PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Some Instruments and Techniques for Measurements of Tidal Tilt

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Phil. Trans. R. Soc. Lond. A 1973 **274**, 219-222
doi: 10.1098/rsta.1973.0045

Phil. Trans. R. Soc. Lond. A. **274**, 219–222 (1973) [219]
Printed in Great Britain

Some instruments and techniques for measurements of tidal tilt

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[Plate 4]

The U.S. Geological Survey has operated continuously recording long-base liquid-level tiltmeters for several years at two locations in the San Francisco Bay Area. The meters are capable of resolving 10^{-8} rad and exhibit long-term drifts of about 1.5 μrad/year. Since these instruments require elaborate vaults for their operation, we have developed a simple pendulum tiltmeter of a geometry suitable for operation in a shallow borehole for measurements at similar sensitivities. Techniques developed for emplacement of instruments in boreholes seem satisfactory, but early results indicate that such sites must be selected with great care and attention to local geology. Sample data presented include plots of output from the long-base instruments and of the pendulum.

The United States Geological Survey has supported a programme for the measurement at tidal sensitivity of Earth tilts for more than 5 years. During this period we have operated continuously a station at the Presidio Vault in San Francisco, and for a period of nearly 3 years we have also operated a similar station in the seismic vault at the University of California at Berkeley through the kind cooperation of the director of the seismographic station.

The instruments in these two vaults are liquid-level devices with base lengths of 5 and 2 m respectively, making use of mercury as the levelling liquid. The displacement sensors are differential capacitance detectors of the resonant bridge or 'Benioff' type. The particular solid-state circuits employed were designed by Mr W. Gile of Caltech who very kindly supplied circuit diagrams for construction of the sensors and loaned us the hardware for our intitial installation.

These long-base liquid-level instruments have several advantages, most notably relative immunity to noise or spurious tilt signals caused by small mechanical changes in the support-point geometry and in the mechanical portion of the meters, such as may occur during thermal stress or ageing.

When operated in the proper thermally stable environment these instruments exhibit excellent long-term drift characteristics, and hence are prime choices for use in tectonic applications.

Sensitivity is limited by the noise spectrum. We do not have an accurate figure on this, as recording is entirely by multi-point strip chart recorder, but inspection of the records indicates that a sensitivity of 10 nrad for short-term phenomena is a reasonable value.

Calibration of the instruments is accomplished by elevating one end of the mercury line with a micrometer adjustment operating through a 10:1 reduction lever incorporating an elastic hinge. With this system it is possible to introduce repeatable tilt steps as small as 100 nrad. In practice the calibration steps are usually introduced when the instrument requires re-zeroing, and the step is usually one of about 500 nrad. Successive steps are repeatable to within reading error of the micrometer and of the strip chart, that is to within about 3 %. Linearity of the system is also within this margin of reading error, about 3 % over a range of 10 μrad.

Figure 1 is a photograph of 60 h of strip chart record from several tiltmeters illustrating the quality of records we normally obtain. The traces marked C and D are the records from liquid-level meters.

Our record of several years tilt at the Presidio Vault indicates that the secular drift of the long base instruments amounts to about 1.5 μrad/year averaged over the entire time. The yearly record reveals a cyclic tilt of several times this value caused by meteorologic phenomena, but after each rainy season the meters return quite near to the previous year's value.

We have concurrently worked at development of an instrument of similar sensitivity but capable of operation in arbitrary locations where elaborate vaults are not available. The result of this development programme is an instrument suitable for emplacement in a shallow bore-hole, at a depth just sufficient to afford temperature stability in relatively mild climates. The

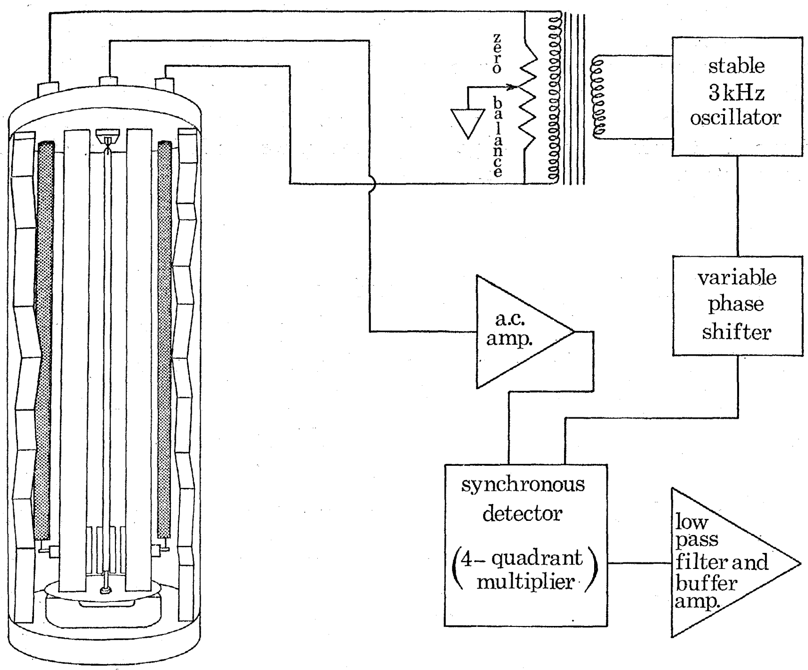

Figure 2. Block diagram of pendulum and electronics.

instrument itself consists of a pendulum suspended between two capacitor plates, and electrically isolated from ground. The pendulum and the two plates constitute the two capacitances to be measured in a differential capacitance bridge. The 50 cm pendulum is housed in an aluminum cylinder 14 cm in diameter and 70 cm long, and the entire meter is fabricated of stress-relieved aluminum except for the elastic hinge which is of steel shim stock. The electronic sensor circuit, illustrated in the block diagram of figure 2, was designed to make maximum use of modern integrated circuits and special purpose modules.

In operation, the stable oscillator with a frequency near 3 kHz drives the two fixed capacitor plates with a.c. voltages of approximately equal amplitude, but of opposite phase. The resulting signal which is capacitively coupled to the moving pendulum will have an amplitude dependent on displacement of the pendulum from the central null position and a phase dependent on direction of displacement from null. This signal on the pendulum is then amplified by high-gain a.c. amplifiers and applied to one input of a modular four-quadrant multiplier operated as a synchronous detector. The advantages of analogue multipliers in this application are discussed

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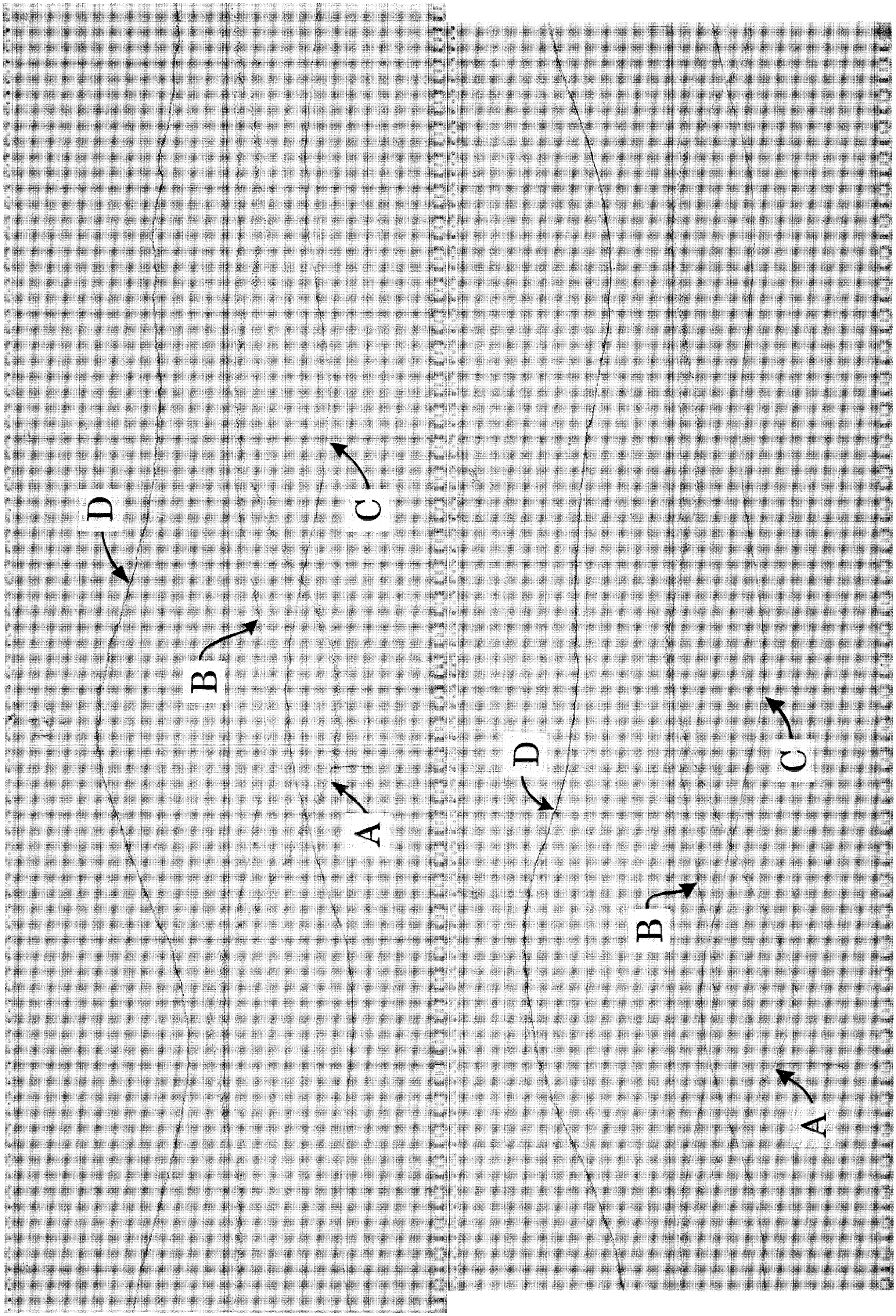

FIGURE 1. Photograph of 60 h of strip chart record. Traces A and B are high- and low-gain pendulum records. Traces C and D are long base mercury level instruments.

by Burwen (1971). A reference signal from the driver oscillator is applied to the other multiplier input. The output of the multiplier may be approximated by

$$V_0 = A_1 \cos \alpha t \, A_2 \cos \alpha t$$
$$= A_3 \cos^2 \alpha t.$$

A_1 is the amplitude coefficient of the reference signal, which will be a constant during operation after initial setup. A_2 is the coefficient of the amplified signal from the pendulum and may vary in both sign and amplitude.

A_3 then may be of either sign and V_0 will be an a.c. voltage with a d.c. offset of magnitude and polarity determined by A_3. This output is now applied to a low-pass filter and buffer amplifier which removes the a.c. component but preserves amplitude and polarity of the d.c. offset. The final output is the analogue voltage representative of tilt.

Sensitivity and signal to noise ratio can be evaluated by referring to figure 1, in which the traces marked A and B are the high- and low-gain record produced by one of these instruments operated in the Presidio Vault parallel to the corresponding long base instrument of trace C.

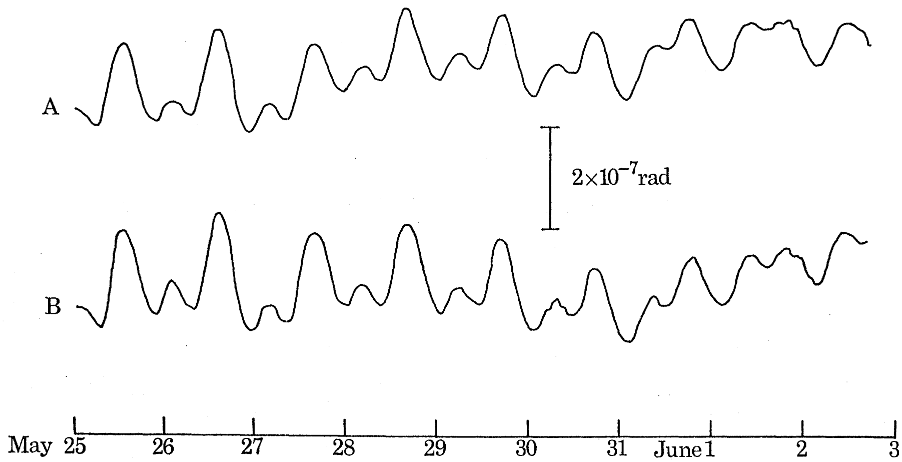

FIGURE 3. Time-compressed tilt records from (A) long base mercury level meter, (B) pendulum operated in vault.

Stability of the instrument under controlled conditions is illustrated in figure 3 which presents a time compressed plot of the pendulum record in trace B beside that of the mercury instrument, trace A. It will be noted that the two traces exhibit coherent secular tilt changes and that disagreement between the two over this 10-day period is less than 10^{-7} rad.

After test in the Presidio Vault the prototype single-axis pendulum was installed in a shallow borehole near the vault. The installation we are using at present is illustrated in figure 4. A pit about 1 m in diameter and 1.5 m deep is drilled and cased with road culvert. Extending downward from this pit is a steel casing about 25 cm in diameter and 2 m long. This casing is partly filled with clean dry sand and the tiltmeter lowered into it. After rough levelling the meter by wiggling it about in the sand, it is then completely buried in dry sand, effectively coupling it securely to the 25 cm casing and isolating it from temperature excursions at the surface. Cables connecting the pendulum with its sensor electronics are led up through the sand to the electronics package which may be located in the same pit or in an adjacent similar pit connected by a short pipe. The electronics circuitry incorporates provision for electrically zeroing the pendulum if it is first physically levelled to an approximate null position.

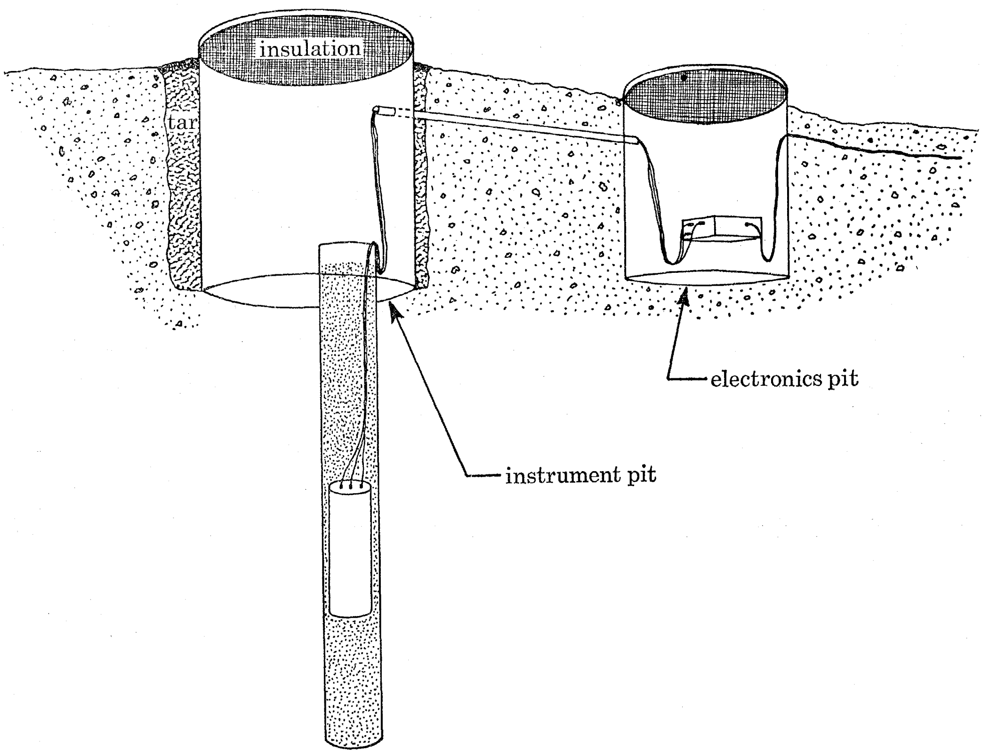

Figure 4. Cutaway view of typical shallow borehole installation.

The layer of tar surrounding the large diameter casing is intended to prevent water from running down the outside of the casing, under the lower edge, and filling the pit. The present design is the result of several early misadventures, including flooding.

We have also found it helpful to fill the pit partially, covering the electronics boxes with bags of styrofoam pellets, thus helping considerably in temperature isolation.

In selecting borehole sites it is important to avoid soils rich in clay minerals. Well-drained river gravel deposits have given good results, and our best site thus far has been in clean aeolian sand. Early results indicate that we can achieve tidal sensitivity and drift rates of about 100 nrad per week. This level of performance cannot be attained in all locations, but when proper attention is paid to details of local geologic conditions, this is a reasonable standard.

Parts of this work were supported by the Advanced Research Projects Agency under A.R.P.A. Order 1684. We would also like to thank the Sixth U.S. Army Command for the use of an ammunition gallery at the Presidio of San Francisco without which much of this work would not have been possible.

Reference (Allen *et al.*)

Burwen, R. 1971 *Electron. Design* **19**, no. 7.

FIGURE 1. Photograph of 60 h of strip chart record. Traces A and B are high- and low-gain pendulum records. Traces C and D are long base mercury level instruments.