Brief introduction to gravity methods: Instruments and anomalies

Lecture 2 of 2 for GEOP572

Alex Rinehart
14 October 2015

Summary of theory implications

$$\boldsymbol{g} = \frac{\boldsymbol{F}}{m} = -G\frac{M}{r^2}\hat{\boldsymbol{r}}$$

$$\boldsymbol{g} = -G\int_V \frac{\rho(\boldsymbol{r}')}{r^2}\hat{\boldsymbol{r}}dV'$$

- **Superposition of conservative field**
  - Final field is result of summing of many parts (many masses affect final measurement).
  - If non-desired components can be identified, then they can be subtracted. Then, the anomalous field from the mass of interest can be measured and interpreted.

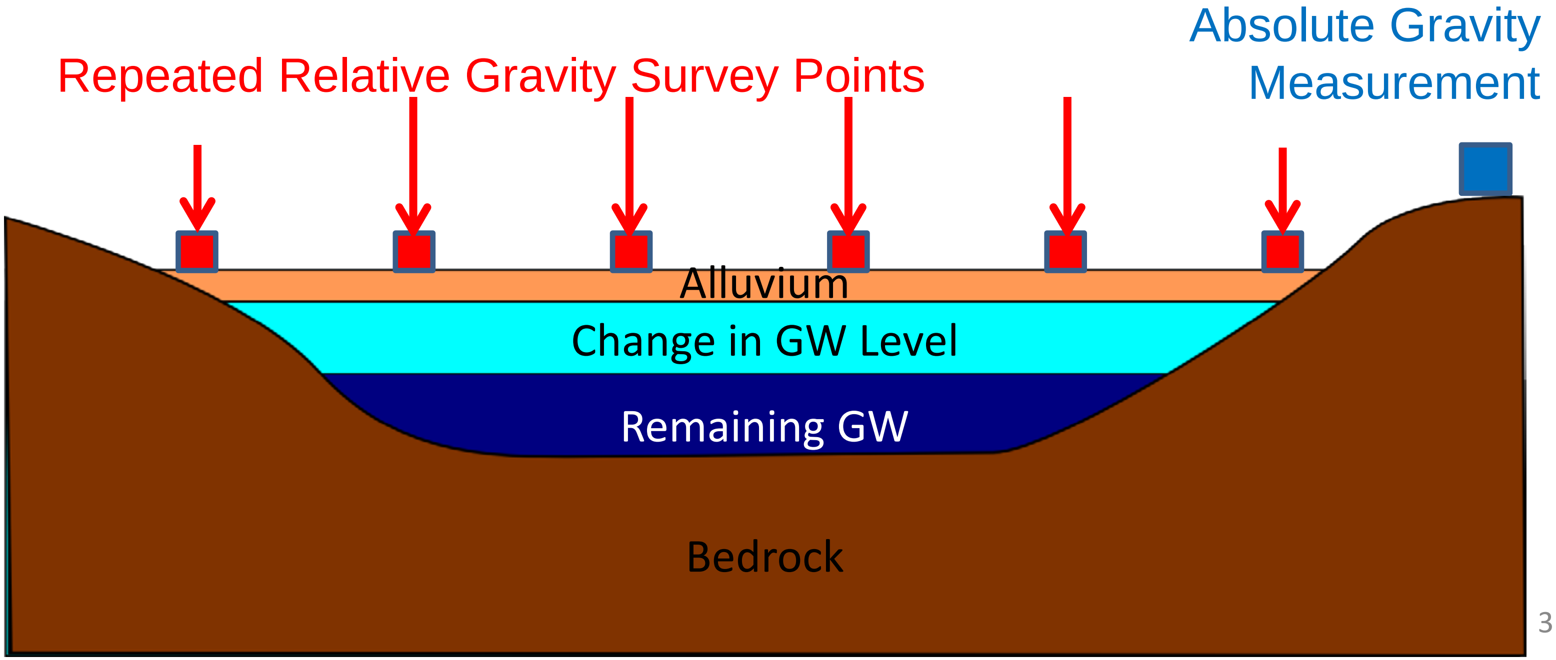
- **Rmk. Deviations in circumferential directions small compared to changes in radial (z) direction.**

What is a ‘Gravity Measurement’?

- **A measurement of the change of the acceleration of gravity (relative), or**
- **A measurement of the acceleration of gravity (absolute).**

As water is removed, the acceleration of gravity underneath the relative gravimeter goes down with repeated measurements.

Needs to be tied to an absolute gravity reference station.



What is a 'Gravity Measurement'?

- A measurement of the change of the acceleration of gravity (relative) in space and/or time, or
- A measurement of the acceleration of gravity (absolute).

Terrestrial relative gravimeters for field surveys

Requirements:

- With corrections, measure the changes in g_z to the 5-10 µGal precision.
- Measure g_z over global range (~7 Gal).
  - Caused by changes in centripetal force with latitude and elevation.
- Limited response to high frequency physical noise.
- Physically robust to field conditions.

Solution: Very precise displacement and/or force measurements based on carefully constructed spring.

Terrestrial relative gravimeters for field surveys

Hinze, Von Frese and Saad (2013) **Gravity and Magnetic Exploration**

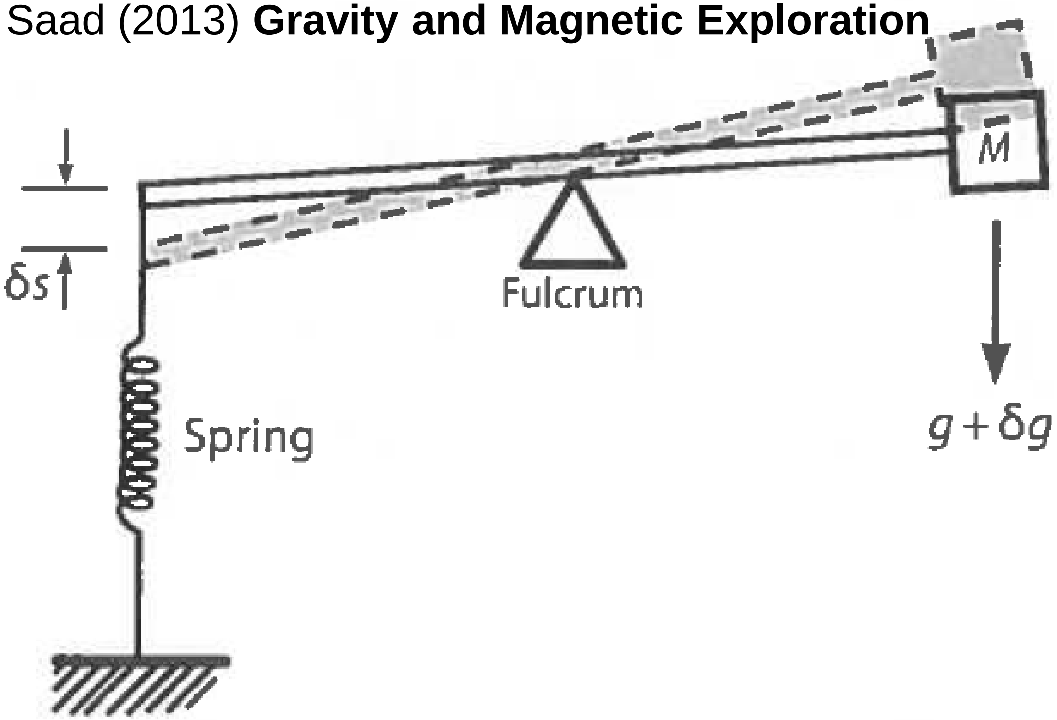


FIGURE 5.2 Principle of the gravimeter showing how a change in gravity, δg, causes a displacement of the lever arm, δs, which can be used to measure the change in gravity.

Use Hooke’s law on a zero-length spring to provide resisting force to the gravitational force on M. Then, measure δs (or a restoring force) to get δg. Spring has low k-constant and instrument has damping mass to drop frequency of response. Relative gravimeters can be used as low frequency seismometers.

Terrestrial relative gravimeters for field surveys

Hinze, Von Frese and Saad (2013) **Gravity and Magnetic Exploration**

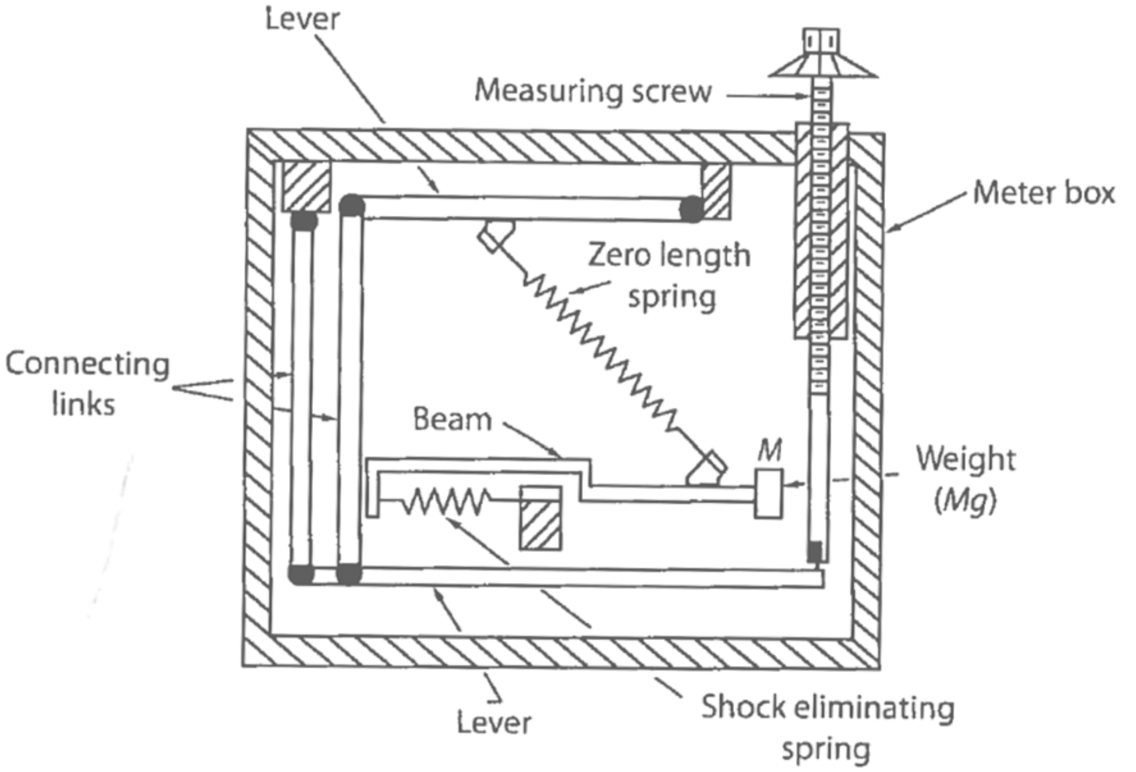
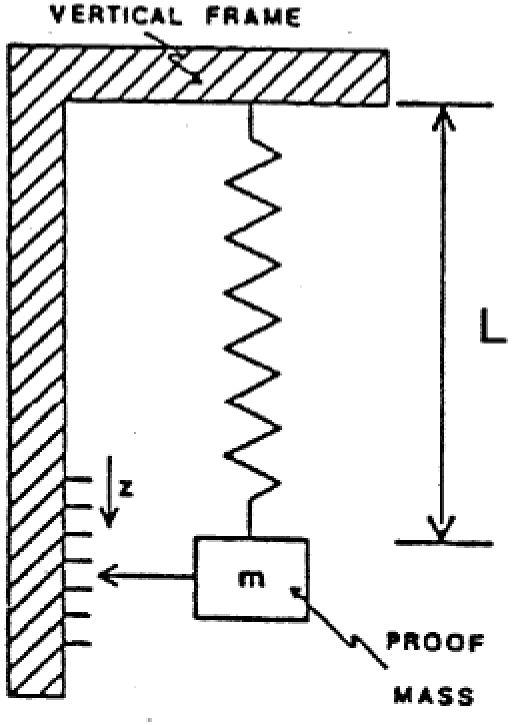


FIGURE 5.4 Simplified diagram of the LaCoste & Romberg gravimeter using the inclined zero-length spring. Courtesy of LaCoste & Romberg-Scintrex (LRS), Inc.

Adjust screw to change location of top of spring, so displacement of mass is in range of acceleration. In current models, M is adjusted to 0 position capacitavely, so the screw also serves to give a known g_z.

Terrestrial relative gravimeters for field surveys

From Seigel (1995) **Guide to High Precision Land Gravimeter Surveys**



Detection:

$$\frac{\Delta z}{L} = \frac{\Delta g}{g_o} \qquad \frac{\Delta g}{g_o} = 10^{-8}$$

$$L = 2\text{cm}; \quad \Delta z = 2\text{x}10^{-10}\text{m}$$

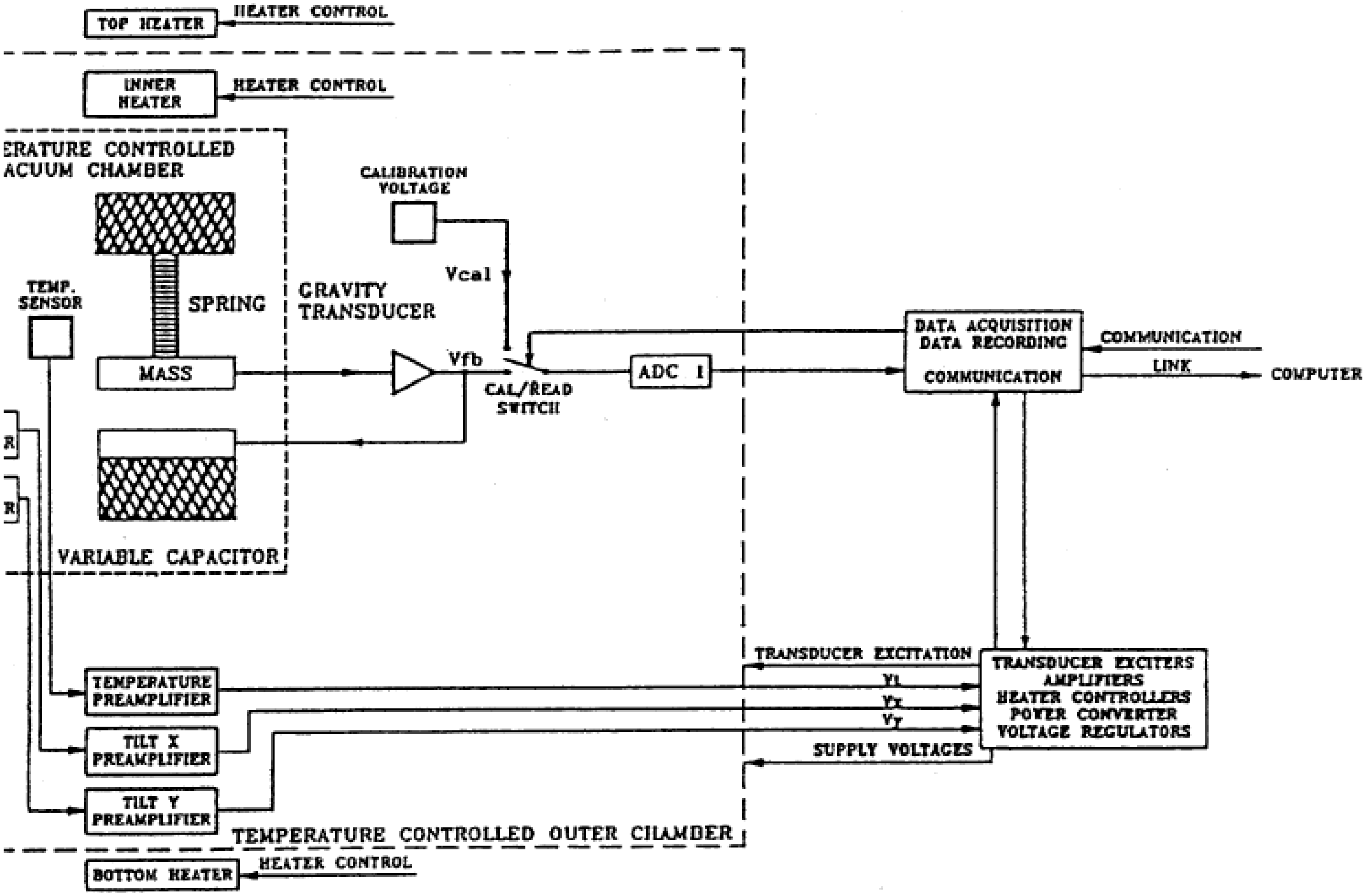
Feedback: Dynamic range ≈1ppm (20 bits)
(0.01mGal / 10^4mGal)

Figure 1 Principle of Operation of a Stable Gravimeter

Quartz-spring type relative meter. Worden (older) or modern Scintrex CG-5.

Terrestrial relative gravimeters for field surveys

From Seigel (1995) **Guide to High Precision Land Gravimeter Surveys**



Capacitor provides reaction force to maintain constant displacement.
Double chamber heater.
Precise leveling required and monitored.

Terrestrial relative gravimeters for field surveys

- A primary correction that must be made is for instrument drift.
- Caused primarily by gradual fatigue of zero-length spring.
- Instruments sensitive to rough handling. Or to, really, moderately not-gentle handling. These cause nonlinear and unpredictable drift.
- Additional second- or third-order effects are abrupt pressure and temperature changes.

- Drift correction made by re-occupying some stations plus a reference station throughout the survey, then linearly interpolating between measurements to get a drift rate.

Absolute gravimeters for field surveys and the laboratory

Requirements:

- With corrections, measure the absolute value of g_z to the 5-10 µGal precision.
- Measure g_z over global range (~7 Gal).
  - Caused by changes in centripetal force with latitude and elevation.
- Limited response to high frequency physical noise.
- Physically robust to field conditions.

Solution: Pendulums swinging in vacuum (not used any more), and precisely aligned and timed weight drops.

Absolute gravimeters for the field and lab

- Corner-weight drop in vacuum. Additional molecules deflected by cart in front of weight.
- Travel time trajectory measured with laser interferometry. Precise alignment achieved by dynamic leveling based on low frequency seismometer in lower half.
- Field version (A-10) has heated chambers and additional housing.
- A-10 used in conditions from Mojave desert to Barrow, Alaska.

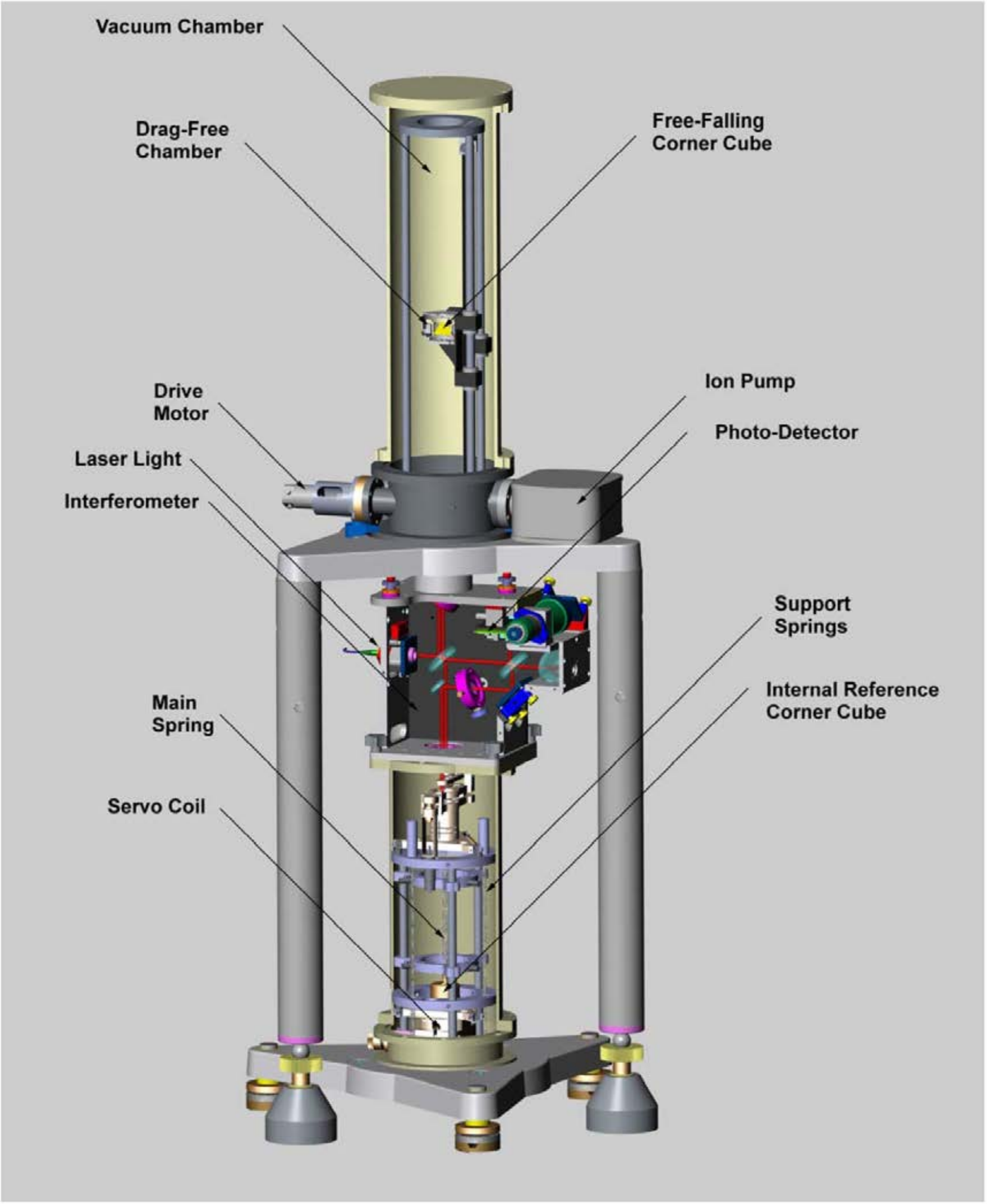


Figure 2. The FG5 System. The laser, system controller, and electronics rack are not shown.

Summary of theory implications

- **Superposition of conservative field**

$$\boldsymbol{g} = -G\int_V \frac{\rho(\boldsymbol{r}')}{r^2}\hat{\boldsymbol{r}}\,dV'$$

observed gravity = attraction of reference ellipsoid
+ effect of elevation above ellipsoid (“free-air”)
+ effect of “normal” mass above ellipsoid (Bougeur and terrain)
+ time dependent variations (tides)
+ effect of moving platform (Eotvos)
+ effect of masses that support topographic loads (isostatic)
+ **effect of shallow to upper mantle density variations (geology)**
+ effect of atmospheric density
+ ….

Adapted from Blakely (1995) **Potential Theory in Gravity and Magnetic Applications**

We can measure g. We want to understand the geology (hydrology). Now, let’s discuss the steps to get rid of the unwanted noise and signals.

Temporal ‘noise’

Spatial ‘noise’

Time varying noise

- Instrument drift (hours)
- Earth tides (hours to months) – the pull of the Moon and Sun.
- Ocean tides near coast (hours to months)
- Major fronts (hours to days)
- Rainfall and soil moisture (10 cm of water infiltrated = 4 µGal signal) (hours to months)
- Groundwater pumping (hours to years)
- Subsidence (years)
- Earthquakes (seconds to days)
- New or changed construction (months to years, mostly affects base stations)
- Measurer location and movement (minutes to hours)
- Mechanical (people walking, trucks, airplanes, motors) (minutes)
- Transportation drift (minutes)
- Buildings and tress (minutes to hours)
- Wind (seconds to days)

Time varying noise – The easily correctable ones

- **Instrument drift (hours)**
- **Earth tides (hours to months) – the pull of the Moon and Sun.**
- Ocean tides near coast (hours to months)
- Major fronts (hours to days)
- Rainfall and soil moisture (10 cm of water infiltrated = 4 µGal signal) (hours to months)
- Groundwater pumping (hours to years)
- Subsidence (years)
- Earthquakes (seconds to days)
- New or changed construction (months to years, mostly affects base stations)
- Measurer location and movement (minutes to hours)
- Mechanical (people walking, trucks, airplanes, motors) (minutes)
- Transportation drift (minutes)
- Buildings and tress (minutes to hours)
- Wind (seconds to days)

Time varying noise – The possible signals

- Instrument drift (hours)
- **Earth tides (hours to months) – the pull of the Moon and Sun.**
- Ocean tides near coast (hours to months)
- Major fronts (hours to days)
- **Rainfall and soil moisture (10 cm of water infiltrated = 4 µGal signal) (hours to months)**
- **Groundwater pumping (hours to years)**
- Subsidence (years)
- **Earthquakes (seconds to days)**
- New or changed construction (months to years, mostly affects base stations)
- Measurer location and movement (minutes to hours)
- Mechanical (people walking, trucks, airplanes, motors) (minutes)
- Transportation drift (minutes)
- Buildings and tress (minutes to hours)
- Wind (seconds to days)

Time varying noise – Work arounds

- Instrument drift (hours) – measure and model.
- Earth tides (hours to months) – the pull of the Moon and Sun. – measure or model.
- Ocean tides near coast (hours to months) – measure or model.
- Major fronts (hours to days) – **wait it out**, re-establish base when calm.
- Rainfall and soil moisture (10 cm of water infiltrated = 4 µGal signal) (hours to months) – measure same time of year for time-lapse.
- Groundwater pumping (hours to years) – **wait** or hosed.
- Subsidence (years) – measure location geodetically every time
- Earthquakes (seconds to days) – **wait**
- New or changed construction (months to years, mostly affects base stations) – re-establish base station.
- Measurer location and movement (minutes to hours) – **hold still in the same relative position every time and wait**.
- Mechanical (people walking, trucks, airplanes, motors) (minutes) – **wait for noise to pass**.
- Transportation drift (minutes) – **wait for instrument to settle**.
- Swaying of buildings and tress (minutes to hours) – **wait it out**.
- Wind (seconds to days) – **sheltering or waiting for steady wind**.

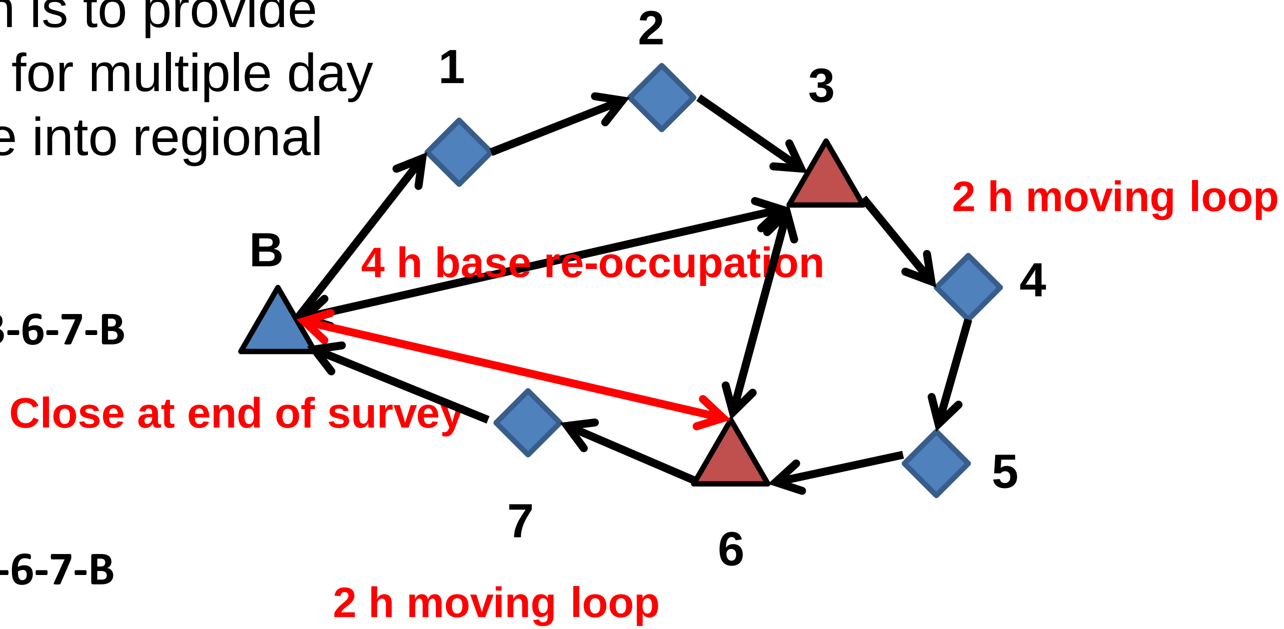
Drift corrections – Measurement loops

- Periodically (1-2 hours) re-occupy last site.
- Every 4 hours, re-occupy local base station.
- End of every day, re-occupy local base station.
- Difference measurements and divide by time between measurements to find drift rate. Rmk. Differencing increases effect of ‘random’ noise.

- Local base station is to provide consistent gravity for multiple day surveys, and to tie into regional absolute stations.

B-1-2-3-B-3-4-5-6-3-6-7-B

B-1-2-3-B-3-4-5-6-B-6-7-B



Earth Tides – Loops, direct measure or model

- Position of Moon (~60% of signal) and Sun (~40% of signal) affects measurements to up to 0.33 mGal. Maximum rate of change is 0.5 mGal/hour.

- Affected by time (models use GMT/UTC) and latitude. Secondary affects include bodies of water, topography and elasticity of the earth.

- With frequent re-occupation of base station (up to 1 hour), Earth tides can be accounted for by linear interpolation between multiple measurements.

- Tidal effects can be modeled. Range of models exist; most commonly used is Longman (1959).

- High precision surveys may have a dedicated earth-tide meter (relative meter that is continuously reading) at the base station, or have a continuously reading absolute meter at the base station.

Summary of theory implications

- **Superposition of conservative field**

$$\boldsymbol{g} = -G\int_V \frac{\rho(\boldsymbol{r}')}{r^2}\hat{\boldsymbol{r}}\,dV'$$

observed gravity = attraction of reference ellipsoid
+ effect of elevation above ellipsoid (“free-air”)
+ effect of “normal” mass above ellipsoid (Bougeur and terrain)
+ time dependent variations (tides)
+ effect of moving platform (Eotvos)
+ effect of masses that support topographic loads (isostatic)
+ **effect of shallow to upper mantle density variations (geology)**
+ effect of atmospheric density
+ ….

Adapted from Blakely (1995) **Potential Theory in Gravity and Magnetic Applications**

We can measure g. We want to understand the geology (hydrology). Now, let’s discuss the steps to get rid of the unwanted noise and signals.

Temporal ‘noise’

Spatial ‘noise’

Get in the right reference frame

- Geographic and vertical datums
  - Use International Terrestrial Reference Frame (ITRF) with the 1980 Geodetic Reference System (GRS80)ellipsoid.
  - WGS84 corresponds to GRS80 to within 10 cm.
  - Lat/long reported to 7 decimal places for all gravity measurement locations.
- Gravity datum
  - Absolute gravity networks have changed in precision and **accuracy** through time.
  - Use International Gravity Standardization Network 1971 (IGSN71), or later measurements. Earlier measurements have inconsistent errors.

Correct for everything else

- Correct for centripetal acceleration on ellipsoid
  - a_{rad}=2πωr, with ω being the angular frequency and r being the distance to center of rotation. ω is pretty constant on human time scales. r varies a bunch.
- Correct for distance from ellipsoid
  - “Free-air” correction. Because of the $1/r^2$ term in gravity.
- Correct for density of atmosphere
  - Range of options, but the atmosphere pulls up (lowers g, positive adjustment, commonly small).
- Correct for ‘normal’ thickness of crust (Bougeur correction).
  - Assumes slab of constant density rock under the measurement point.
  - Secondary correction for curvature of slab for large surveys.
- Correct for terrain
  - Mountains pull gravimeter mass up, valleys don’t.