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Modern Seismometric Instruments

by

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MODERN SEISOMETRIC EQUIPMENT*

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The article describes seismometric equipment developed in recent years at the Seismological Institute of the Academy of Sciences USSR. For recording ground displacements during earthquakes there has been developed a new type of seismograph with galvanometric registering; for recording dynamic ground deformations - an electromagnetic extensometer.

There are presented theoretical fundamentals relative to the instruments described and their characteristics, and their scope of their utilization is indicated.

Until recently the principal attention of seismologists was directed to the study of the internal structure of the earth and only to a small extent toward investigating the physics of the earthquake proper. This is explained, among other reasons, also by the fact that the method of the study of internal earth structure is characterized by a relative simplicity. It is based on an analysis of the durations of progress of elastic waves from the focus of the seismic stations. In this all that is required of the seismograph is, that the seismogram produced by it makes it possible to differentiate clearly the moments of arrival of separate wave groups at the point of observation. Such equipment was available to the founders of modern seismology and to their immediate successors.

In recent time the problems faced by seismology have been expanding. For the study of the internal structure of the earth more precise methods are drawn upon; the current problem has become the study of phenomena taking place at the very focus of the earthquake. The demands on seismic equipment have increased accordingly.

B. B. Golitsyn considered that the basic task of seismometry is the recording of displacements of a point of the earth's surface during an earthquake. This task remains a fundamental one, even at the present time, and as yet is far from being fully resolved. The fact of the matter is, that in the course of an earthquake there are generated elastic waves of widely divergent periods - from fractions of a second to tens of minutes. To encompass this entire range of periods by means of a single instrument does not appear to be practicable, and evidently at present there is also no need for it. In the study of distant earthquakes the first phase is of primary interest; the periods of ground oscillations in these instances rarely exceed 6 seconds. Near-by and local earthquakes display ground oscillations the period of which is from 0.2 to 5-6 seconds. Hence the attempt at an accurate reproduction of the ground oscillations can be limited to this section of the seismic spectrum.

Of considerable interest are also the velocity and acceleration of a point of earth's surface, as well as its deformations on passage of seismic waves. However, in physical seismology these quantities are as yet of a subordinate significance.

The simplest and most reliable apparatus for recording oscillations of the earth's surface is the pendulum seismograph with a direct optical recording system (that is without any intermediate mechanical amplification levers). In order to reduce to a minimum the distortions caused by the device, it is indispensible that the amplitude of the pendulum oscillations be little affected by frequency of impelled oscillations, and that the phase approximate zero or π.

Considering the frequency and phase characteristics of the seismograph it follows that quality of registration is improved with increasing period and decreasing damping of the pendulum.

The period can be increased by two methods - by astatization and by increasing the reduced length. Astatization is a very effective means, but, of course, it has a natural limit in the proximity of which the pendulum loses stability. Increase in the reduced length can be made fairly considerable, but with it, amplification of the system is correspondingly decreased, which compels us to resort to electrical recording methods; the technical possibilities for which are sufficiently diversified. However, all electrical methods of measuring small displacements, with the exception of the induction method, require external sources of current. Conditions of seismic station observations, as a rule exclude the possibility of utilizing such sources, since this would greatly complicate the organizational aspects of seismic work. For this reason B. B. Golitsyn in devising his well known seismographs, has utilized the induction method.

B. B. Golitsyn's seismographs operate in accordance with the diagram shown in figure 1.

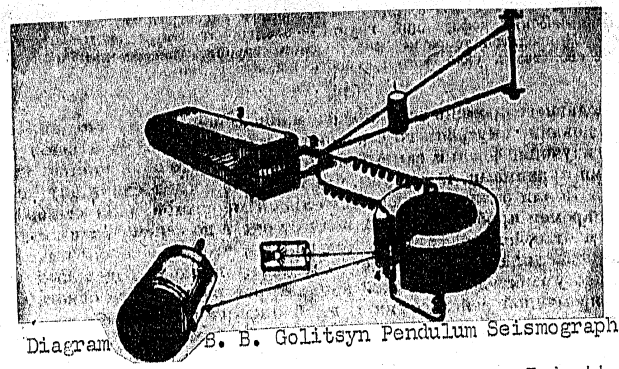


Fig. 1: Diagram B. B. Golitsyn Pendulum Seismograph with galvanometric registering device: 1. Pendulum, 2. Induction Coil, 3. Permanent Magnet, 4. Galvanometer.

Pendulum 1 supports at the end of an arm the induction coil 2. The latter is located within the field of a permanent magnet 3. The induction coil is connected to the electro-magnetic mirror galvanometer 4. The circuit is assumed non-inductive. Thus, within the circuit the current is proportional to the velocity of the motion of the coil within the magnetic field.

The action of this system is determined by the conjoint differential equations

$$\ddot{\theta} + 2\varepsilon\dot{\theta} + n^2\theta = -\frac{\ddot{x}}{l_0} + k\frac{I_1}{I}\dot{\varphi}$$

and

$$\ddot{\varphi} + 2\varepsilon_1\dot{\varphi} + n_1^2\varphi = k\dot{\theta},$$

wherein θ and φ, respectively, are the angle deflection of pendulum and galvanometer; ε and ε_1, the corresponding damping coefficients; n and n_1, - angular frequencies; l_0 - reduced length of the pendulum; I and I_1, - the inertia movements of pendulum and galvanometer, respectively; k- conversion factor of galvanometric recording; $\ddot{x}(t)$ ground acceleration at the point of installation of the pendulum.

In designing his instruments, B. B. Golitsyn assumed the inertia movement I of the pendulum to have a value greatly exceeding the movement of Inertia I_1, of the galvanometer. Hence the Second member in the right hand portion of the first of the above equations, is omitted by Golitsyn. In other words, the Golitsyn system is characterized by lack of correlation between pendulum and galvanometer. A second characteristic of this system is the peculiar selection of the other parameters; i.e., Golitsyn makes the period of the pendulum equal to that of the galvanometer, and sets both of them up at the limit of aperiodicity. In such a case $\varepsilon = \varepsilon_1 = n = n_1$, and the analytical expression of frequency characteristic for the entire unit assumes an extremely simple form.

A graphic representation of frequency and phase characteristics of Golitsyn's system is shown in figure 2.

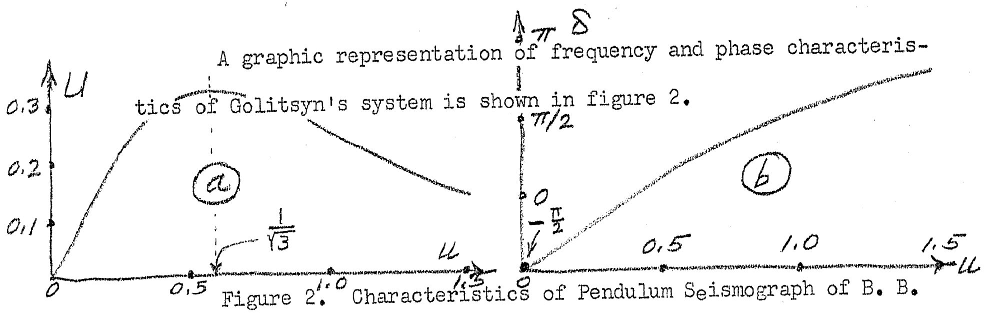


Figure 2. Characteristics of Pendulum Seismograph of B. B. Golitsyn: a. frequency, b. phase.

The extreme lack of uniformity of these characteristics limits the scope of the problems which can be solved by means of such instruments, and deprives their recordings of any definite mechanical meaning. Nevertheless these seismographs served their purpose, since the excellent seismograms obtained by their use make it possible to determine with sufficient accuracy the azimuth of the epicenter and to delineate movements of initiation of individual groups of seismic waves.

Subsequent investigators (Wenner, Ribner, Schmerwitz, Coulomb and Grenet) expended much effort to improve the properties of Golitsyn's instruments.

The entire theory of galvanometric recording has been reviewed and developed. Special attention has been given to use of correlation between pendulum and galvanometer. As a result of these efforts there has been attained a fully satisfactory frequency characteristic, an adequate phase characteristic, however, was not obtained.

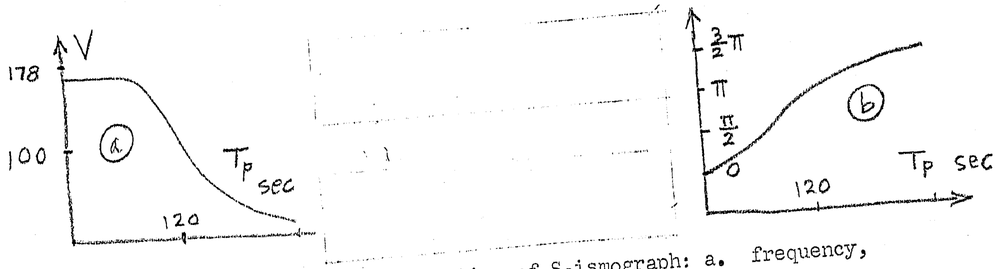


Figure 3. Characteristics of Seismograph: a. frequency, b. phase. Pendulum period 5 seconds, damping - 7.3; galvanometric period - 120 sec., damping - .51. (From Grenet and Coulomb).

All of the above authors have used exclusively long-period galvanometers with a freely suspended mobile coil. These instruments do not withstand jarring, and therefore can not be utilized to record local and many of the near-by earthquakes.

Thus these contributions did not provide the necessary solution of the basic problem of seismometry.

The authors of the present article have made it their goal to provide a type of seismograph which would meet the present-day requirements of seismology, that is one which reproduces ground oscillations, during an earthquake, with a period from 0.2 to 5 seconds, with amplitudinal and phase distortions not exceeding 5 percent of the values being measured. In so doing we have reverted to the initial system of B. B. Golitsyn, that is we have abandoned the use of a correlation between pendulum and galvanometer.

A more detailed study of the problem has shown that frequency characteristics can be conveniently represented in the form of:

$$U = \frac{U_M}{2D_1} \cdot \frac{1}{\sqrt{1+\xi}}$$

where

$$U_M = \frac{1}{\sqrt{(1-u^2)^2 + 4D^2u^2}}$$

is the frequency characteristic of the pendulum proper, and

$$u = \frac{T_p}{T} = \frac{\text{Period of ground oscillations}}{\text{Period of free oscillations of pendulum}}$$

$D = \frac{\varepsilon}{n}$ Constant of pendulum damping

$D_1 = \frac{\varepsilon_1}{n_1}$ Constant of galvanometer damping

The value ξ given by the expression

$$\xi = \frac{1}{4D_1^2}\left(\frac{1}{u_1} - u_1\right)^2$$

where

$$U_1 = \frac{T_p}{T_1} = \frac{\text{Period of ground oscillations}}{\text{Period of free oscillations of the galvanometer}}$$

The quality ξ is the one causing a distortion of the frequency characteristic of the entire unit with respect to the frequency characteristic of the pendulum.

It is apparent that one must strive to render the value

$\xi < 1.$

In such case

$$U = \frac{U_M}{2D_1} \quad ;$$

that is, the frequency characteristic of the seismograph having a galvanometric recording system will be similar to the frequency characteristic of a simple mechanical pendulum.

In order to make ξ small over a sufficiently wide range of ground oscillation frequencies, it is necessary to increase the constant of galvanometer damping D_1. For our purpose it suffices to maintain D_1 within the limits from 10 to 15.

It can be readily shown that if these conditions are maintained the phase characteristic of the entire unit will also coincide with the phase characteristic of the pendulum proper.

Based on these considerations D. P. Kirnos has devised new designs of seismographs.

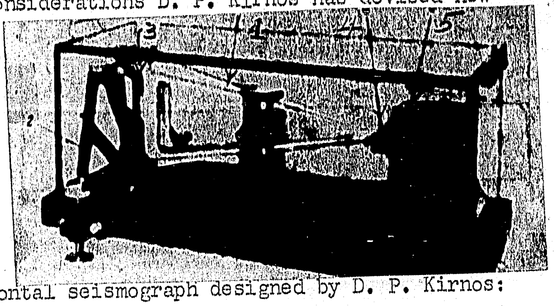


Figure 4. Horizontal seismograph designed by D. P. Kirnos: 1. Pendulum, 2. Stand, 3. Leaf springs, 4. Induction coil, 5. Permanent magnet.

The seismograph for recording horizontal displacements of the ground is shown in figure 4. Pendulum 1 is suspended from stand 2 on two pairs of leaf springs 3. Induction coil 4 is fastened at the end of the pendulum arm and is located within the clearance of the permanent magnet 5. Extensive and detailed computation and experimental work has been conducted to ensure the stability of the pendulum at a large period. The reduced length of the pendulum is of about 26 centimeters. The period of free oscillations can be brought up to 25 seconds. Damping of the pendulum $0.4 \leq D \leq 0.5$. Over the entire seismic range of period the instrument is free of parasitic oscillations.

The design of the galvanometer differs somewhat from those of the conventional systems. The mobile coil is suspended by means of two tension springs and is immersed in a clear oil. As a whole it is reminiscent of a low frequency loop of greatly expanded dimensions. The damping constant of the galvanometer can be brought to 50-60. With only electromagnetic throttling, the damping constant is equal to 10-12. Sensibility of the galvanometer is of about

$1 \cdot 10^{-8}$ ampere per millimeter. This galvanometer is not affected by jarring and can be utilized even within the epicentral zone.

Figure 5 shows a comparison of the frequency and phase characteristics of the following seismographs: (a) Nikiforov system with direct optical recording; the purpose of the instrument is recording of local and near-by earthquakes; (b) Golitsyn system with galvanometric recording; the instrument is intended for recording distant earthquakes; c) Kirnos system with galvanometric recording; the instrument is adapted for recording local and near-by as well as a major portion of distant earthquakes.

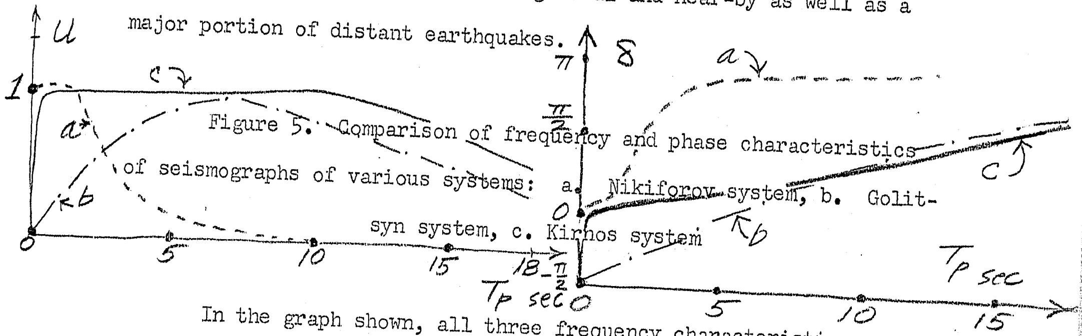


Figure 5. Comparison of frequency and phase characteristics of seismographs of various systems: a. Nikiforov system, b. Golitsyn system, c. Kirnos system

In the graph shown, all three frequency characteristics are reproduced on the same scale.

Figure 6 shows a vertical seismograph designed by Kirnos. Its reduced length is of 150 centimeters. The stable period of natural oscillations up to 15-20 seconds.

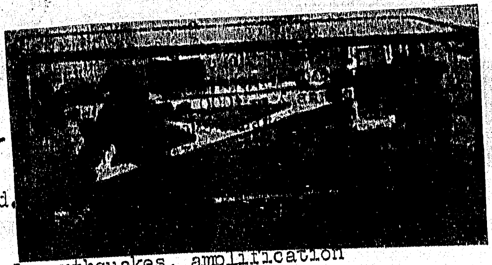
Figure 6. Vertical seismograph designed by D.P. Kirnos.

[Figure 6 is on the next page, top.]

Amplification of these seismographs can be brought up to 3000-4000. For seismical purposes this amplification is excessive, and has to be reduced to 1000.

Ground oscillations with periods from 0.2 to 5 seconds, are rendered by these instruments with distortions not in excess of 5

Figure 6



per cent of the quantity being measured.

For the recording of severe local earthquakes, amplification of 1000 is obviously not suitable. With this purpose in view a mirror is fastened near the pendulum axis, by means of which direct recording is made using a special recording device. Amplification in this case is equal to 4.

The seismographs described above are installed and in normal operation at seismic stations in Tadzhikstan: Stalinabad, Obi-Garm, Murgab, Kulyab and also at Yalta. During the current year they are to be installed also at a number of our other seismic stations.

Records obtained by means of these instruments have demonstrated the possibility of their use in the determination of the angle of egress of seismic radiations. Appearance of individual groups of seismic waves is indicated with great clarity; as a result it was found possible to arrive at a number of interesting conclusions relative to peculiarities in the internal structure of certain districts of Tadzhikistan.

The possibilities inherent in these instruments are not confined to those pointed out. Thus, for example, should it become necessary to record not the displacement but the velocity of the ground during an earthquake, it would be sufficient to substitute for the above-described aperiodic galvanometer a short-period galvanometer with damping approximating the limit of aperiodicity. If it is necessary to record ground acceleration, it will be sufficient to make more rigid the suspension device of the seismograph.

Study of earthquakes by means of instruments is not limited to investigations of displacement of earth's surface, and of its derivatives, in time. It is expedient to supplement these investigations by a study of deformations, arising within the ground on the passage of seismic waves. This is necessary also because such deformations are important not only in physical seismology but also in seismic geology and engineering seismology.

The few attempts undertaken in this direction at various times by foreign scientists, up to now have not yielded a satisfactory result. This is explained on the one hand, by the fact that the necessity of studying deformations has not been sufficiently realized, and on the other, because a measurement of deformations is considerably more difficult than measurement of absolute displacements.

As is known, measurement of deformations is reduced to a measurement of a relative transposition of two proximate points of the environment. In the simplest instance this relative transposition Δu is given by the formula:

$$\Delta u = \frac{\partial u}{\partial x} dx,$$

wherein u is the absolute transposition of one of the points, while dx is the distance between the points selected.

Let us now assume, that within an unlimited medium, along the axis X there is propagated the wave

$$u = u_0 \sin 2\pi \left(\frac{t}{T} - \frac{x}{\lambda}\right)$$

where u_0 - is the amplitude, t - time, T - period of the wave, X - current coordinate, λ - wave length.

Change of length of the selected portion will be:

$$\Delta u = \frac{\partial u}{\partial x} dx = u_0 \frac{2\pi}{\lambda} \cos 2\pi\left(\frac{\tau}{T} - \frac{x}{\lambda}\right) dx.$$

Comparing the maximum value of this expression with the maximum of absolute displacement, we have:

$$\frac{(\Delta u)_{MAX}}{u_0} = -\frac{2\pi}{\lambda} dx$$

This is a very small quantity. Actually the length of seismic waves is measured in kilometers and tens of kilometers; the length of the base - by several meters. Assuming λ = 1000 meters (usually much higher) and dx = 2 meters, we find that the relative displacement of two such points will be about 100 times less than their absolute displacements; and this in the most favorable instance.

For the recording of deformations we have designed equipment which also does not require external sources of electrical current. The corresponding instrument is called a seismic extensometer; a diagram of its configuration is shown in figure 7.

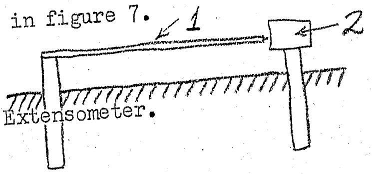


Figure 7. Diagram of Seismic Extensometer.

Two iron pipes are fixed in the ground at a distance of 1.5 meters, from each other. To one of the pipes is fastened a horizontal rod 1, to the other an electromagnetic transformer of induction type, 2. During an earthquake the distance between the pipes changes, as a result of which the horizontal rod acts upon the electromagnetic transformer (figure 8). Thus the flux of magnetic induction which permeates the induction coil changes. This change of flux is proportional to the value of relative convergence or divergence of the pipes, towards or from each other.

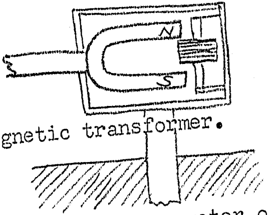


Figure 8. Diagram of Electromagnetic transformer.

The induction coil is connected to the galvanometer of the above-described type. With sufficiently extensive damping such a galvanometer operates as a fluxometer, that is, its deviations are proportional to the changes of the magnetic flux, and consequently, in the final analysis, to the relative transposition of the pipes.

If three of such extensometers are placed at right angles to one another and are connected in series to a galvanometer of the above-mentioned type, deviations of the latter will be proportional to changes of cubic unit of the ground along whose edges are located the extensometers. Such an instrument may be called a seismic dilatometer. By its use there can be obtained a recording of purely longitudinal waves, a recording not complicated by the presence of transveral waves.

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Extra Thermoprints
of Figures 1, 4, 6.

Fig 1

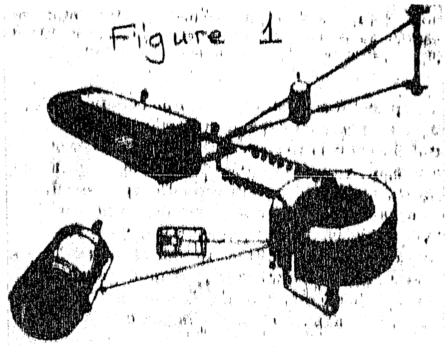

Fig. 4

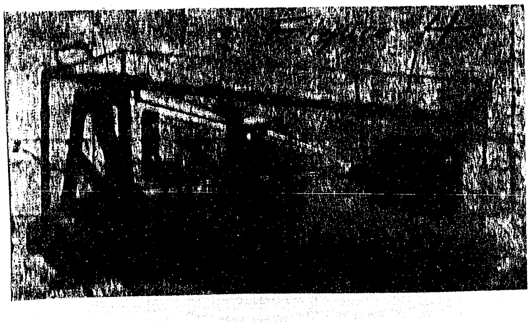

Fig. 6