal
- Scintrex CG-3M: 0.001 mGal
- Geodetic control: Laser Total Station (a few mm)
- Real-time elevation of the instrument
- Base station repeated hourly
- Repeat measurement: 10% of all stations
- Fully terrain corrected: 25-m grid DTM + precise local survey near the station

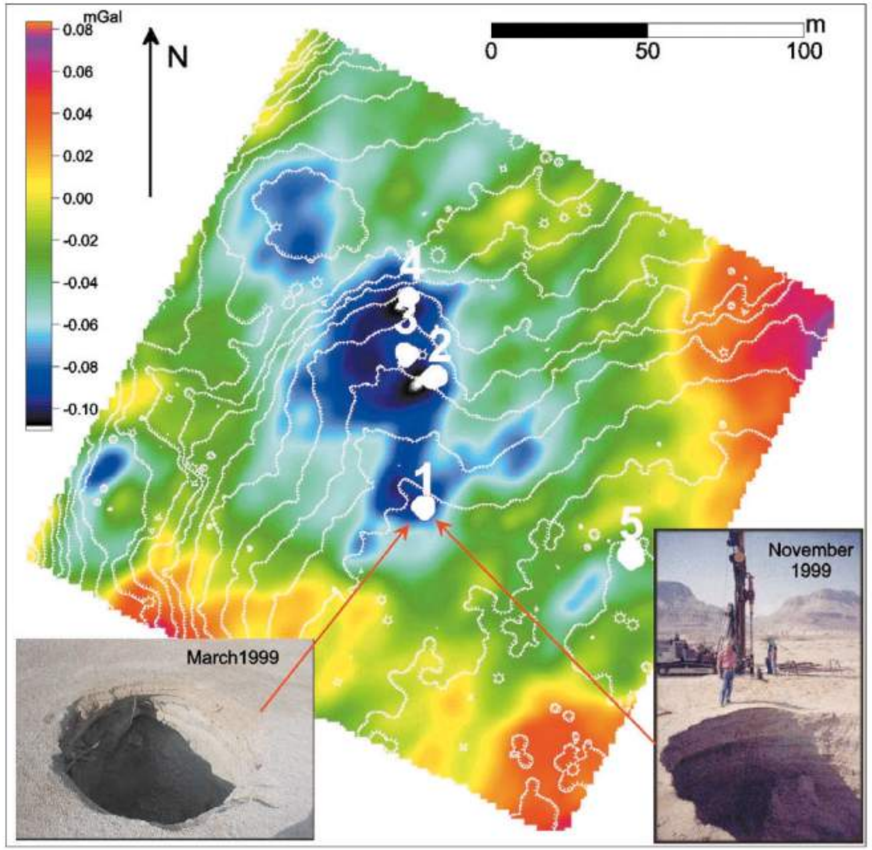


Figure 9. Residual gravity map of the Hever site superimposed by detailed topography (white contours - 0.25-m interval). White circles denote open sinkholes. Photos show growth of sinkhole 1 between March and November 1999.

Military – Submarine Navigation

Gradient Tensor

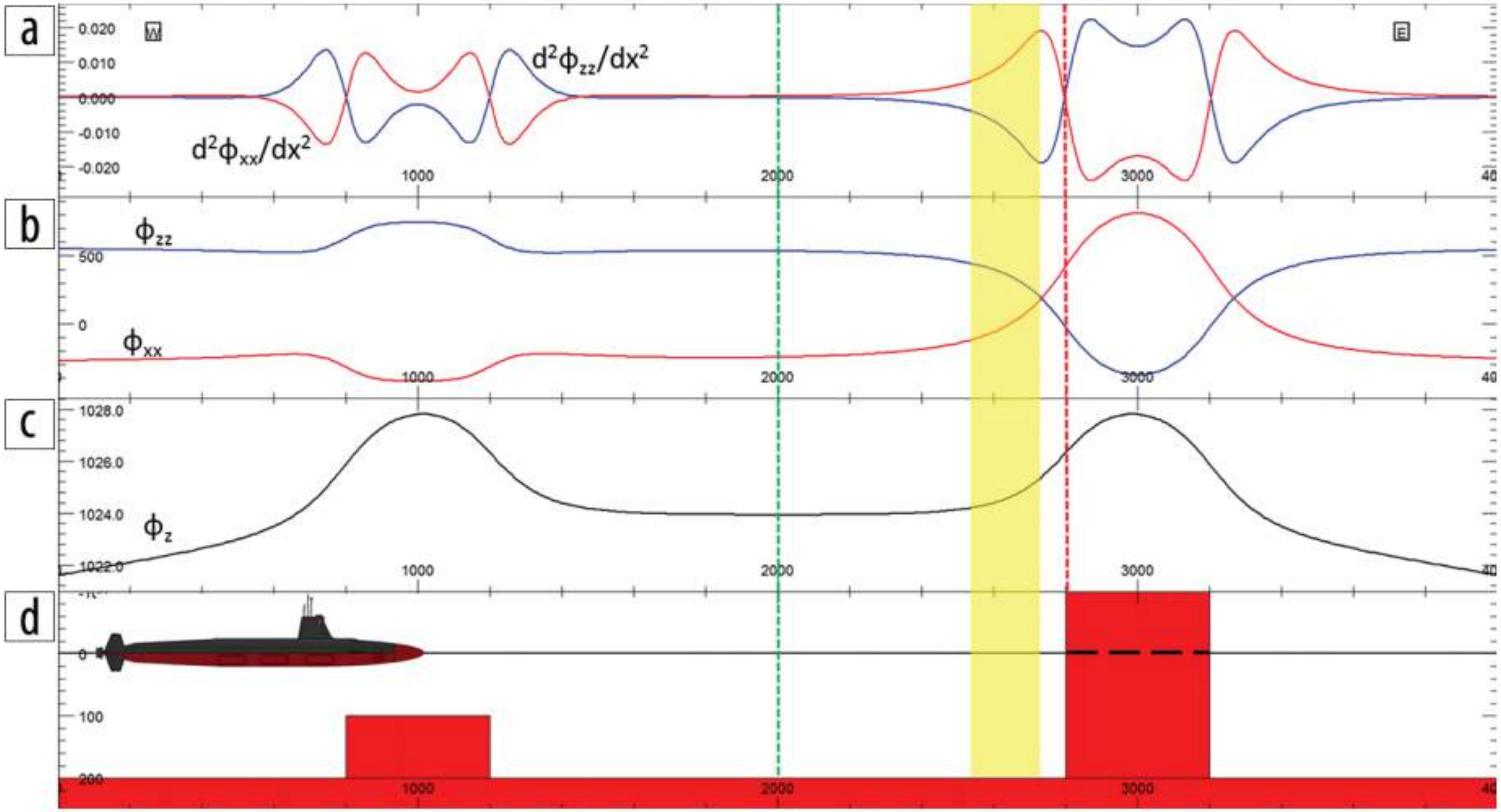
$$\begin{bmatrix} G_{xx} & G_{xy} & G_{xz} \\ G_{yx} & G_{yy} & G_{yz} \\ G_{zx} & G_{zy} & G_{zz} \end{bmatrix}$$

How do submarines use gravity gradients to avoid collisions with underwater mountains?

Carlos Cevallos[1]

https://library.seg.org/doi/pdf/10.1190/tle34121498.1

Military – Submarine Navigation



Collision warning:

- **Φxx** is increasing
- **Φzz** is diminishing
- The second horizontal derivatives of **Φxx** and **Φzz** attain a maximum and a minimum, respectively

Can gravity gradient be used to detect another submarine?

Summary of Gravity

- Density: Which heavy? Which light?
- How to detect an object (like cavity) below subsurface?
- Properties of gravity data: Superposition, ambiguity, $1/r^2$ decay
- Approaches to identify sources of signals:
  - Regional removal
  - Upward/downward continuation
  - Derivatives
  - Full tensor gradients
- Gravity inversion
- Applications: Planetary science, environmental, military, basin, etc.