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An Improved Servo-Controlled Tiltmeter System and Latest Measurements in Sweden

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An improved servo-controlled tiltmeter system and latest measurements in Sweden

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Two serious shortcomings in horizontal pendulums used for tilt measurements are nonlinearity in their response to tilt and sensitivities which vary with time. These difficulties may be eliminated if a horizontal pendulum is used as a null indicator. A description is given of a horizontal pendulum apparatus which automatically compensates for ground tilt. The pendulum apparatus is designed so that it may be tilted by varying the pressure in an expansible bearing plate made of stainless steel which is placed at its base. Pressure changes are produced in the bearing plate by varying the height of a column of mercury, a process which can be previously calibrated with great precision. The position of the pendulum beam is sensed by an electro-optical transducer which provides a suitable servo signal to adjust the height of the mercury column when the instrument undergoes tilting. The servo signal can be recorded directly on an ink chart recorder or digitally.

First results have been obtained in a test station. It is planned to establish an array of geodynamic stations in Scandinavia incorporating these tiltmeters alongside recording gravity meters in order to study crustal movements by tidal forces, atmospheric pressure effects, ocean loading effects and possibly the process of land uplift in Fennoscandia.

Introduction

Modern research on variations of the Earth's gravity potential with time and on crustal movements due to tidal forces, ocean loading, atmospheric pressure as well as tectonic forces requires instrumentation of high sensitivity and accuracy. Precise measurements of the variations of crustal tilt against level surfaces of the Earth's gravity potential field have become an important tool for investigating the physical state and processes in the Earth's interior.

The design of modern tiltmeters is based on three classical principles, namely the hydrostatic tiltmeter, the vertical pendulum and the horizontal pendulum. The advances in electrical measuring technique make it possible to use these tilt indicators for measurements of extremely small tilt angles. These small tilt angles can be expressed in terms of horizontal acceleration if one considers tilt to be caused by deflexions of the vertical.

Background of the measuring principle

The original design of the servo-controlled tiltmeter system and first results were described earlier by Vogel (1970, 1971). Its construction is based on the horizontal pendulum principle. The suspension is of Hengler–Zöllner type and made of quartz.

According to the theory for horizontal pendulums the amplification of the tilt angle is given by the following expression:

$$\delta\psi = (T^2/T_0^2)\,\delta\phi,$$

where $\delta\phi$ denotes the tilt angle, T_0 the period of the pendulum in vertical position, T the period when it is astatized and $\delta\psi$ the deflexion of the beam.

On conventional pendulums the deflexion of the beam is recorded optically on photographic paper. In order to reach the sensitivity of $\delta\psi/\delta\phi \simeq 10^5$, the requirements in modern research, the light path was supposed to be several metres long and the pendulum had to be almost astatic, i.e. the natural period had to be close to 100 s. However, in such a position the sensitivity is extremely unstable because it changes very rapidly with the natural period (Graf 1967). In addition, the sensitivity also varies with the azimuth of the pendulum beam. For this reason it is necessary to calibrate these pendulums continuously.

Instrumental design

Figure 1 shows the block diagram of the system. The position of the pendulum beam is sensed by an electro-optical transducer. When the instrument undergoes tilting the electrical signal from the transducer is amplified, filtered and by a phase differential a.c. servo generator converted into a suitable signal to drive a phase-sensitive servo motor. By changing the height of a mercury level the motor adjusts the expansion of a pressure sensitive-bearing plate and produces a compensating tilt. The variations of the mercury level are a direct measure of the ground tilt. These are recorded with time marks obtained from a time signal generator.

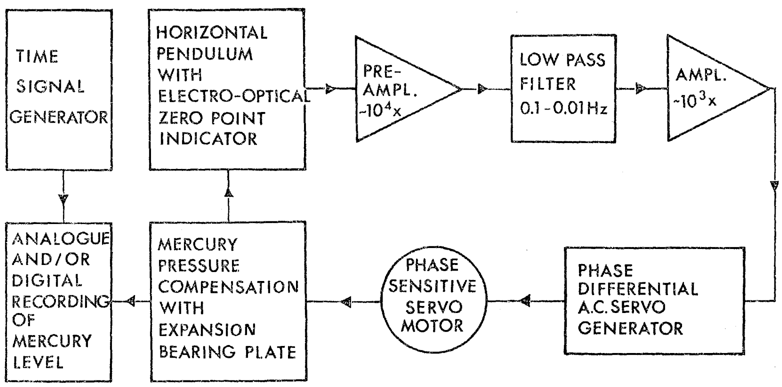


Figure 1. Block diagram of the servo-controlled tiltmeter system.

System analysis and calibration

The servo system compensates perfectly for ground tilt and horizontal acceleration for long periods beyond the natural period of the pendulum. Static calibration of the expansible plates is the only calibration required. For determination of the sensitivity of the system as a whole, the expansion of the bearing plates as a function of height of the mercury column is measured.

To do this we use a 'mikrokator', a mechanical device for measuring small displacements. Its accuracy is better than 1 % through the full range of calibration. When using interferometrical optics directly the expansion of the bearing plates can be calibrated with an accuracy of approximately 1 % using a number of measurements for one fringe interval only (Verbaandert 1964). The expansible bearing plates which we use are made of stainless steel with a topwall of 4 mm thickness. When the mercury column varies between 1500 and 2000 mm, within the range where the system is usually operated, a rise of the mercury level of 1 mm produces a bearing-plate expansion of 8.8×10^{-7} mm (88 nm). For a pendulum base of 400 mm this means a tilt angle of 2.2×10^{-9} rad or 0.0005″. The variations of the mercury level can be recorded with an accuracy of about 0.1 mm, which means a resolving power for the system of 2.2×10^{-10} rad or about 0.05×10^{-3} sec arc. If tilt is regarded as deflexion of the vertical the resolving power would be equivalent to a change in horizontal gravity or kinetic acceleration of $2.2 \times 10^{-10} g$ or about 0.2 μGal (2×10^{-6} mm s^{-2}).

The threshold tilt angle for the servo system response is given by the sensitivity of both the pendulum and the electro-optical transducer. The system responds to less than 10^{-3} mm deviation of the lightspot on the transducer. The threshold tilt angle corresponding to 10^{-3} mm lightspot deviation as a function of the natural period of the pendulum is given in figure 2. The threshold tilt angle should be smaller than the resolution tilt angle of 22×10^{-11} rad, otherwise steps will occur on the record. In our case (figure 2) the natural period should be longer than 47 s. However, we operate our pendulums at a natural period of less than 20 s without observing any steps. This means that the threshold given by the transducer obviously is considerably smaller than that of a 10^{-3} mm lightspot deviation.

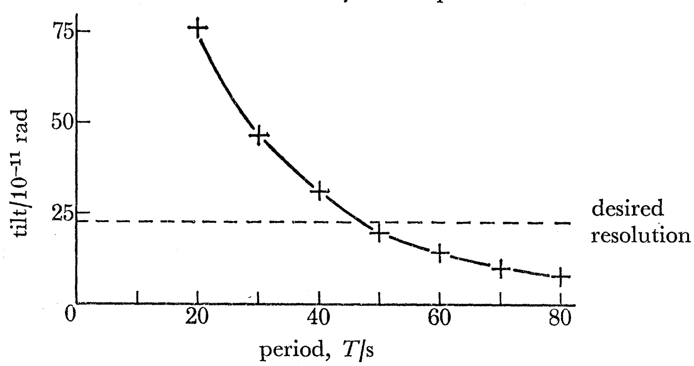


FIGURE 2. Characteristics of the servo system.

ADVANTAGES OF TILT COMPENSATION

Compared with the conventional way of recording the deflexions of the pendulum beam, the compensating system has many advantages. In the low-frequency range the pendulum remains in its zero position and consequently the quartz system is not affected by varying stresses. The sensitivity is constant and the only calibration required is that of the expansible bearing plates. There is no need to control the natural period of the pendulum as long as the threshold tilt angle of the servo system response is smaller than the required resolving power. The azimuth of a pendulum component is given by the base screws. An exact alinement of the pendulum beam is not necessary.

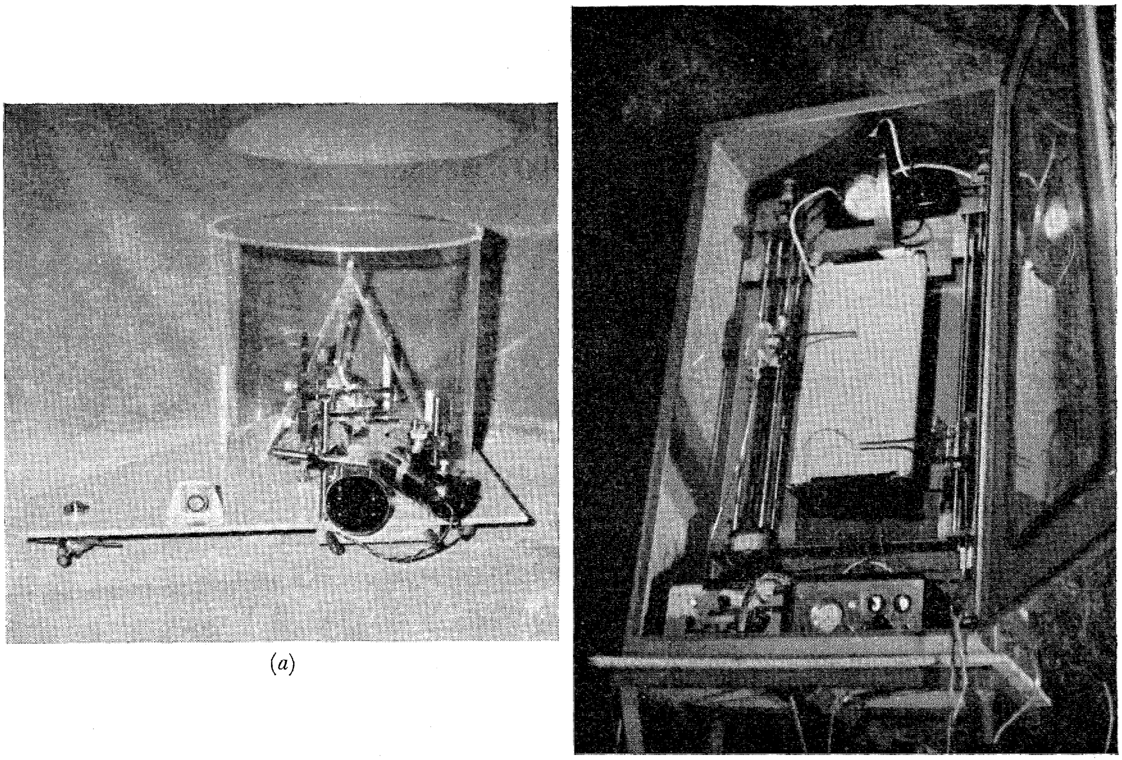
Higher sensitivity than conventional pendulums can be obtained when operating the pendulum at natural periods of less than 30 s. This keeps the pendulum away from extremely high periods where it is nearly astatic.

Centring of the pendulum in a mechanical way is particularly difficult. Here it can be achieved with the use of an electrical offset voltage, which can be calibrated.

The electro-optical transducer senses a wide frequency range. The measurement of ground tilt and horizontal accelerations due to tectonic forces, atmospheric pressure and ocean loading, tidal forces and free oscillations of the Earth can easily be extended into the frequency spectrum of seismic waves.

Records can be obtained in different ways. Difficulties with photographic paper handling are eliminated. There is no need of long galleries in total darkness. The signal can be recorded directly visible and the recording speed is easily selectable.

Electrical signals of the compensated tilt from the precision potentiometers and of the uncompensated tilt directly from the electro-optical transducer can be registered either on analogue or digital recorders. Simultaneous digitization of the data eliminates the time consuming preparation of the data for digital processing.



(*a*) (*b*)

FIGURE 3. Photographs of (*a*) a pendulum and (*b*) a compensation system with recorder and quartz clock.

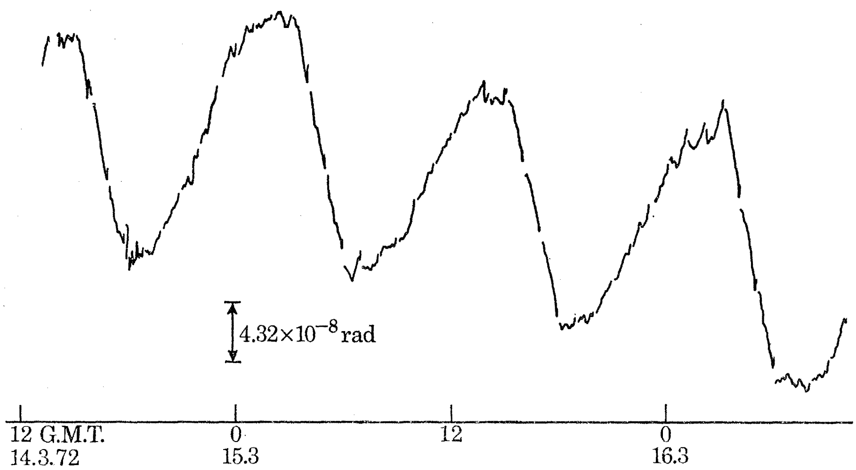


FIGURE 4. Actual record of the mercury level indicator from the Uppsala–Läby station.

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Results

Figure 3*a* shows the photograph of a pendulum and figure 3*b* the photograph of a box with compensation devices, recorder and quartz clock. Such a system has been installed in a gallery near Uppsala. This place is not the most ideal. It is very suitable as a test station, however, while improvements still have to be made.

Figure 4 shows records of a few days with Earth-tides as the most prominent feature. Disturbancies are caused by earthquakes, local ground tilt and some changes of temperature. The long-term drift arises from aging of the quartz suspension. The feed back system has been checked and found to be extremely stable.

Plans for the future

We have plans to have the tiltmeters alongside recording gravity meters in an array of geodynamic stations of broad frequency range (figure 5), in order to study crustal movements by tidal forces, atmospheric pressure, ocean loading and possibly recent tectonic movements such as the process of land uplift in Fennoscandia.

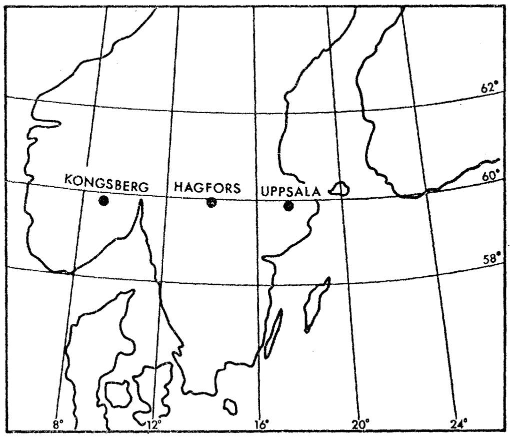

Figure 5. Array of geodynamic stations of broad frequency range.

One station will be placed in the mine of Kongsberg, Norway alongside long-period seismographs. Another station will be installed at the Swedish seismological array observatory at Hagfors. At the Uppsala station recording will be continued and attempts will be made to increase the sensitivity and to broaden the frequency range.

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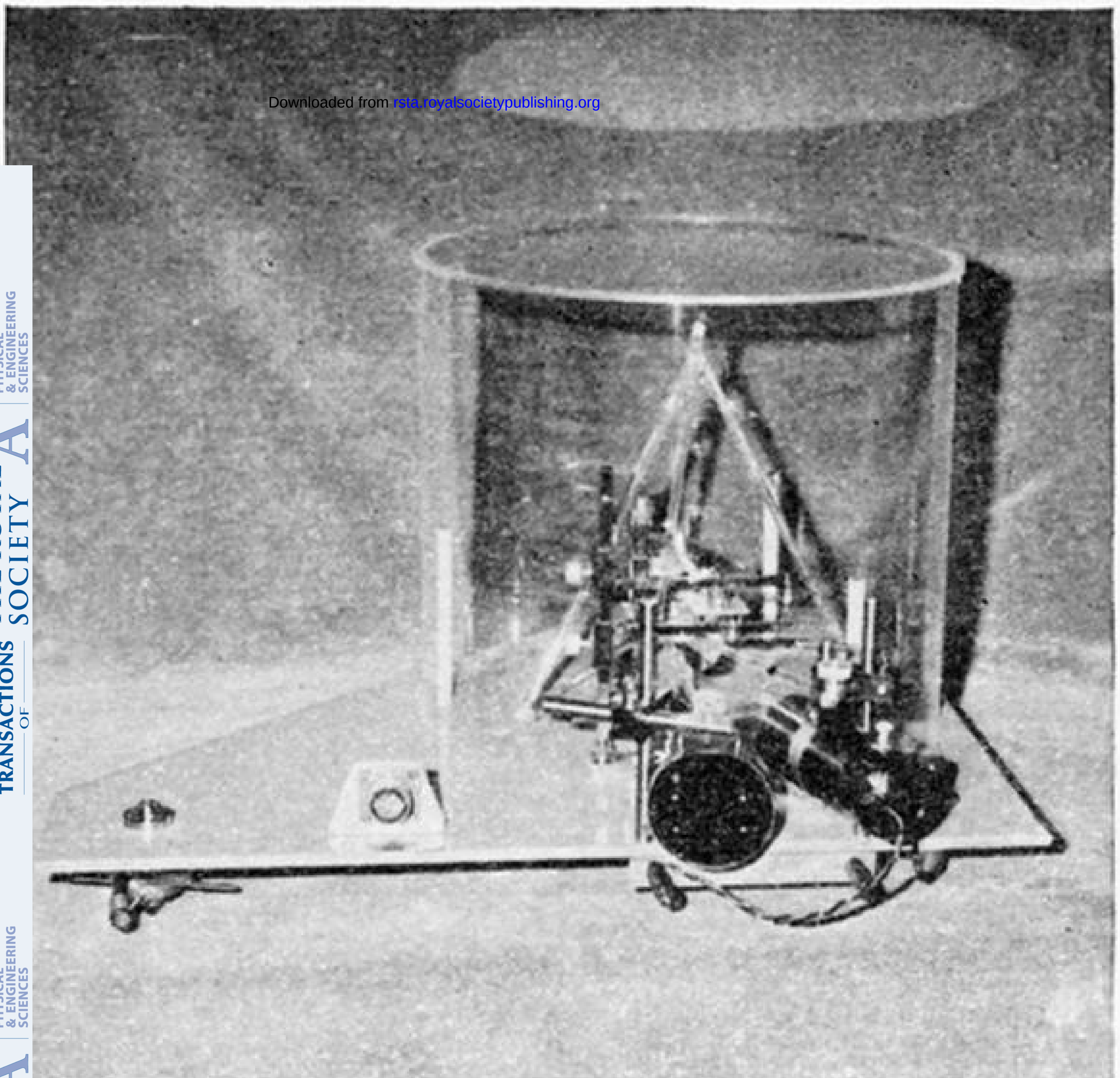
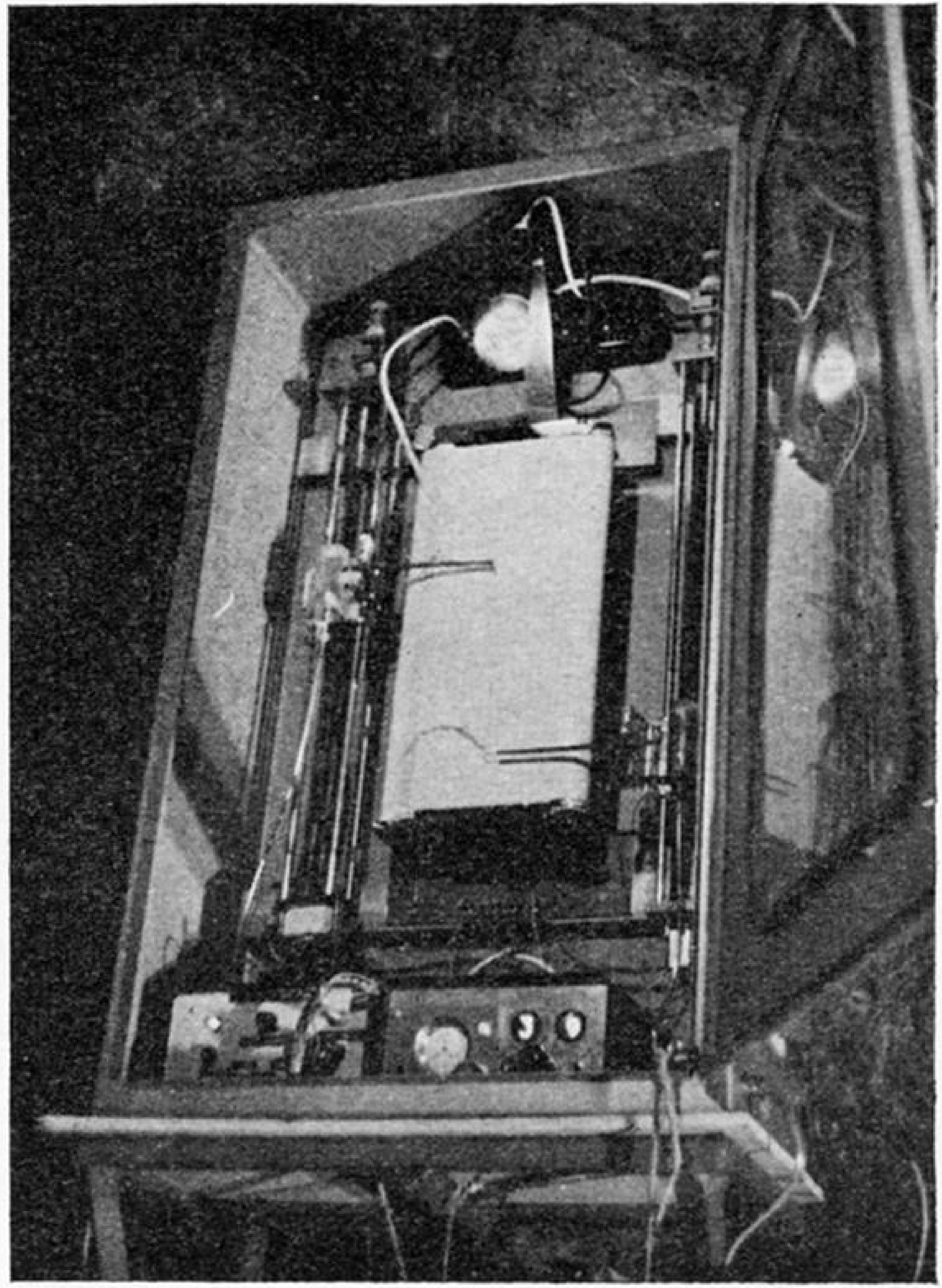


(*a*)



(*b*)

FIGURE 3. Photographs of (*a*) a pendulum and (*b*) a compensation system with recorder and quartz clock.

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