EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

Introduction to Geophysics

R. Drews

Gravity Method

Introduction

Introduction to Geophysics

- Who?
- What?
- How?

Who's teaching?

- R. Drews (Prof. Geophysics at UT)
- P. Dietrich (Prof. Env./Eng.- Geophysics at UFZ, Leipzig)
- R. Ershadi (PhD Geophysics)
- A. Vinson (TA, MSc Geosciences)
- L. Naumann (TA, BSc Geosciences)

Who’s teaching?

Introduction to Geophysics - R. Drews

Prof. for Geophysics since 2022

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What are we teaching?

Geophysics is a branch of earth science dealing with the physical processes and phenomena occurring especially in the earth and in its vicinity.

[Merriam-Webster]

Applied Geophysics is a branch of Geophysics dealing with different observational methods imaging the sub-surface.

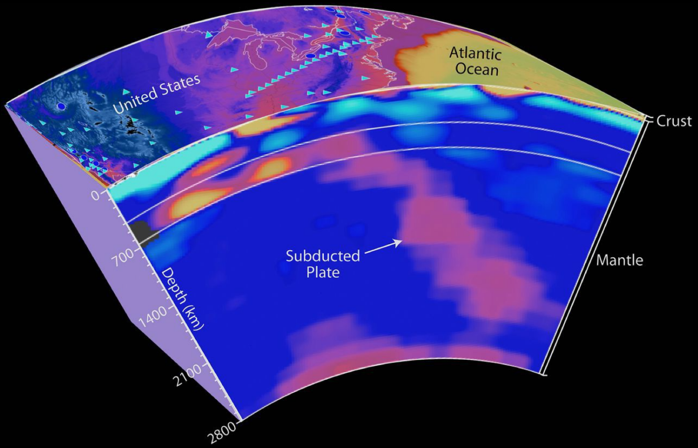
[The lecture focus will be here.]

What are we teaching?

Applied Geophysics contains, e.g, gravity, magnetics, electrics, electrical induction, electromagnetics (radar), seismics.

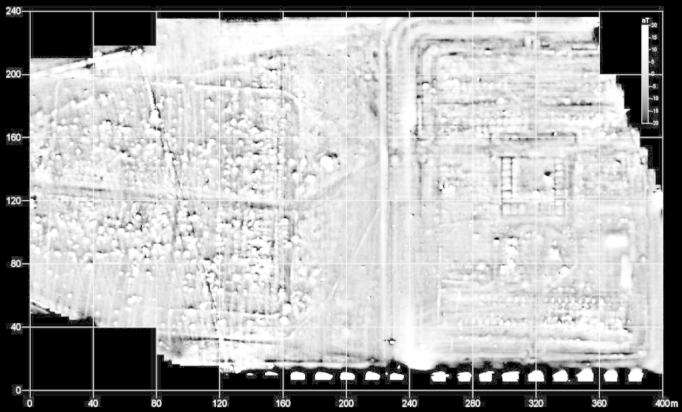
[Focus on physical principals rather than aquisition specifics.]

Example: Seismics



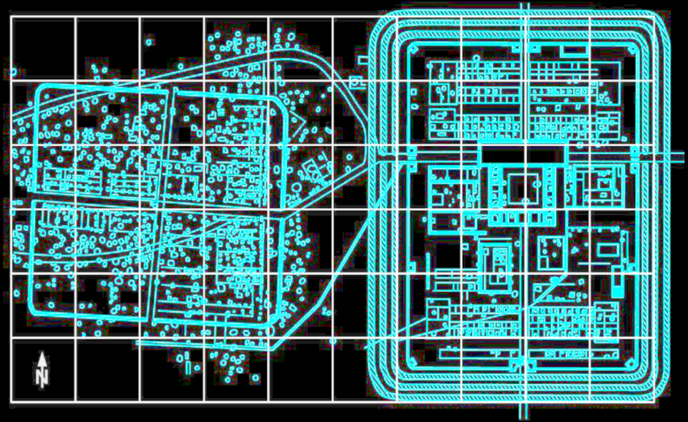
[S. van der Lee, Northwestern University, Evanston, IL]

Example: Magnetics



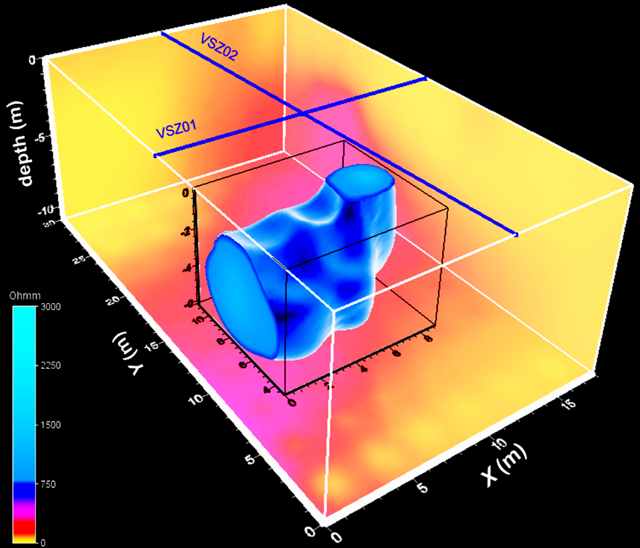
[Fassbinder, Bavarian Academy of Sciences]

Example: Magnetics



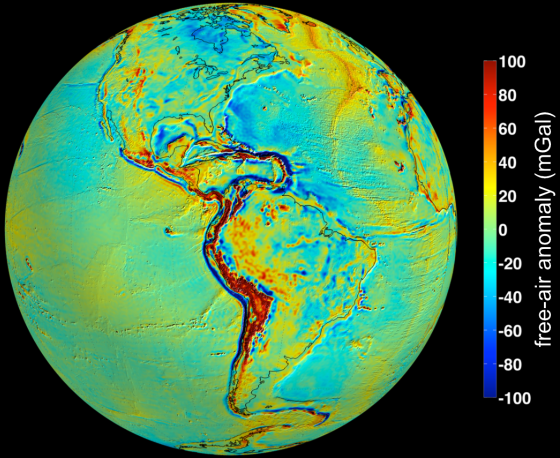
[Fassbinder, Bavarian Academy of Sciences]

Example: Geoelectrics



[Plank et al., Near Surface Geophysics, 2019]

Example: Gravity



[JPL/Caltec GRACE-FO (DT-10)]

How do we teach?

- Video Lectures or Plenum (Tuesdays)
- Exercises & 1-1-Interaction (Thursdays)
- Applied Exercises (Magnetics, Electrics, Seismics)

How do we teach?

Learning Goals

- Obtain a broad overview of geophysical methods for sub-surface imaging.
- Understand the underlying physical principles.
- Learn how to think logically & quantitatively.

How do we teach?

Expectations

- Be prepared.
- Ask questions.
- Do the work.

How do we teach? → Ilias

Introduction to Geophysics

Geow-B402-V2

Instructor Info —

- Reinhard Drews
- Office Hrs: on demand.
- GUZ 3M07/3U03/3F03
- Website
- reinhard.drews@uni-tuebingen.de

Course Info —

- Prereq: None
- Tues & Thurs
- 16:15-18.00
- Online

Field Exercises —

- In sub-groups of 6

Overview

[Document version Wednesday 9th March, 2022 at 16:28:15]

This course provides a broad overview in applied geophysics with a focus on the most common sub-surface imaging techniques: gravimetry, magnetics, geoelectrics, electromagnetic induction, ground-penetrating radar and seismics. We will discuss applications in industry as well as for general scientific questions in the geo- and environmental sciences.

Everything is subject to change with news University regulations regarding the pandemic, but at this stage I anticipate a large in-person component.

Lecture Format

The lecture is accompanied with three mandatory, hands-on field exercises that will be conducted in small groups. The field measurements take approximately six hours and will be concluded by a joint group report. The lecture format contains frontal lectures on Tuesdays in 3M07, group work on experimental & theoretical exercises on Thursdays in 3U03 and 3F03 and online videos.

Learning Goals

You should get a broad overview for a number of geophysical methods imaging the sub-surface. You should understand the underlying physical principles, which will enable you to go deeper into specific methods that you may encounter later on. Most importantly you should learn to think straightforwardly, to ask the right questions, and to apply quantitative mathematical methods in problem solving.

In-class exercises

Exercises are an important part of the Geophysics lecture. They will treat some aspects of the lecture in more detail, but also cover new ground. We expect that you work on the exercises at home and we will discuss questions and solutions interactively together (typically Thursdays). The joint meetings will start with randomly chosen students presenting their approach. It is ok if the full solution is not available at this stage and there will be no interrogation. However, please don't show up unprepared because this will inevitably be awkward.

Field exercises

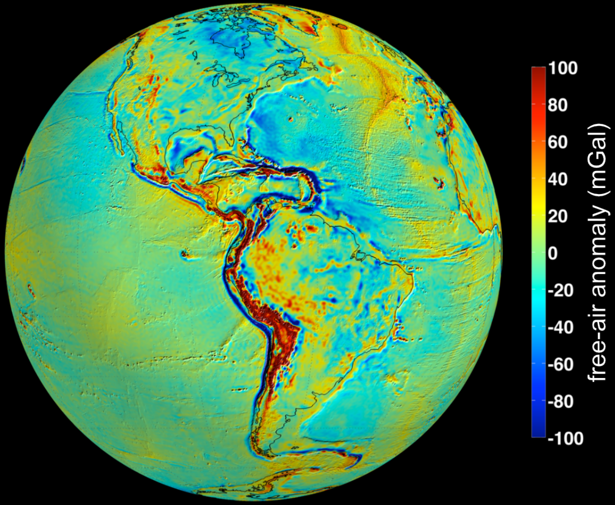
We will conduct field exercises for magnetics, geoelectrics and seismics. This is your maybe once-in-a-lifetime chance to work with professional geophysical equipment. The practical part of the exercises will typically take about six hours. Exercises are mandatory and absence is only permissible with a substantiated excuse approved by the instructor before the exercise takes place. The exercise will then need to be repeated another day. Don't miss the submission deadline of your group reports communicated by the instructor. If you fail, you will have a chance to revise the report.

Learning Goals

Learning goals today:

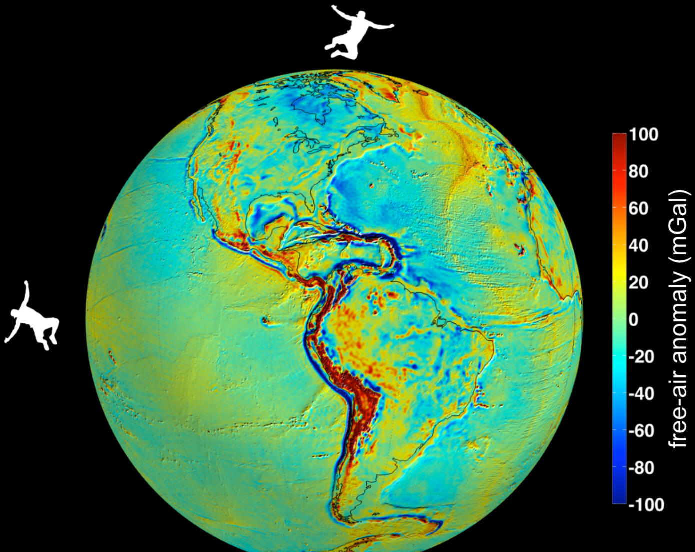
- Understand that gravity methods map sub-surface density variability
- Understand the gravitational force, its potential field, and one underlying measurement principle.
- Understand the Earth's geoid and reference ellipsoid

Example: Global variability



Example: Global variability

Your mass is constant but your weight is not.



What is a force?


[Newton (1642-1726) / G. Johnson.]

$$\vec{F} = m\vec{g}$$

$\vec{F}$: Force (N; $\mathrm{kg\,m\,s^{-2}}$)

$\vec{g}$: Acceleration ($\mathrm{m\,s^{-2}}$)

m : Mass (kg)

The gravitational force

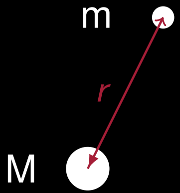
[Newton (1642-1726) / G. Johnson.]

$$\vec{F} = G\frac{mM}{r^2}\hat{r}$$

$G = 6.674 \cdot 10^{-11} \, (m^3 kg^{-1} s^{-2})$

$\hat{r}$: unit vector

r : distance between point masses



Example: The gravitational constant

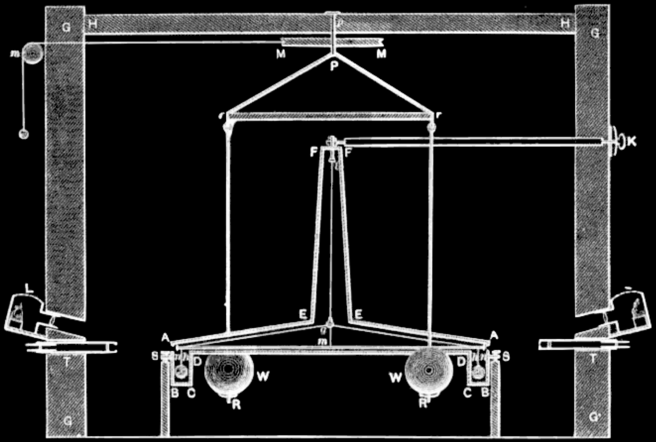
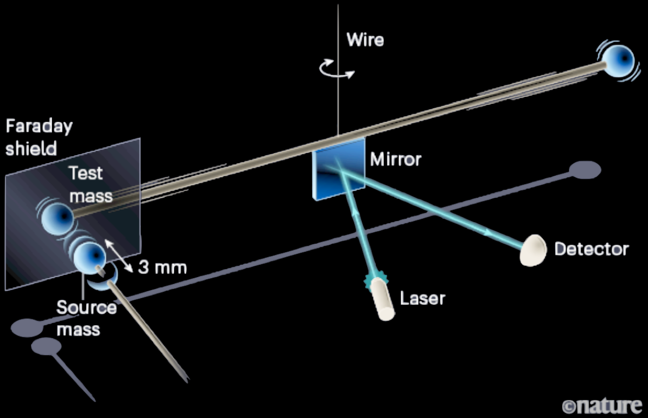


Fig. 1

Cavnedish, PNAS, 1798

Example: The gravitational constant



Westphal et al., Nature, 2021

G is the worst known constant in physics. Why?

Example: Measuring acceleration

$$\vec{F} = m\vec{g}$$

$$\vec{F} = G\frac{mM}{r^2}\hat{r}$$

Example: Measuring acceleration

$$\vec{F} = m\vec{g}$$

$$\vec{F} = G\frac{mM}{r^2}\hat{r}$$

$$\rightarrow \vec{g} = G\frac{M}{r^2}\hat{r}$$

$$\rightarrow \frac{d^2\vec{x}}{dt^2} = G\frac{M}{r^2}\hat{r}$$

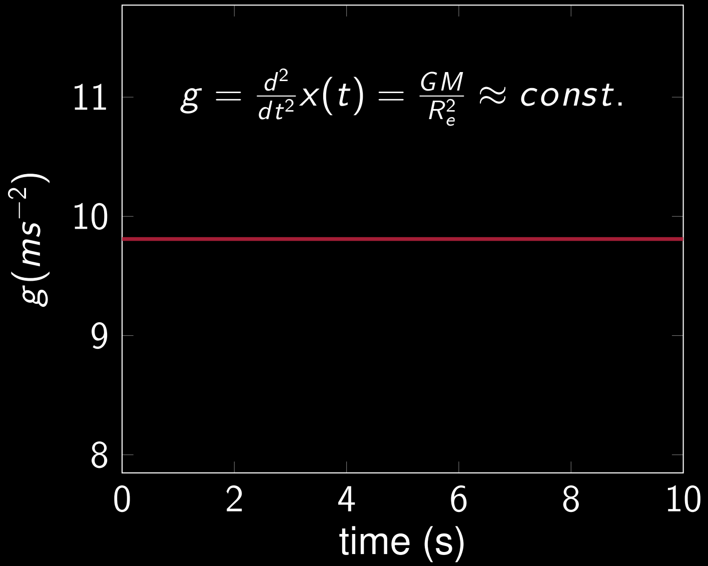
This is a differential equation.

Example: Measuring acceleration

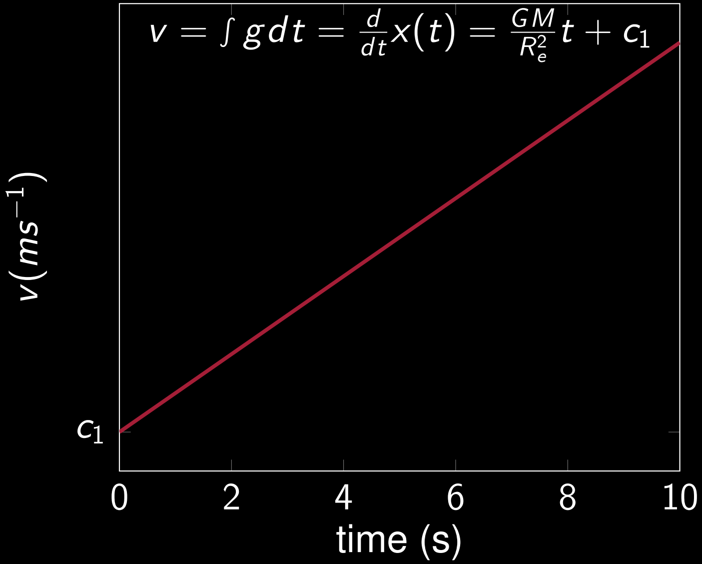
$$\frac{d^2\vec{x}}{dt^2} = G\frac{M}{R_E^2} \approx const.$$

At the Earth's surface (R_E) g is close to constant and only vertical. (Later we will see that none of this is quite true).

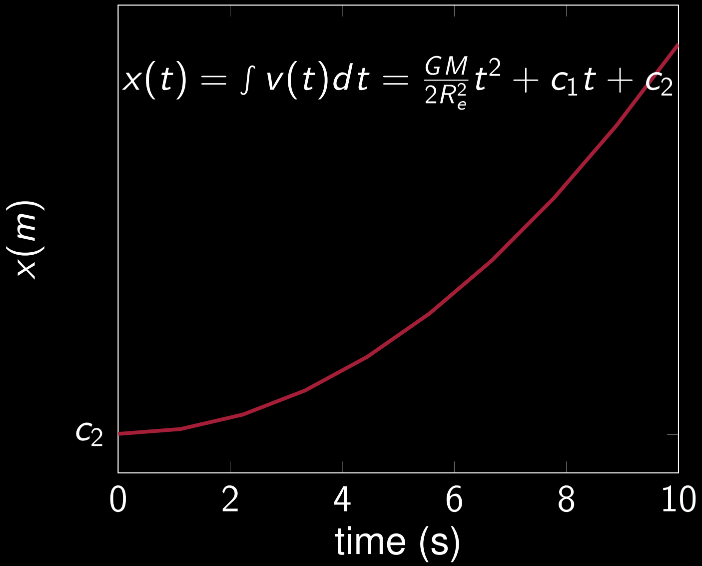
Example: Measuring acceleration



Example: Measuring acceleration



Example: Measuring acceleration



Example: Measuring acceleration

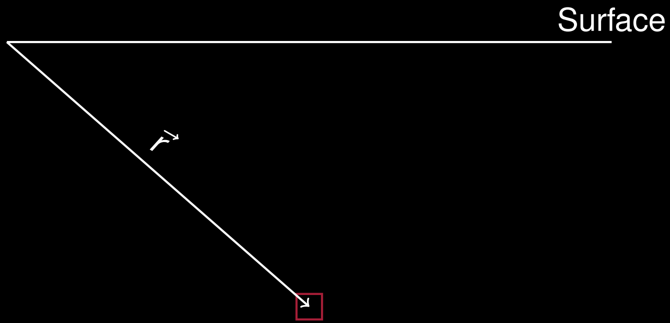
$$x(t) = \frac{GM}{2R_e^2}t^2 + c_1 t + c_2$$

- Setting, e.g., $c1 = 0$ (initial velocity) and $c_2 = 0$ (initial position) is quite convenient.
- This is the principal of a free-fall gravimeter.

Exercises: Group-Work Thursdays

- Thanks to the Greeks we know the radius R_E for the Earth. However, its mass was unknown for a while.
- Go ahead and determine the mass of the Earth M with your Smartphone!
- There is an important first-order finding in Earth Sciences that you can (re-) discover. Which one?

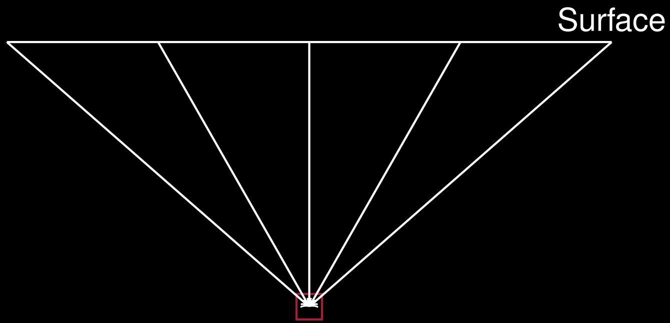
Beyond point masses



$$\vec{F} = G\frac{dM}{r^2}\hat{r}$$

For a small mass dM the point mass approximation holds.

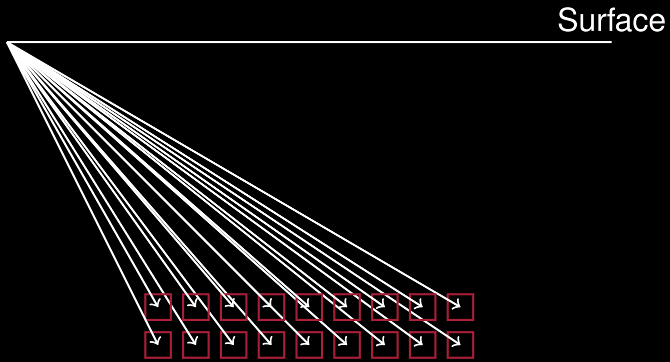
Beyond point masses



$$\vec{F} = G\frac{dM}{r^2}\hat{r}$$

Profiling across a sub-surface target results in a gravity anomaly ($\rightarrow$ Exercises).

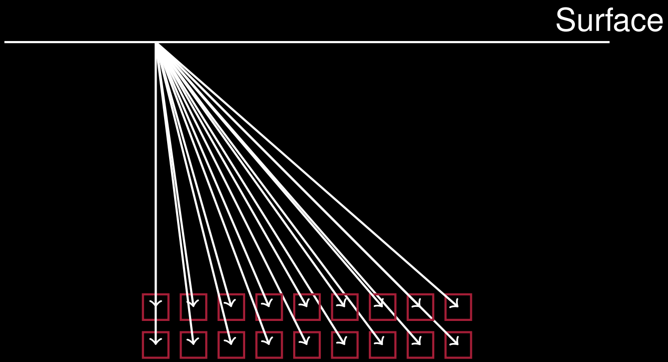
Beyond point masses



$$\vec{F}(\vec{r}) = \sum_i G \frac{dM_i}{r_i^2} \hat{r}_i$$

For *i* point masses the effect adds up.

Beyond point masses



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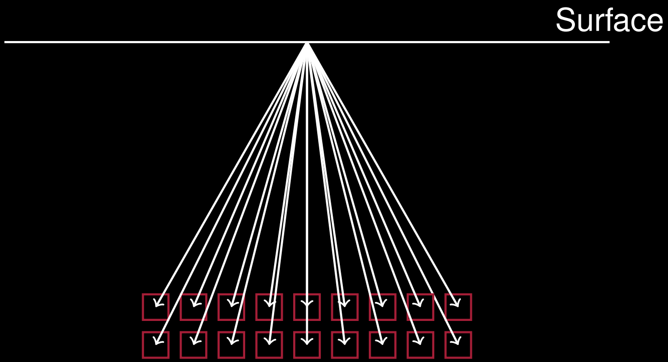
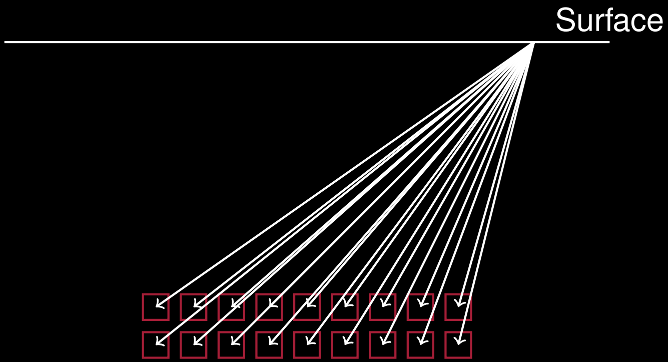
Beyond point masses



$$\vec{F}(\vec{r}) = \sum G \frac{dM_i}{r_i^2} \hat{r}_i$$

Beyond point masses

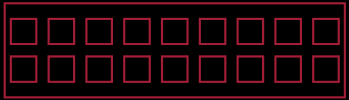


$$\vec{F}(\vec{r}) = \sum G \frac{dM_i}{r_i^2} \hat{r}_i$$

Beyond point masses

Surface

$$\vec{F}(\vec{r}) = G \int \rho \frac{1}{r^2} \hat{r} dV$$

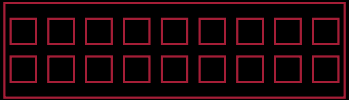


The summation can be replaced by an integration over a volume enclosing a continuous density.

Beyond point masses

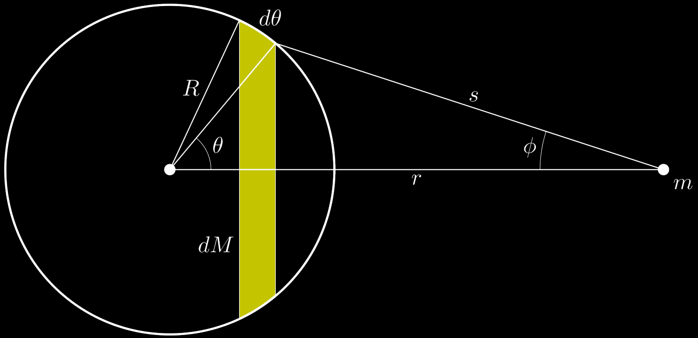
Surface

$$\vec{F}(\vec{r}) = G \int \rho \frac{1}{r^2} \hat{r} dV$$



The integration is a triple integral. Integration limits and coordinates depend on the viewpoint. Example is a Bouger plate, in general not easy to solve ($\rightarrow$ Exercises).

Example: Shell



[Xaononl CC BY-SA 4.0]

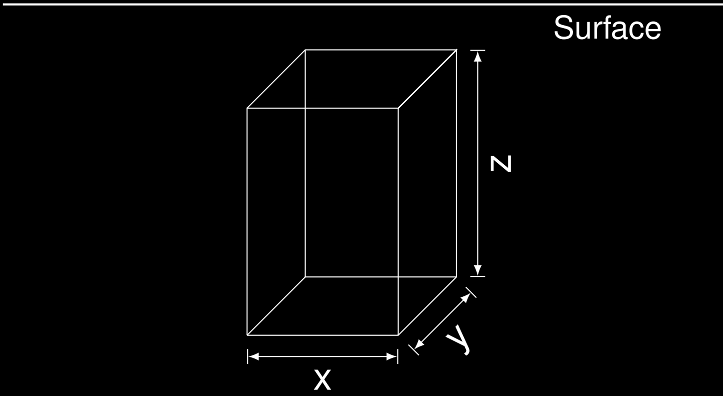
Newton's shell theorem solves the volume integral inside and outside spherical objects ($\rightarrow$ Ex.-Discussion)

Newton’s Shell Theorem

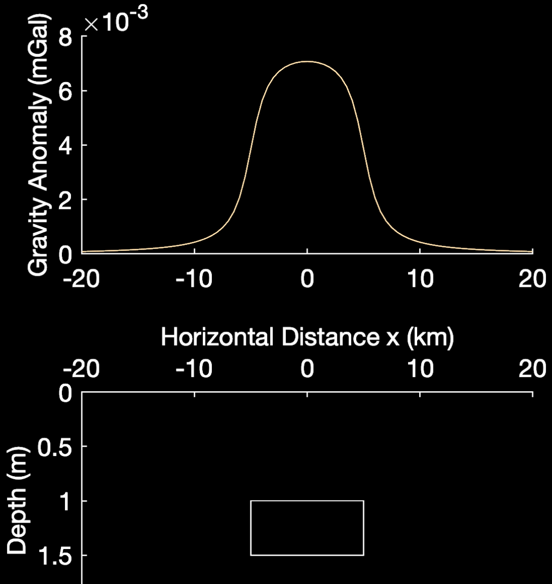
- The field outside a shell is the same as the one from an equivalent point mass
- The field inside a shell is zero. Everywhere.

Other shapes

- There are analytical solutions for other shapes (e.g., Nagy 1966 for Prism).

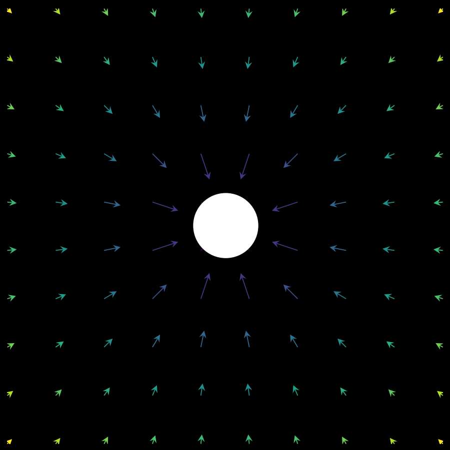


Numerical forward modelling (→ Ex)



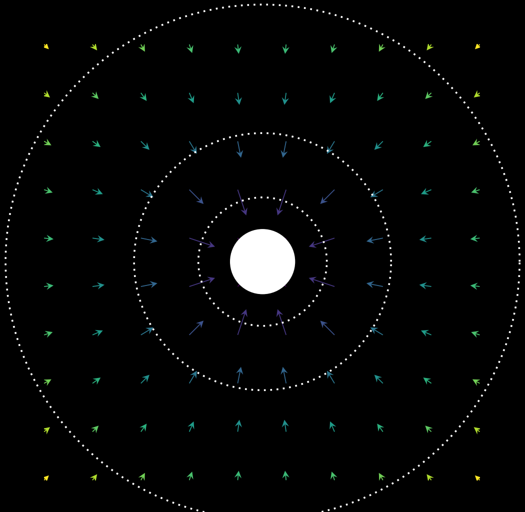
Vector fields

$$\vec{g} = G\frac{M}{r^2}\hat{r}$$



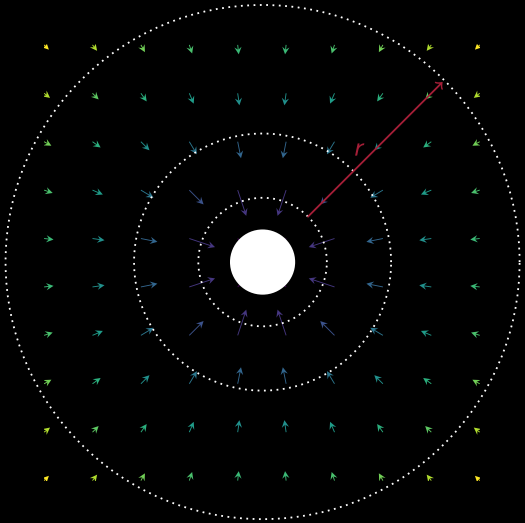
Potential Field

$$\vec{g} = G\frac{M}{r^2}\hat{r}$$



Potential Field

What is the amount of work required?



Potential Fields

$$
\begin{aligned}
U(r) &= -\int_{\infty}^{r} \vec{g}\, d\vec{r} \\
&= -\int_{\infty}^{r} g\, dr \\
&= -GM \int_{\infty}^{r} \frac{1}{r^2} dr \\
&= -GM \left[-\frac{1}{r}\right]_{\infty}^{r} \\
&= GM\frac{1}{r}
\end{aligned}
$$

Potential for a point mass.

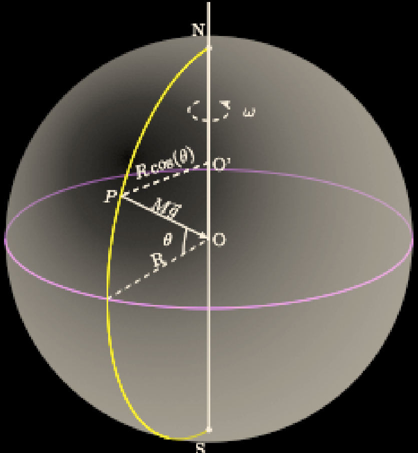
Potential Fields

$$\vec{g}(r) = -\nabla U(r)$$

- It is sometimes easier to calculate the potential of an anomaly and to infer the acceleration via the gradient.
- Equipotential lines are perpendicular to the field direction.
- Equipotential lines are in general NOT lines of equal field strength (cf. with down-hill slope force in landscape)

Gravitational field of a spherical Earth

The Earth's rotation minimizes gravitational acceleration at the equator. At the poles it does nothing.



Gravitational field of a spherical Earth

Centripedal acceleration at P perpendicular to rotation axis parallel to O'-P:

$$g_{r.} = \omega^2 R \cos(\theta)$$

Centripedal acceleration at P perpendicular to rotation axis parallel to O'-P:

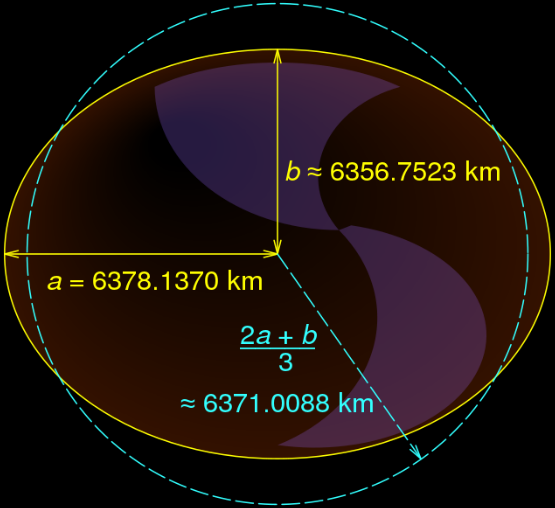
$$g_{r.,proj.} = \omega^2 R \cos^2(\theta)$$

Angular Frequency: ω

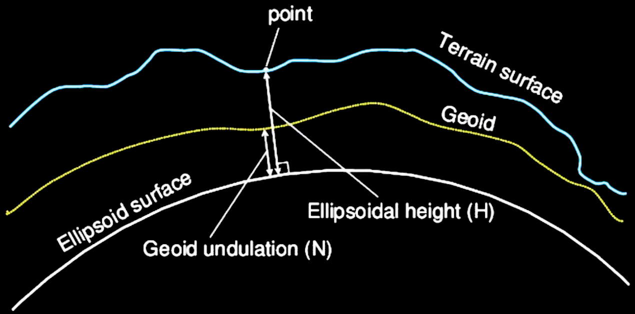
Angular Velocity: $\vec{v}_r = \vec{\omega} \times \vec{R} \cos(\theta)$

Angular Acceleration: $\vec{g}_r = \dot{\vec{v}}_r = \vec{\omega} \times \vec{\omega} \times \vec{R} \cos(\theta)$

An ellipsoidal Earth



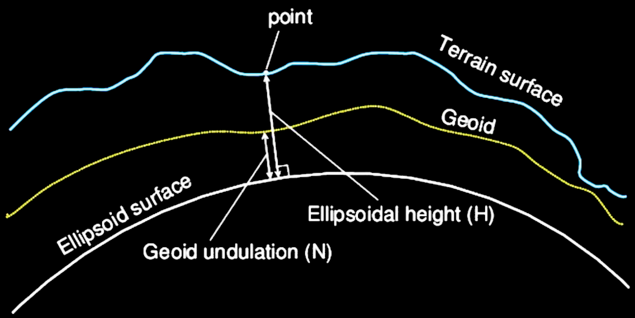
An ellipsoidal Earth



[Ziebart et al., 2004]

- Geoid is a real-world equipotential line approximating sea level.
- It is referenced to the geometric ellipsoid.

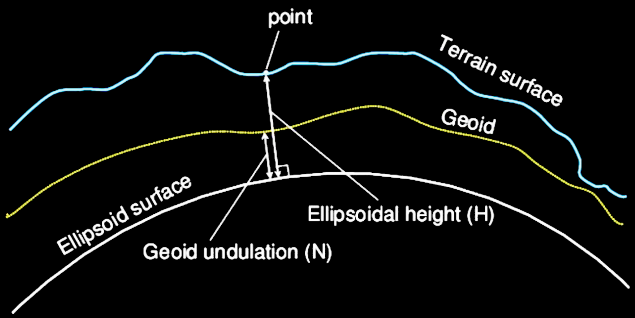
An ellipsoidal Earth



[Ziebart et al., 2004]

- The reference of elevation is a constant source of confusion.
- The geoid defines the local vertical direction.

An ellipsoidal Earth



[Ziebart et al., 2004]

- Upwarping of geoid indicates mass excess.
- Downwarping of geoid indicates mass deficit.

Learning Goals

Learning goals today:

- Understand that gravity methods map sub-surface density variability
- Understand the gravitational force, its potential field, and one underlying measurement principle.
- Understand the Earth's geoid and reference ellipsoid