Instruments for Earth Deformation

All such instruments have the following elements:

A. Some kind of **reference**, which is supposed to be fixed.

B. An **instrument frame**.

C. Some way of measuring the **displacement** of the reference relative to the frame.

D. Some way of **attaching** the frame to the ground.

The development of these has been:

- For ground-based systems, A has not changed since the early 20th century, except for the application of lasers in strainmeters, now 40 years old. Space geodesy has created a whole new class of references.
- C has become much easier for small displacements, making for simplifications in other areas.
- D remains a problem, and a challenge.

Space Geodesy—True Displacement Measurements

(....by which we mean that the system will tell you your position, not just the change in displacement. Only navigation systems do this.)

Reference I: The Earth's center of mass, and inertial space (for satellite systems).

- How close do we get to inertial space? The unmodeled accelerations for GPS are around $10^{-??}$ g and for laser-ranging satellites can be as low as 10^{-13} g.

Reference II: Really distant radio sources (for VLBI).

Space-Geodesy Sensors: All use some form of time-of-flight of electromagnetic radiation:

- Light pulses (for SLR)
- Correlated random signals (VLBI)

  Phase of a sine wave (GPS): measure to a fraction of a cycle.

All measurements using radiation are affected by **path-length variations** (index of refraction not equal to 1), also known as **propagation effects**.

Potential Fields: Absolute gravity

This is a *very*-low-orbiting satellite—briefly.

Reference: Inertial space— not so easy to do: errors of $10^{-9} g$ are the best we can do.

Sensor: Laser interferometery

Interferometry, like GPS phase, relies on getting the phase of a carrier wave: but in this case, measuring to *lambda*/4, but with $\lambda \approx 6.3 \times 10^{-7}$m: a lot less than GPS, or light pulses. (But phase not usually as well resolved).

Sensitivity to displacement comes from gravity gradient:

$$g = G \frac{M_E}{r^2} \quad \text{so} \quad \frac{dg}{dr} = \frac{-2GM_E}{r^3} = \frac{g}{r} \approx 1.5 \times 10^{-6} \mathrm{s}^{-2}$$

so this system is sensitive to **acceleration only**. This is **not** a navigation system.

Potential Fields: Vertical accelerometer

Depending on the period of motion this may be called a **gravimeter** or a **vertical seismometer**.

There is NO DIFFERENCE between these sensors: they both measure (apparent) acceleration in the vertical.

The difference is in the period of motion: displacement u produces acceleration $\varpi^2 u$, vs gravity-gradient effect $2gu/r$; $\varpi^2 = 2g/r$ gives a period of about an hour.

Reference: Mass on a spring—so sensitive only to acceleration.
Spring may be physical, or magnetic levitation.

Sensor: "Laboratory displacement"

- Capacitor: 10^{-10} to 10^{-14} m resolution (nuclear dimensions).
- Inductor (LVDT): 10^{-10} m: readily available commercially, but applies more force.
- Moving-coil velocity
- Optical interferometry (under development).

Length: A Basic Parameter for Strainmeters and Tiltmeters

The **baseline length** *L* of an instrument that senses differential displacement is a fundamental way to characterize it, because:

1. The displacement is *L* times the strain or tilt (which are both dimensionless).
   - 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.
2. The local ground stability needed is also equal to the strain (or tilt) times *L*.
3. The ways in which the instruments can be sited depend on *L*:
   - Short-base: in borehole.
   - Long-base: in tunnel (for *L* in tens of meters), and on the surface.

The main divide is between short-base in a borehole, and long-base on the surface; the Japanese program has many ~10-30 m instruments in special-purpose tunnels).

Tiltmeters

All tiltmeters have a **vertical reference**, which points along **g**, the *apparent* direction of gravity.

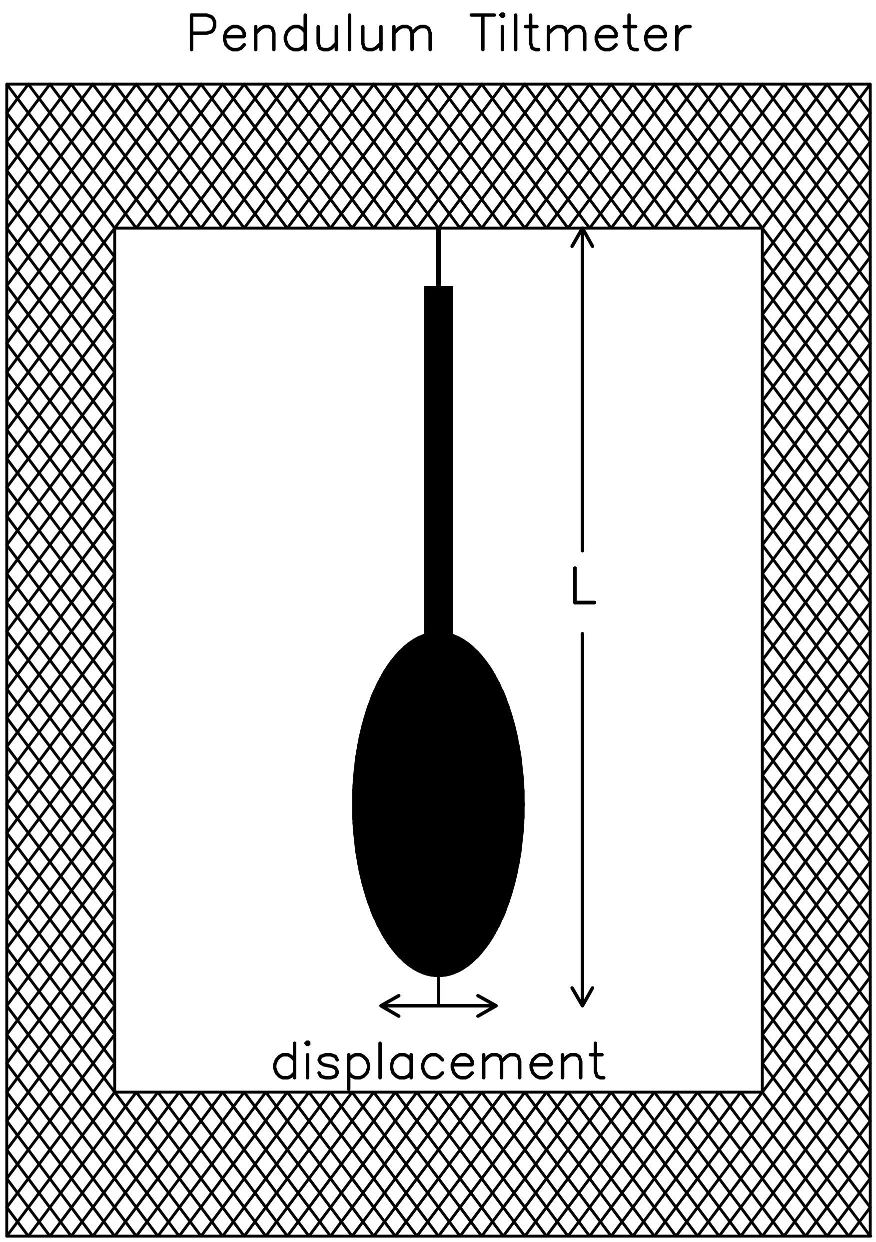
Important: This means that tiltmeters *also* measure horizontal acceleration,

> There is no difference between a tiltmeter, a horizontal seismometer, or a horizontal accelerometer: they all measure the same combination of quantities.

Pendulum Tiltmeter

Uses a "movable density interface"—that is, a mass on a pivot.

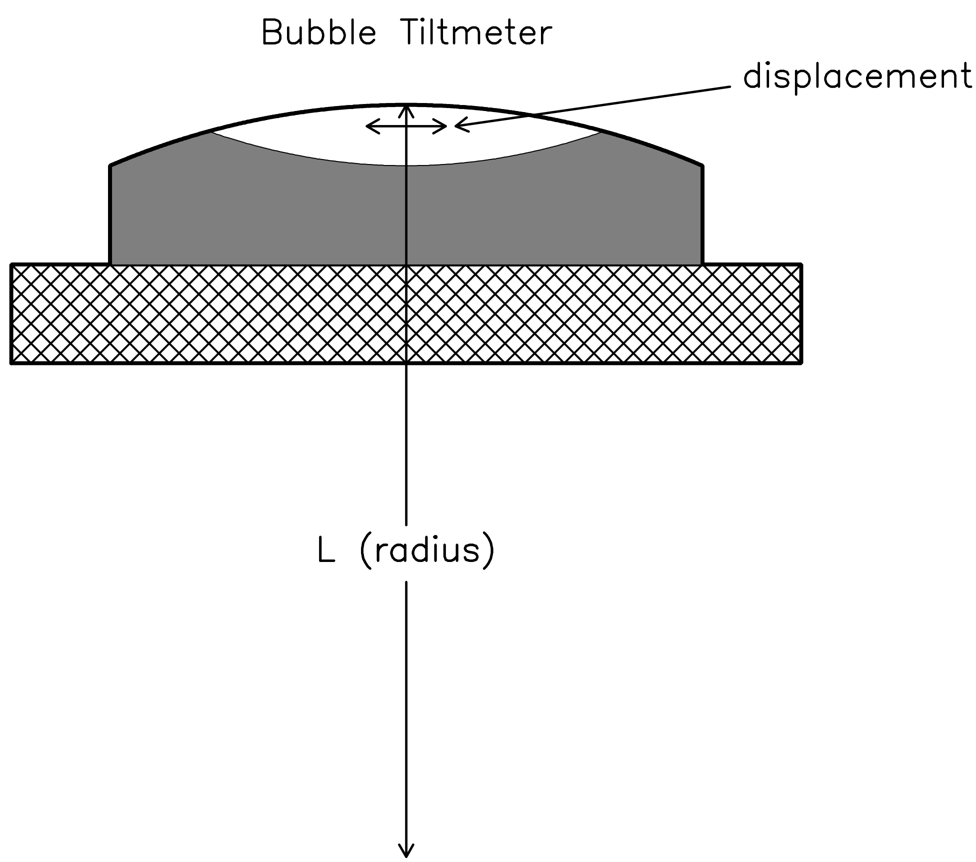
Length L is length of pendulum: 0.05 to 1 m.

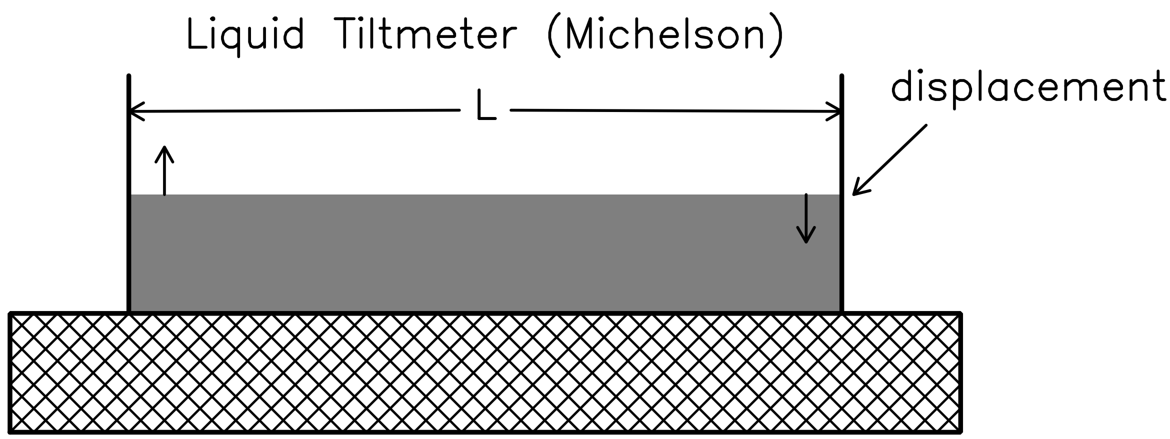


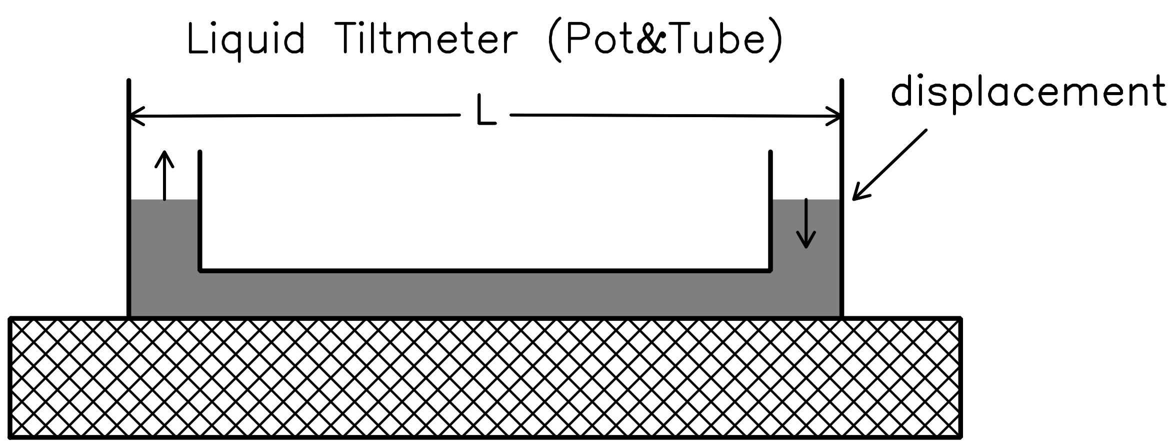
Liquid-based Tiltmeters

Use a "movable density interface"—in this case, the surface of a liquid.

L may be the radius of the surface of a bubble level, (up to 1 m) or the instrument length (up to hundreds of meters).







These two designs are commonly used for longbase instruments. The pot and tube design is sensitive to temperature, and must be installed in a tunnel. The "Michelson" design (developed in 1916!), with an unbroken free surface, can be extended to hundreds of meters.

Strainmeters

Strainmeters come in two flavors:

Extensometers, which measure linear strain ε. These strainmeters have a **reference length**, and some way to use it to measure the **relative displacement** ΔL between two points: we take

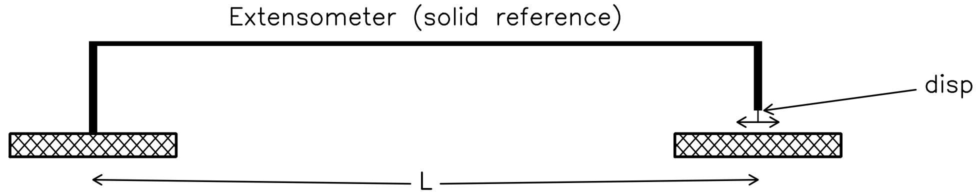
$$\varepsilon = \frac{\Delta L}{L}$$

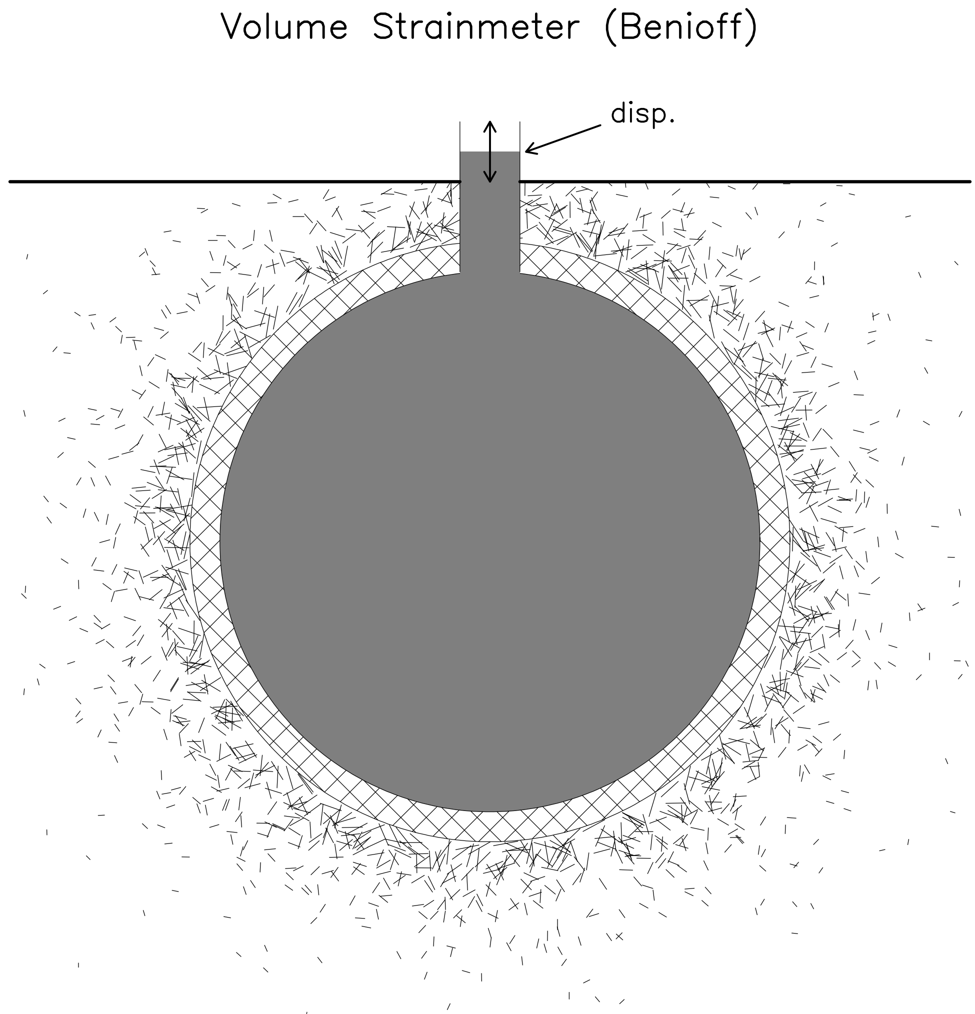
Dilatometers, which measure the dilatation

$$\varepsilon_V = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}$$

which is invariant (independent of coordinate system). These strainmeters have a **reference volume** V (filled with liquid), and measure the displacement of the liquid to get ΔV; then we take

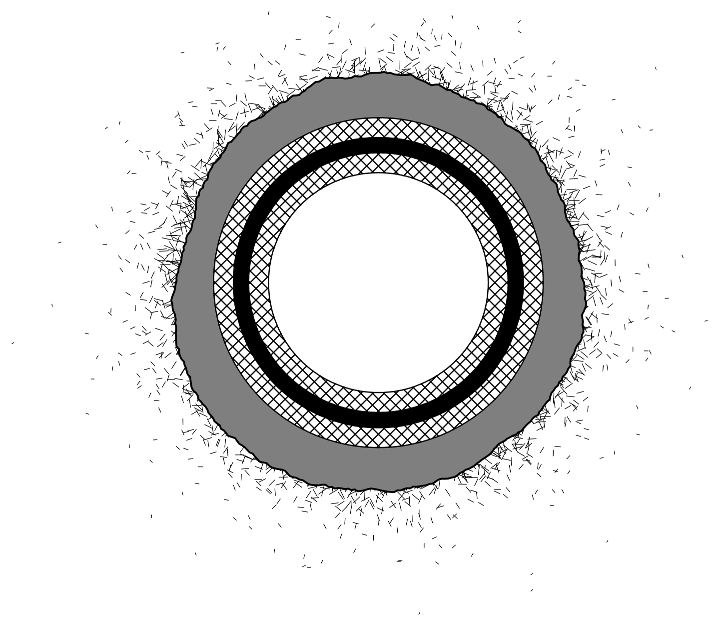
$$\varepsilon = \frac{\Delta V}{V}$$

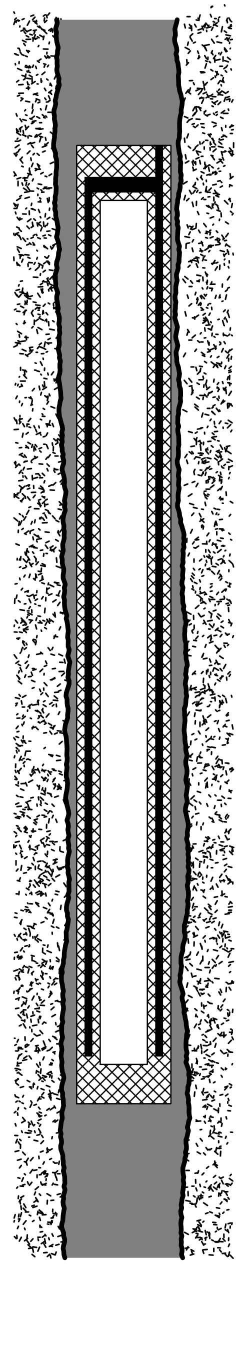




The original proposal for a volume strainmeter was by Benioff, in the same 1932 paper in which he described the first useful extensometer. However, nothing seems to have come of this.

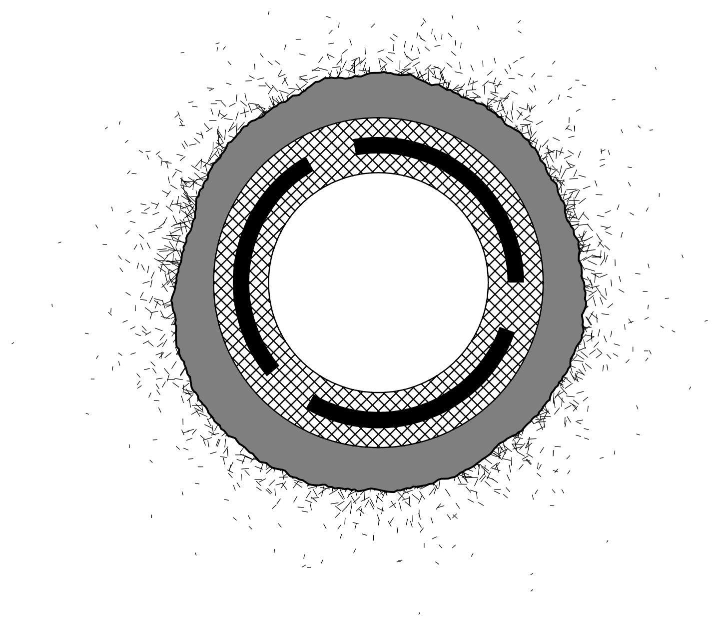
Sacks-Evertson Dilatometer

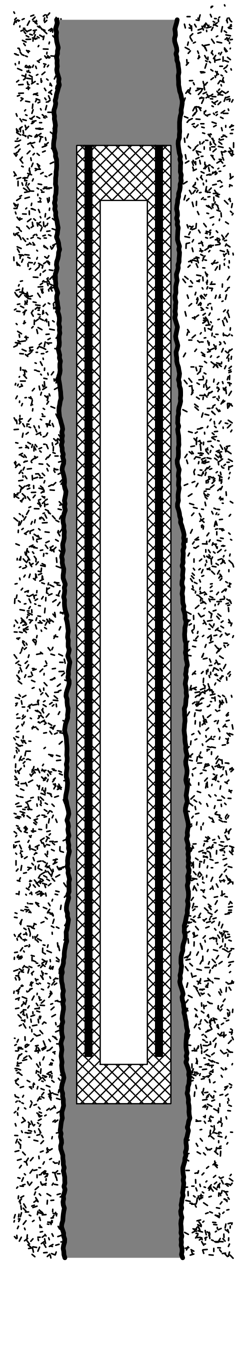




In this instrument, developed from around 1970, the fluid volume is a cylindrical annulus, with the change in volume being measured as the displacment of a metal bellows. This measures areal and vertical strain. The length in the borehole is about 2 m, but the amplification of the hydraulic system gives it an effective L of around 50 m.

Sakata Directional Volume Strainmeter

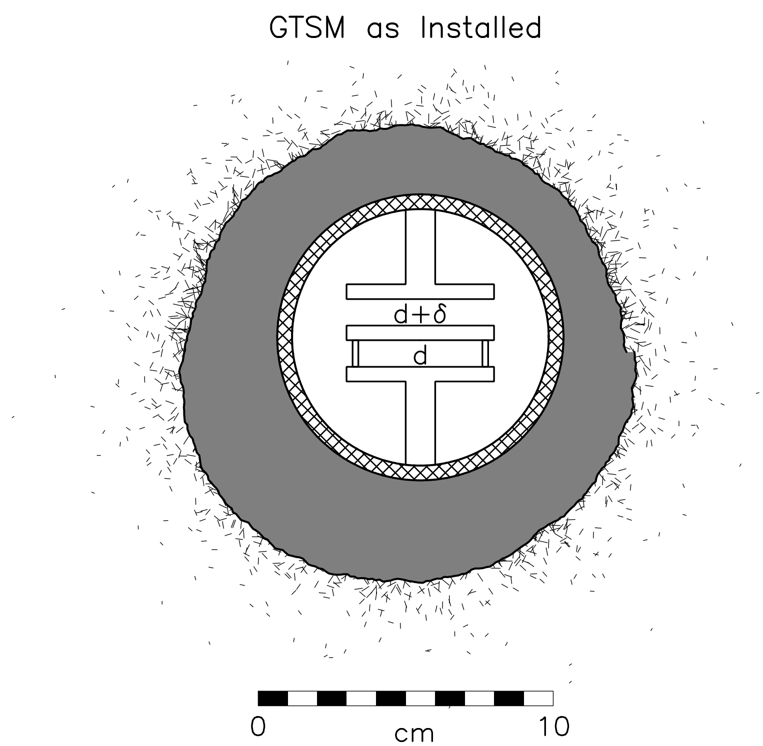


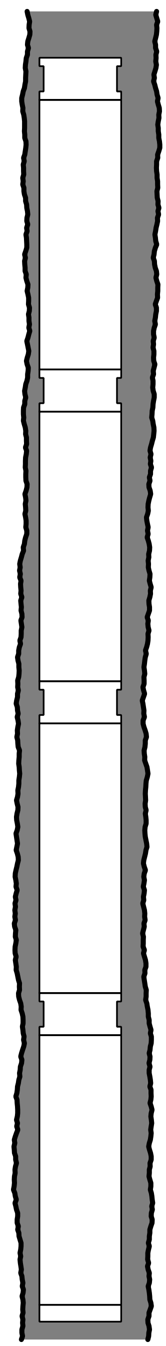


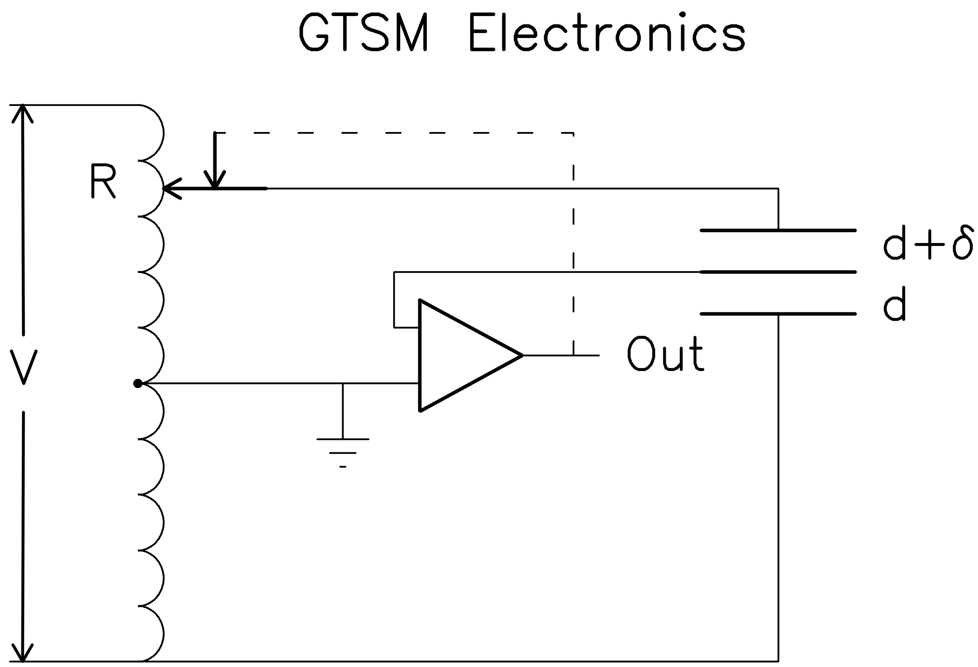
This instrument has three fluid volumes, each sensed separately, with the relative changes in different volumes allowing the measurement of the full strain tensor. A version of this instrument was used in the "Mini-PBO".

Gladwin Tensor Strainmeter

This has an L of 0.097 m; displacement is measured using a capacitive sensor.







An input voltage is divided in a 7-digit ratio transformer, with the output applied to the capacitor plates. (The ratio transformer is a very precise, and stable, voltage divider). R is adjusted to keep the output from the center plate small, is also dithered to calibrate the system.

The two capacitances $Csub1$ 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” found from the R and the output voltage is found from this equation.

Rotation meter

Reference: inertial space
Sensor: radiation (Sagnac effect)

Reference: mass on a pivot (short periods only)
Sensor: displacement

Reference: gyroscope (noisy)
Sensor: displacement

Strainmeter and Tiltmeter References

General

D. C. Agnew (1986).). Strainmeters and tiltmeters, *Rev. Geophys.*, **24**, 579–624.

Exhaustive, and exhausting, coverage of this class of instrumentation as of 1986 (not that much has changed since then in instrument design). Does show any data or discuss data processing.

D. C. Agnew (1987).). The continuous measurement of crustal deformation, *Methods in Experimental Physics*, **24B**, 409-439

A condensed version of the above.

Borehole Strainmeters

I. S. Sacks, S. Suyehiro, D. W. Evertson, and Y. Yamagishi (1971). Sacks-Evertson strainmeter, its installation in Japan and some preliminary results concerning strain steps, *Pap. Meteor. Geophys.*, **22**, 195–207

Description of the original Sacks-Evertson dilatometer; note that some of the methods used have changed since that time.

M. T. Gladwin (1984). High precision multi-component borehole deformation monitoring *Rev. Sci. Instrum.*, **55**, 2011–2016

The basic paper on this instrument.

S. Sakata and H. Sato (1986). Borehole-type tiltmeter and three-component strainmeter for earthquake prediction *J. Phys. Earth*, **34**, S129–S140

Describes the 3-component hydraulic strainmeter, as used in the "mini-PBO".

Gladwin, M. T., and R. Hart (1985). Design parameters for borehole strain instrumentation, *Pure Appl. Geophys.*, **123**, 59-80.

Hart, R. H. G., M. T. Gladwin, R. L. Gwyther, D. C. Agnew, and F. K. Wyatt (1996). Tidal calibration of borehole strainmeters: removing the effects of local inhomogeneity, *J. Geophys. Res.*, **101**, 25553-25571.

Two papers on the coupling problem. The first describes how to find the coupling from the elastic constants of the system; the PIASD program `borecouple` does this (using much simpler methods). The second describes a variety of tidal calibrations.

Laser Strainmeters

J. Berger and R. H. Lovberg (1969). A laser earth strain meter *Rev. Sci. Instr.*, **40** 1569-1575

J. Berger and R. Lovberg (1970). Earth strain measurements with a laser interferometer *Science*, **170**, 296–303

The original papers on this instrument.

F. Wyatt, K. Beckstrom, and J. Berger (1982). The optical anchor – a geophysical strainmeter *Bull. Seismol. Soc. Am.*, **72**, 1707–1715

M. A. Zumberge and F. K. Wyatt (1998). Optical fiber interferometers for referencing surface benchmarks to depth *Pure Appl. Geophys.*, **152**, 221-246

The original paper on this system, and its extension to optical fibers.

D. C. Agnew and F. K. Wyatt (2003). Long-base laser strainmeters: a review, *SIO Technical Report*, **2**, `http://repositories.cdlib.org/sio/techreport/2/`

Another exhaustive description of the instruments, their operation and design, and results from those installed at the time.

Long-Base Tiltmeters

J. Beavan and R. Bilham (1977). Thermally induced errors in fluid tube tiltmeters, *J. Geophys. Res.*, **82**, 5699−5704

R. Bilham, R. Plumb and J. Beavan (1979). Design considerations in an ultra-stable, long baseline tiltmeter: results from a laser tiltmeter. Pp 235−254 of *Terrestrial and Space Techniques in Earthquake Prediction Research*, ed by A. Vogel. (Friedrich Vieweg, Wiesbaden, Germany)

Optical Rate-of-Rotation Sensors

Stedman, G. E. (1997). Ring-laser tests of fundamental physics and geophysics, *Rep. Progr. Phys.*, **60**, 615-688.

Schreiber, K. U., T. Klugel, and G. E. Stedman (2003). Earth tide and tilt detection by a ring laser gyroscope, *J. Geophys. Res.*, **108**, doi:10.1029/2001JB000569.