Strainmeters

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Basic Principles

We want to to measure how the Earth deforms.

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

- Some kind of **reference**; we assume this is fixed.
- An **instrument frame**.
- Some way of measuring the **displacement** of the frame relative to the reference.
- Some way of **attaching** the frame to the ground.

Changes in Technology

- It keeps getting easier to measure small displacements.
- Space geodesy has created a whole new class of references.
- The reference for most ground-based systems hasn't changed in decades.
- Attachment to the ground remains the biggest challenge:
    - It cannot be engineered completely.
    - Every site is different.

Sensing Small Displacements

To measure diaplacements < 1 mm.

- Capacitor: 10^{-10} to 10^{-14} m resolution (nuclear dimensions).
- Inductor (LVDT): 10^{-10} m and readily available commercially.
- Moving-coil velocity (only useful for higher frequencies).
- Optical interferometry; calibration reproducible, but the wavelength of light ($\lambda \approx 10^{-7}$m) is large.

Deformation Measurements

Consider instruments that sense the **spatial gradients** of displacement.

These gradients are dimensionless.

Sensors are

- **Tiltmeters**: spatial gradient of vertical displacement (and more).
- **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 discuss only the middle category.

Length: The Most Important Parameter

The **baseline length** L of an instrument that senses differential displacement is its most important characteristic:

- The displacement is L times the (dimensionless) gradien; for extension, strain is $\varepsilon = \frac{\Delta L}{L}$.
- 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

How stabily the frame has to be attached to the ground equals the strain (or tilt) times L.

How instruments can be sited depends on L:

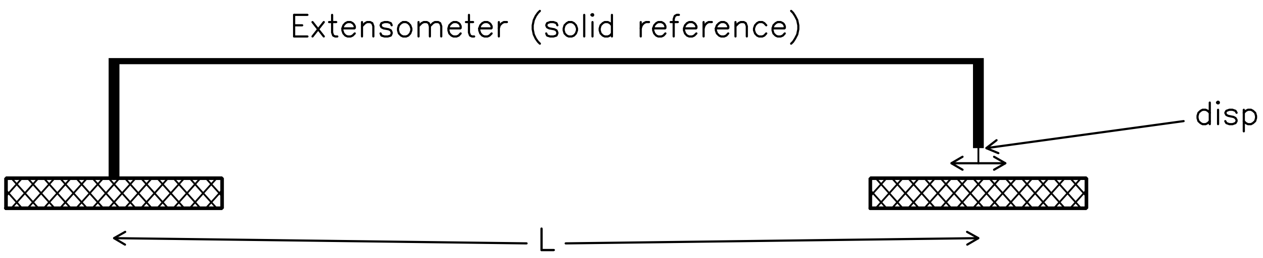
- Short-base: in borehole, or tunnel.
- Long-base: in tunnel (for L 10-100 m), and on the surface.

Best results from **short-base in a deep borehole**, and **long-base on the surface** (or in tunnel).

Strainmeters I: Bar Extensometers

These measure linear strain ε.

- **Instrument frame** is two endpoints a distance L apart.
- **Reference length** is L: a physical length standard.
- Measure the **relative displacement** ΔL between the two ends; then $\varepsilon = \dfrac{\Delta L}{L}$



The reference can be a bar, or a hanging wire, of anything with a small coefficient of thermal expansion: quatrz or invar.

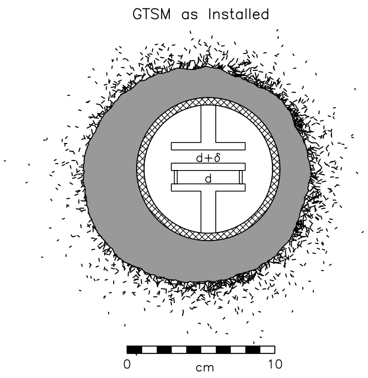
Gladwin Tensor Strainmeter

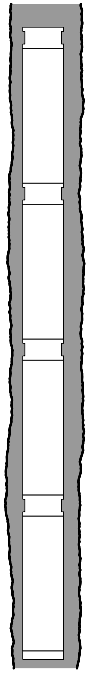
The basic module is a very short bar extensometer, with $L = 0.087$m. Displacements are measured with a capacitive sensor.

Because it is in a thermally stable environment, the bar can be stainless steel.

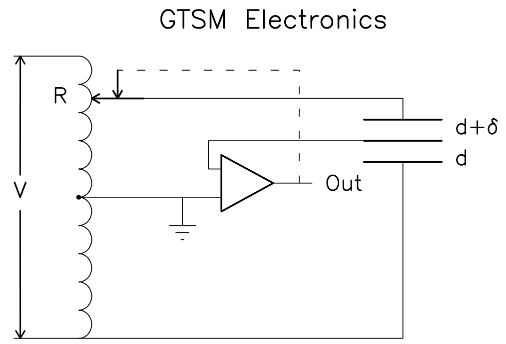
The PBO instrument has 4 modules, one for each direction: the first three are at 120° to each other, and the fourth at 90° to the first.

This provides redundancy, a calibration check – and [useful] confusion.





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 $\dfrac{1-R}{R} = \dfrac{C_2}{C_1} = \dfrac{d+\delta}{d}$ so that $d+\delta = d\,\dfrac{R}{1-R}$; 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 don't use this).

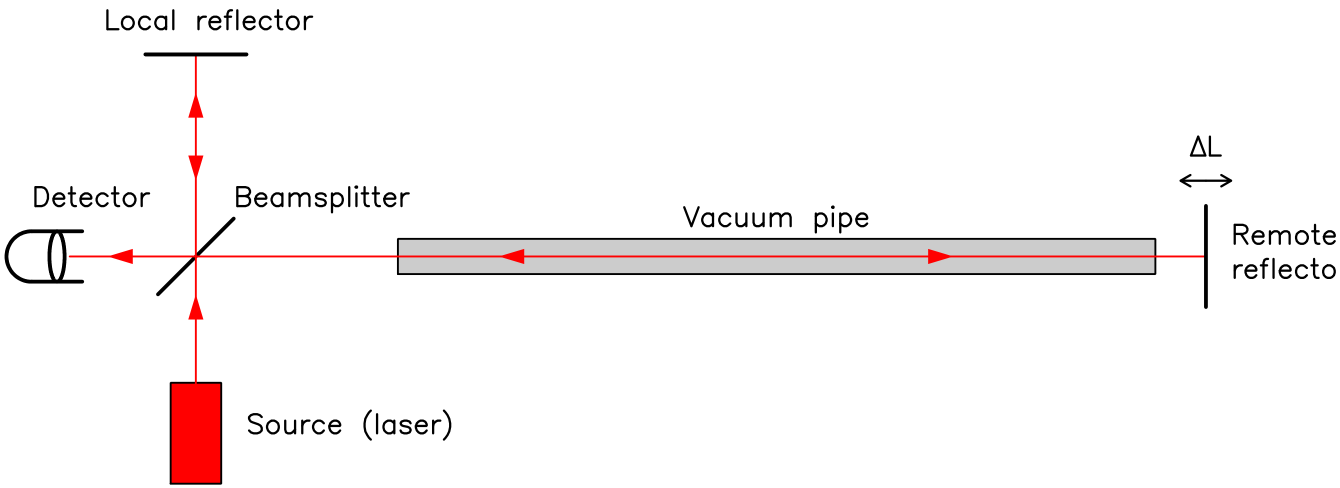
Strainmters II: Laser Extensometer

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 I: Main Interferometer

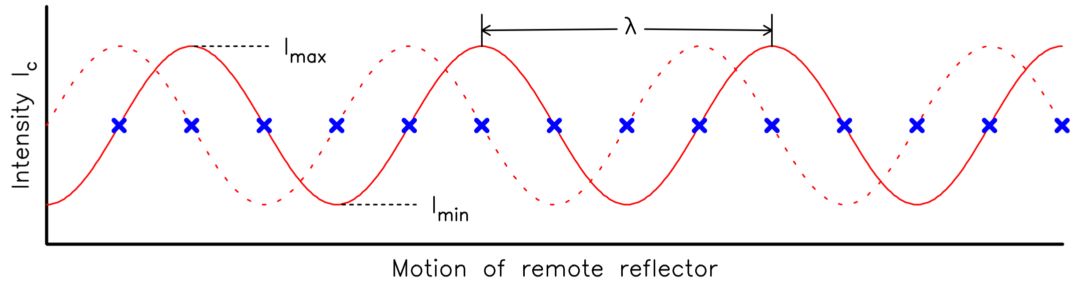


A **Michelson interferometer** has two arms, one fixed (to the local reflector) and one variable (to the remote reflector).

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.

Basic Design Overview II: Interferometer Signal

The red lines show how the intensity changes as the remote reflector moves; different polarizations are used to get two intensities, shifted by $\lambda/4$.



The electronics counts zero-crossings, using the sign of the nonzero component to find the direction.

If the remote mirror moves by $\lambda/8$, the path length changes by $\lambda/4$, which crosses zero.

This is 7.25×10^{-8} m: $\varepsilon = 1.53\times10^{-10}$ for L 500 m.

All this is “just like” GPS carrier-phase, in miniature.

Optical Paths

We 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.

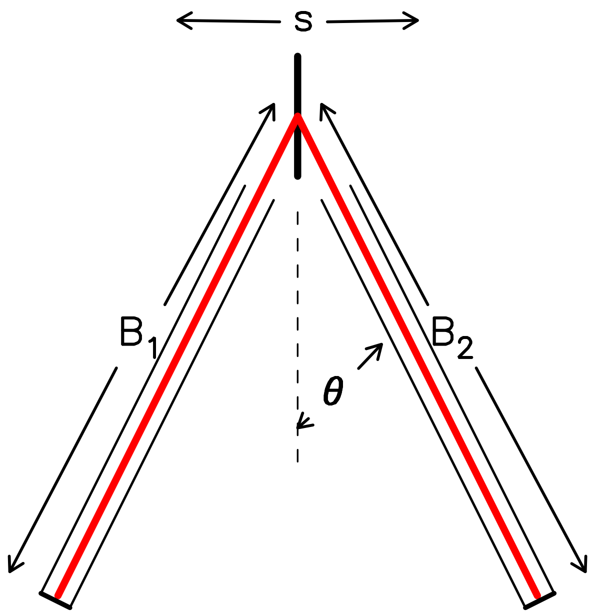
Index n drifts with time, as the fiber "ages": about 10^{-6} yr^{-1}.

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

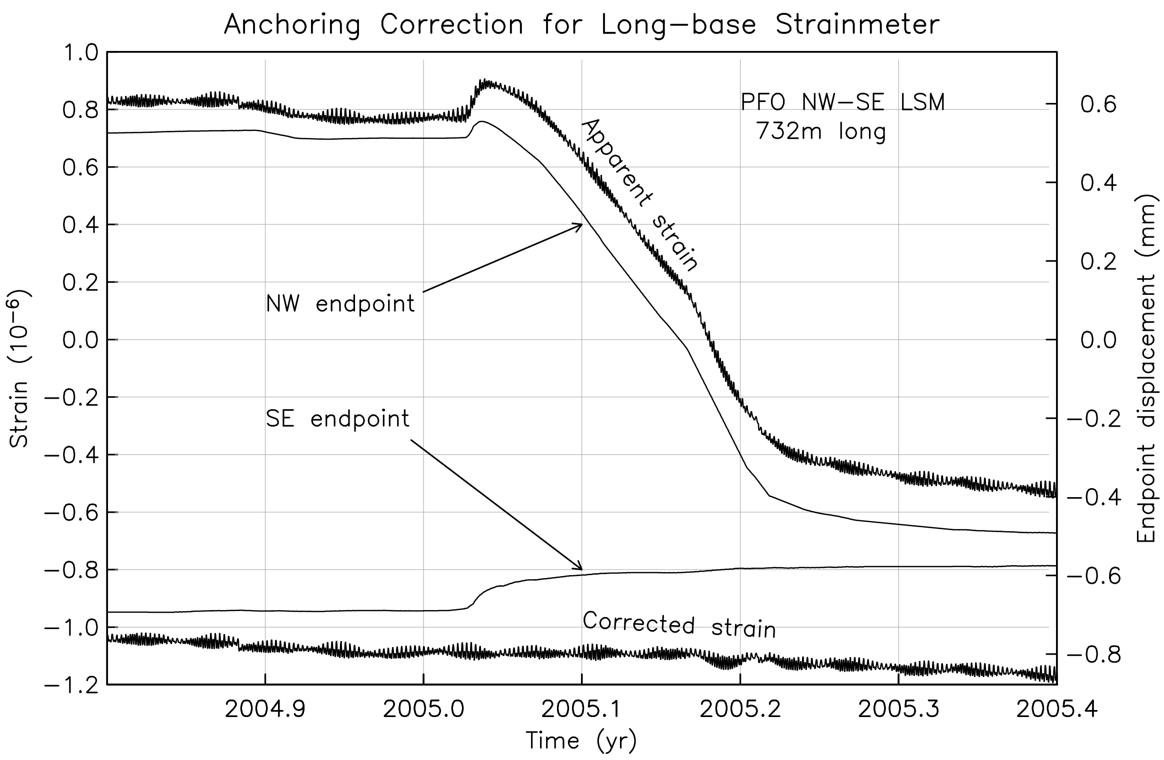
Anchoring

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.



Example of Anchoring



Not all the anchors work this well: there is a tradeoff between anchor depth and stability.

Cholame: Looking North

438 m long.

Laser Strainmeter Data Processing

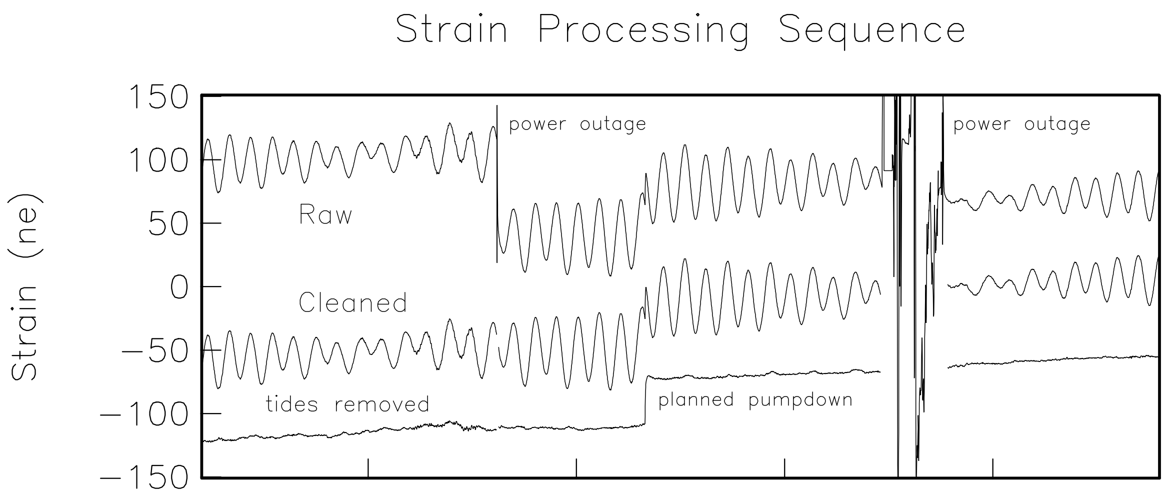
Aim to produce data ready for scientific use (all problems addressed) – for a system that in some ways is still a “lab” device.

Data channels to be considered are usually:

- 1. The main interferometer (both in 1-s and filtered form)
- 2. Both anchors (also interferometers)
- 3. The vacuum pressure (not a big contributor, depending on pumping and leaks).
- 4. The laser frequency (interpolated).
- 5. End-point temperatures (occasionally).

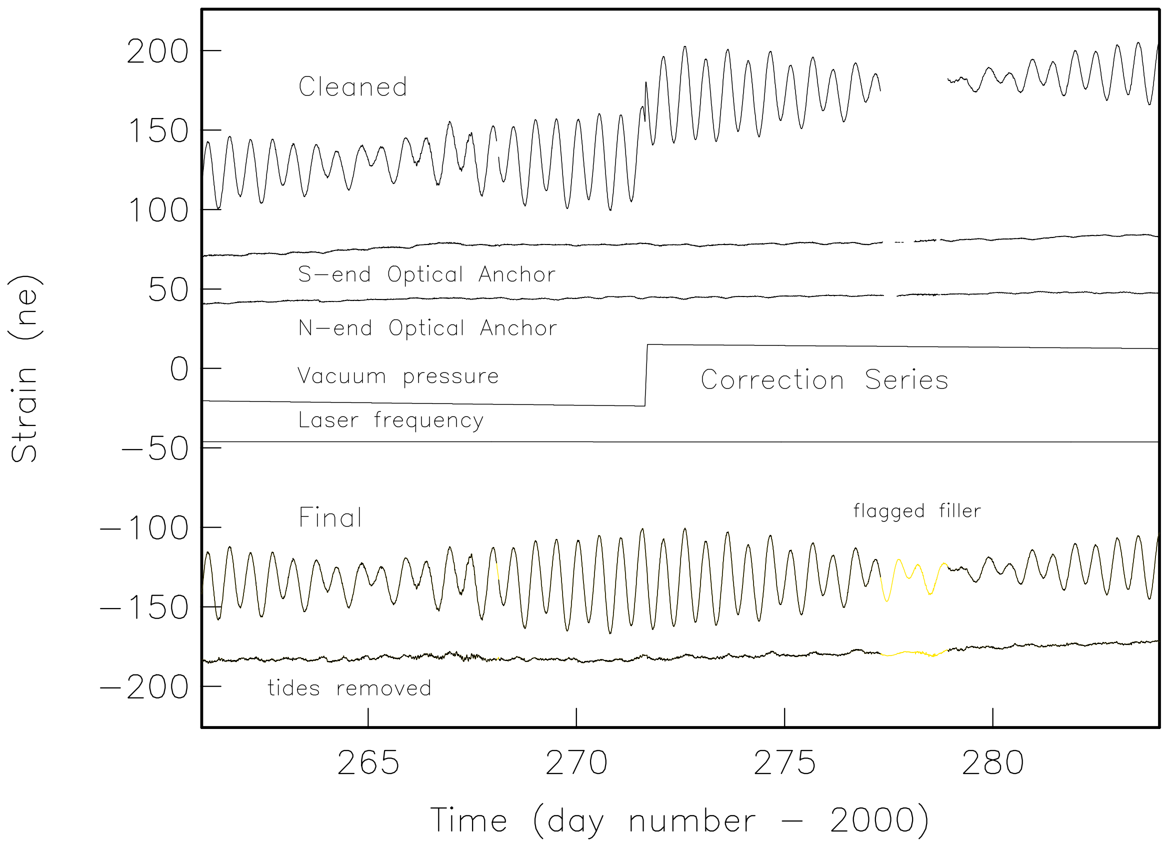
Along with records from visits to the field.

An Example of Editing



There is a (valid) offset in the main interferometer because of a (known) vacuum change; also a period when something went wrong.

Combining the Data



Access to Laser Strainmeter Data

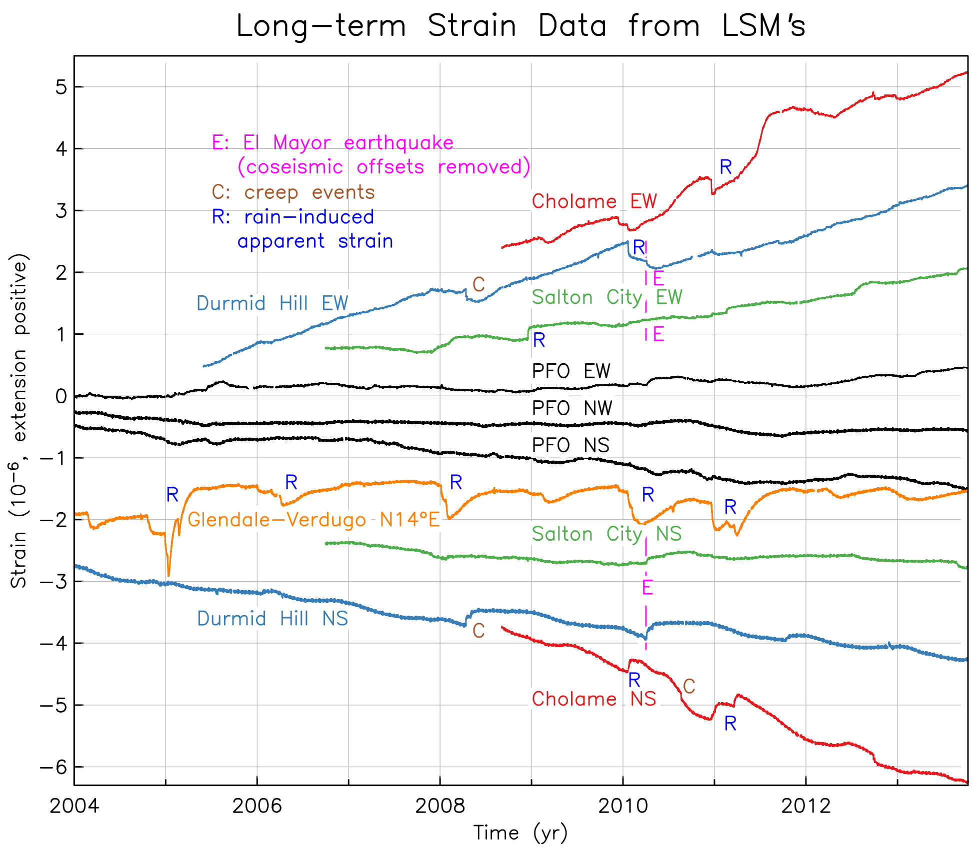
All raw and processed data are available from PBO Strainmeter Data Center (IRIS).

High-frequency (1-s) available as raw and SEED.

Low-frequency (5-m) data available as XML.

Low-frequency data also available at PBO website: probably the easiest to use.

The Payoff: Measuring Strain at all Frequencies



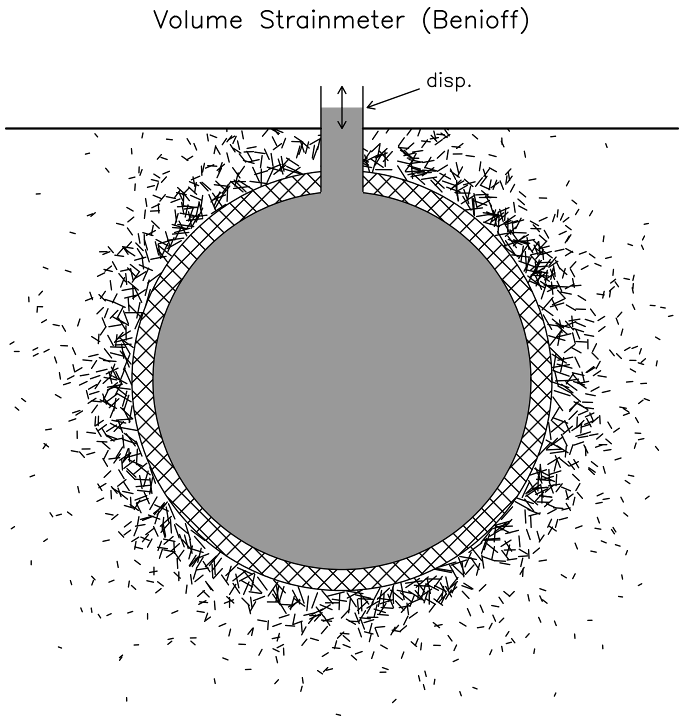
Strainmeters III: Dilatometers

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.

A Dilatometer Concept



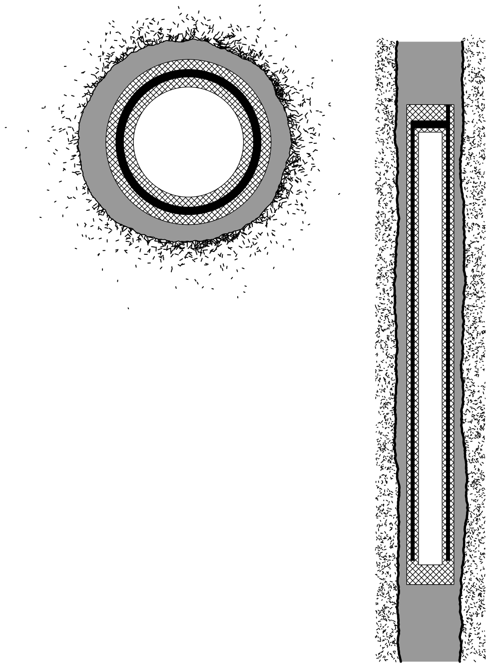
The original proposal for a volume strainmeter was by Benioff, in the same 1932 paper in which he described the first useful extensometer. However, nothing seems to have come of this.

Sacks-Evertson Dilatometer

Fluid volume is a cylindrical annulus, with the change in volume being measured through the displacment of an attached bellows. Instrument senses arealc[1] 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".