PBO Strainmeters and Tiltmeters

Duncan Carr Agnew

IGPP/Scripps Institution

UC San Diego

Basic Principles

We want to to measure how the Earth moves or deforms.

To do this, our measuring systems (instruments) must include:

- Some kind of **fixed reference**.
- An **instrument frame**.
- A way to measure the **displacement** of the frame relative to the reference.
- Some **attachment** of the frame to the ground.

Examples of Components

	GPS	Tiltmeter	Strainmeter
Reference	Whole Earth	Vertical	Length/Volume
Frame	Antenna	—Body or End points—	
Displacement	Radio/Software	—Displacement Transducer—	
Attach	Monument	—Borehole/Anchor—	

Changes in Strainmeter/Tiltmeter Technology

Main advance is

- It keeps getting easier to measure small displacements.

However, other things haven't changed:

- The reference used.
- How to attachment to the ground; difficult because:
  - It cannot be engineered completely: we have to attach to the (messy) Earth.
  - And so every site is different.
- No market for these instruments, so much less engineered than GPS.

Sensing Small Displacements

To measure displacements < 1 mm, the options are:

- **Capacitive:** 10^{-14} to 10^{-10} m resolution (nuclear dimensions).
- **Inductive (LVDT):** 10^{-10} m, commercially available.
- **Moving-coil velocity:** useful for higher frequencies.
- **Optical interferometry;** calibration reproducible. The wavelength of light ($\lambda \approx 10^{-7}$m) is large, though resolution can be 10^{-11} m.

Deformation Measurements

GPS measures ground displacement.

Seismometers measure ground acceleration (basically the same thing).

But other instruments measure the **spatial gradients** of displacement.

These gradients are dimensionless.

Gradient sensors are

- **Tiltmeters**: horizontal spatial gradient of vertical displacement (or the other way around).
- **Strainmeters**: the symmetric part of the gradient tensor of (mostly horizontal) displacements.
- **Rotation meters**: the antisymmetric part of the gradient tensor of (mostly horizontal) displacements.

We mostly discuss strainmeters, but the next few slides (on instrument length) apply to all.

Instrument Length: The Most Important Parameter

The most important characteristic of an instrument that senses **differential displacement**, is the **baseline length** L: how big the instrument frame is.

- What is measured, the differential displacement, is L times the (dimensionless) gradient; e.g., for extensional strain, $\varepsilon = \frac{\Delta L}{L}$.
- There are two length classes:
  - **Short-base** (0.1 to 1 m): strain (tilt) of 10^{-9} is 1-10 atomic diameters: so seismic strains are ~size of atomic nucleus. Annual tectonic (10^{-7}) is 0.00001 mm.
  - **Long-base** (10 to 1000 m): strain (tilt) of 10^{-9} is 0.01 to 1 wavelengths of light (largest would be 0.001 mm). Annual tectonic is 0.1 mm.

Length and Ground Attachment

The bigger L is, the more stably the instrument frame can be attached to the ground.

How instruments can be sited depends on L:

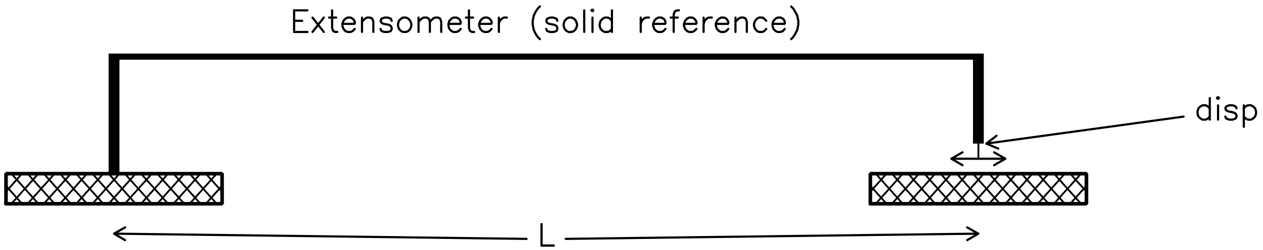
- Short-base: must be in a borehole or tunnel (usually).
- Long-base: in tunnel (for L 10-100 m), or on the surface.

Best results from **short-base in a deep borehole**, and **long-base on the surface**

Strainmeters I: Bar Extensometers

These measure linear strain ε.

- **Instrument frame** is two endpoints a distance L apart.
- **Reference length** is L: some (we assume) stable piece of material.
- System measures the **relative displacement** ΔL between the two ends; then $\varepsilon = \frac{\Delta L}{L}$



The reference can be a bar, or a hanging wire, of anything "stable", in terms of temperature changes and/or time.

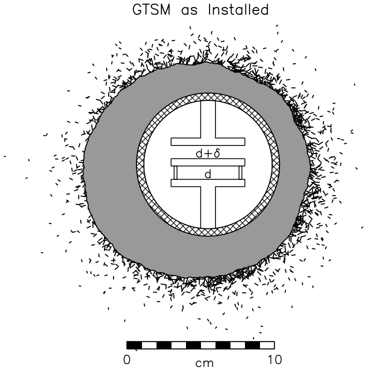
Gladwin Tensor Strainmeter (GTSM)

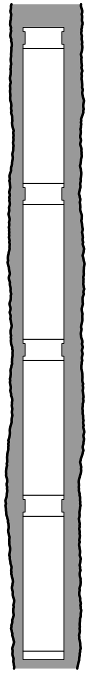
The basic module is a very short bar extensometer: $L = 0.087$m. Displacements are measured with a capacitive sensor.

Whole module is stainless steel.

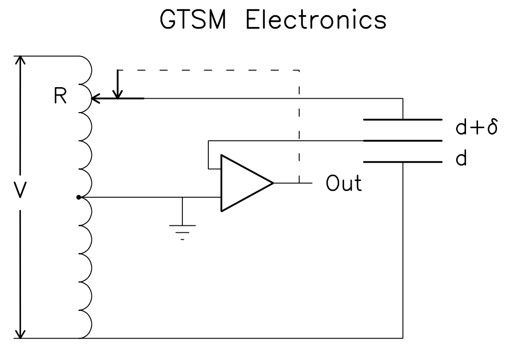
PBO GTSM has four modules, differently oriented: the first three are at 120° to each other, and the fourth at 90° to the first.

This provides redundancy, and (in principle) a calibration check.





Gladwin Tensor Strainmeter: Electronics



An input voltage is divided in a ratio transformer, with the output (ratio to input good to 7 figures) applied to the capacitor plates. The ratio R is varied both to minimize the output from the center plate, and also to calibrate the system.

The two capacitances C_1 and C_2 are proportional to d^{-1} and $(d+\delta)^{-1}$; the output voltage is zero if $\frac{1-R}{R} = \frac{C_2}{C_1} = \frac{d+\delta}{d}$ so that $d+\delta = d\,\frac{R}{1-R}$; the "linearized strain" is found from R and the output voltage using this equation.

R and the center-plate output are sampled at high speed, then filtered to produce 20 Hz data (and 1 Hz -- but use 20 Hz for seismic).

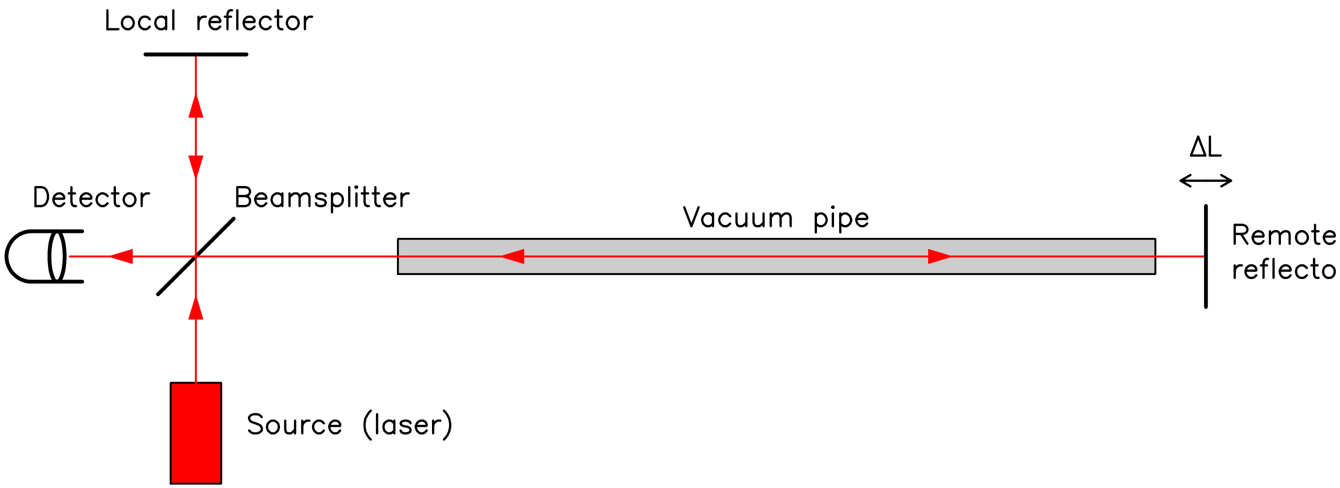
Strainmeters II: Laser Extensometer

Measures changes in distance optically, using an interferometer, which can be (using laser light) very long.

Three features needed:

- A narrowband light source that has a very stable frequency.
- An unchanging propagation delay.
- A stable attachment to the ground.

Basic Design Overview: Main Interferometer



A **Michelson interferometer** has two arms, one fixed (to the local reflector) and one variable (to the remote reflector).

Light from the source is split at the beamsplitter; after making the round trip, the beams recombine, and a detector D measures the changes in intensity.

Optical Paths

Measure the change in **optical path length**: the actual path length times n, the index of refraction: again, just like GPS.

Air and Vacuum

Through air, the effect of pressure and temperature changes is about 10^{-6} K^{-1} and 3×10^{-4} Pa^{-1}: much too large. For a "good" vacuum (1 Pa pressure) these numbers are are multiplied by 10^{-5}: this creates a stable path, but at a cost:

- The path must be straight, which makes for a high first cost.
- There is the ongoing cost of maintaining the vacuum.

Optical Fiber

Basically, this is *really* transparent glass.

Temperature coefficient of n is about 10^{-5} K^{-1}: very high.

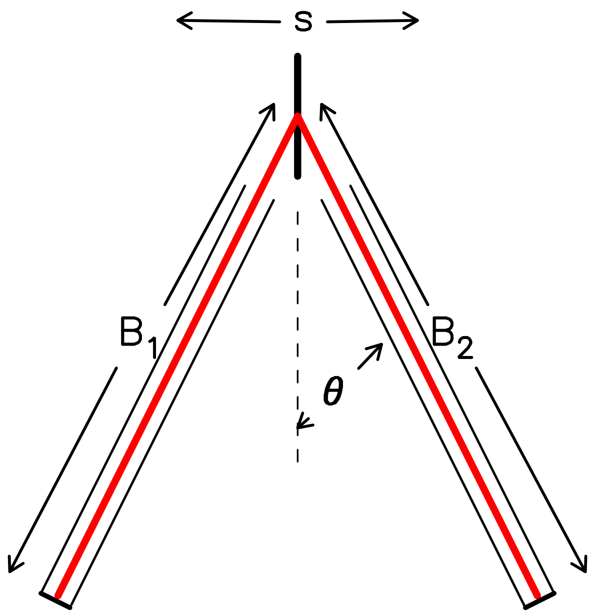
Index n drifts with time, as the fiber "ages": about 10^{-6} yr^{-1}.

Does not need to be exactly straight, and requires no maintenance.

Anchoring

Longbase laser strainmeters use “optical anchors” to minimize noise from the near surface.

- Equal-arm interferometer at each end of the “main” system, going to 10-30 m depth.
- Best results come from a pair of vacuum pipes, but fibers are adequate and much cheaper.



Cholame: Looking North

438 m long.

Strainmeters III: Dilatometers

These measure the **dilatation**, which is $\varepsilon_V = \dfrac{\Delta V}{V}$ where V is the volume and ΔV is the change in volume.

In tensor strain, this is $\varepsilon_V = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}$, independent of the coordinate system used.

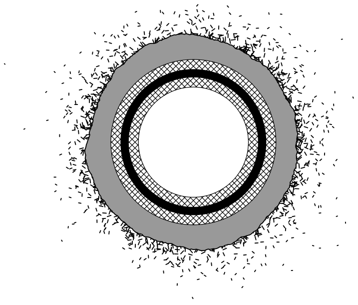
- **Instrument frame** is a volume containing a liquid.
- **Reference volume** is the volume of liquid.
- Measure the **fluid volume** that moves in and out of the reference volume to get ΔV.

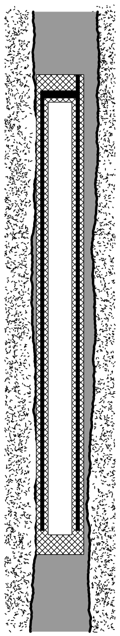
Sacks-Evertson Dilatometer

Fluid volume is a cylindrical annulus, with the change in volume being measured through the displacement of an attached bellows. Instrument senses areal and vertical strain.

The baselength *L* is about 2 m

Hydraulic amplification (volume/tube area) can makes *L* for the sensor over 100 m, so the displacement transducer can be less sensitive.



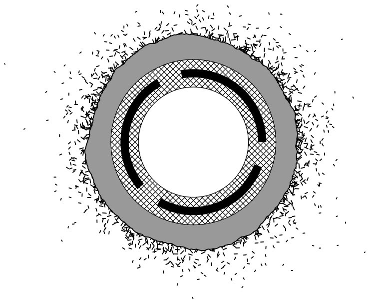


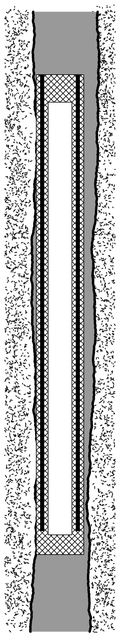
Sakata Directional Volume Strainmeter

This instrument has three fluid volumes, each sensed separately, with the relative changes in different volumes allowing the measurement of the full strain tensor.

Works because a non-cylindrical space with fluid responds to different horizontal strains with different volume changes.

A version of this was used in the "Mini-PBO".





Tiltmeters

Have a **vertical reference**, which points along **g**, the *apparent* direction of gravity.

So tiltmeters *also* measure horizontal acceleration,

> A tiltmeter, a horizontal seismometer, and a horizontal accelerometer all measure the same quantities.

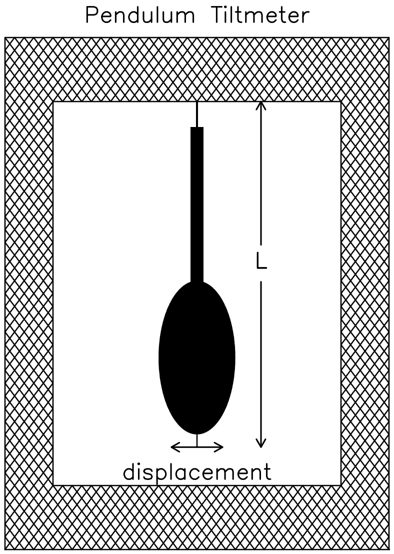
Rule of thumb for many Earth motions: periods longer than 1 hr, tilt dominates; shorter periods, acceleration dominates.

Pendulum Tiltmeter

Mass on a pivot (think of this as a “movable density interface”).

Measure displacement relative to frame.

Length of pendulum L is 0.05 to 1 m.

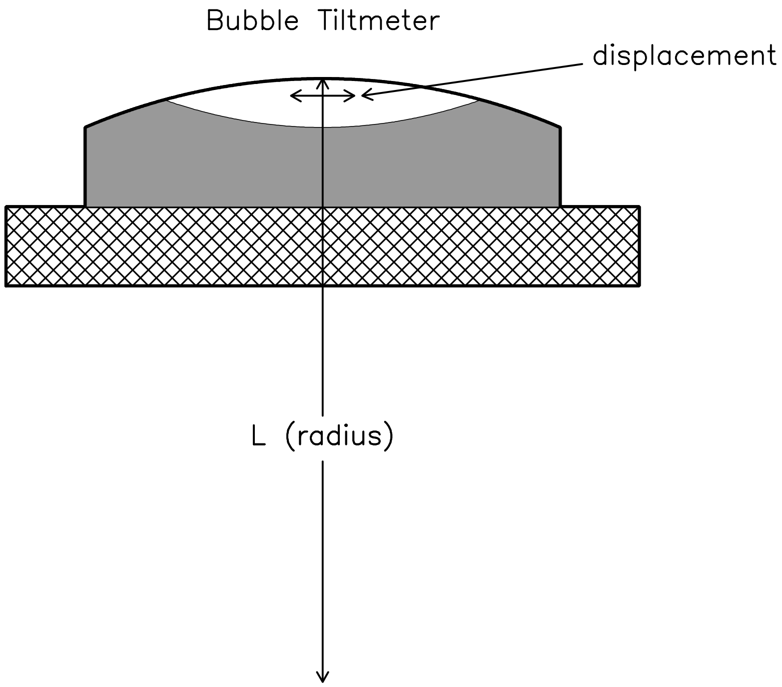


Current example: tiltmeters in Japan’s borehole seismic network.

Liquid Tiltmeters I: Bubble

Here, the "movable density interface" is a liquid surface.

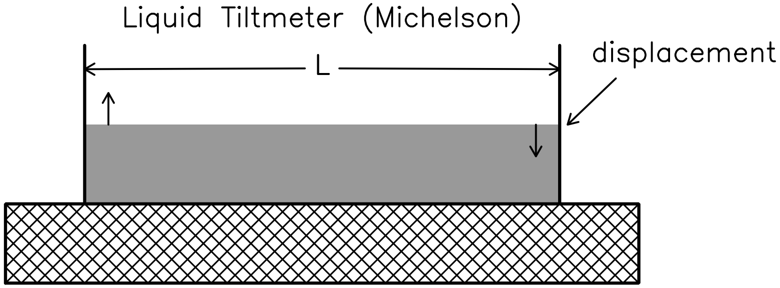
For sensing purposes, L is the radius of the surface the bubble is under; the baselength may be much shorter.

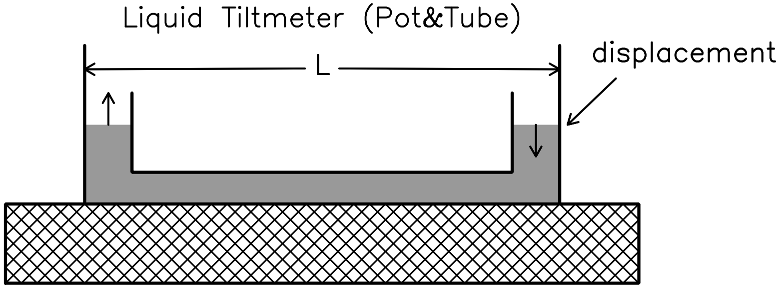


Current example: PBO borehole tiltmeters (from Applied Geomechanics).

Liquid Tiltmeters II: Long-base

The “Michelson” design (from 1916!), has an unbroken free surface; can be hundreds of meters long. The pot/tube design is sensitive to temperature, so must be in a tunnel.





Current examples: Michelson in Pacific NW, Pinon Flat; pot-and-tube in Japan and Europe – and neither is in PBO.