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SEISMOLOGY at KEW OBSERVATORY

By A. W. LEE, D.Sc.

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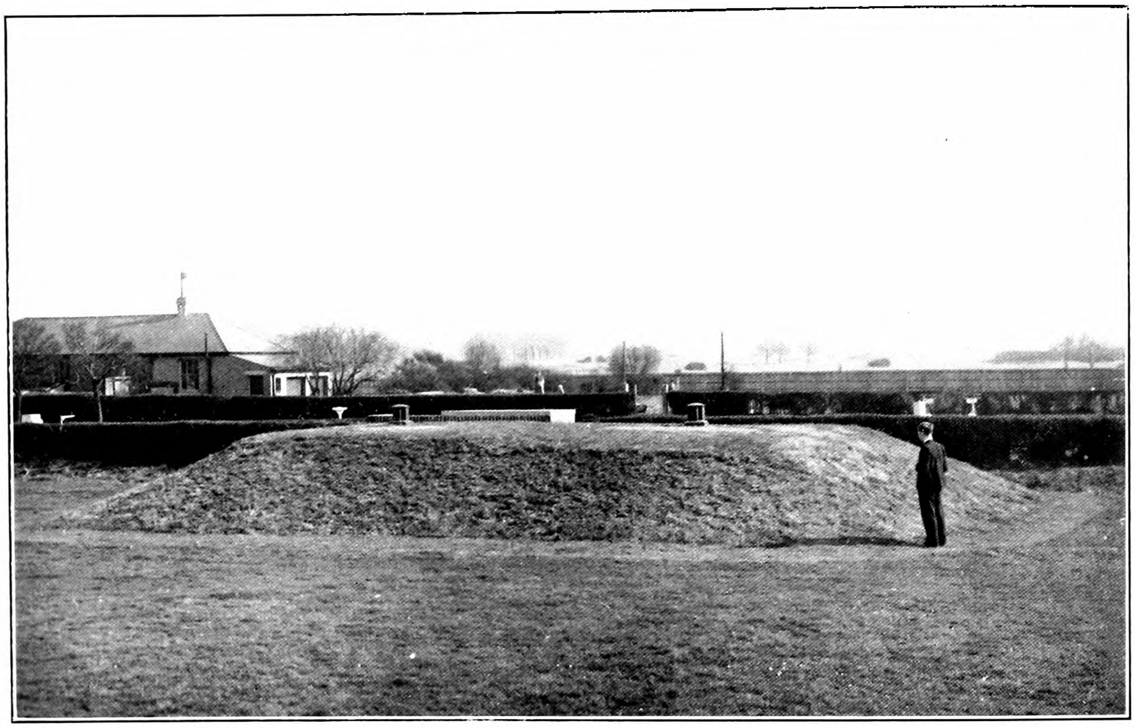

FIG. 1.—THE SEISMOGRAPH HOUSE AT KEW OBSERVATORY FROM WEST-SOUTH-WEST.

SEISMOLOGY AT KEW OBSERVATORY

PART I: THE SEISMOGRAPH HOUSE AND THE INSTRUMENTS

§ 1—THE NEED FOR THE NEW SEISMOGRAPH HOUSE

It has been recognised for many years that the records of sensitive seismographs show disturbances caused by strong winds in the vicinity, even when the instruments are housed in well-closed rooms and protected from draughts. These disturbances have been very troublesome in the records of the Galitzin seismographs at Eskdalemuir from 1910 to 1925 and subsequently at Kew. The disturbances of the horizontal seismographs, recording the N-S and E-W components of the earth movement, are more marked than the disturbance of the vertical seismograph. At Kew the instruments were housed until 1937 in the basement of the main Observatory building, the pendulums being placed on a massive concrete pillar which is isolated from the floor of the basement and rests on gravel. A discussion of the mechanism by which the wind disturbances are generated was published (1)* in 1928. The explanation put forward was that, as the whole building rocks in strong winds, there is yielding of the underlying stratum on which the foundations rest, and the movement is conveyed to the seismograph pillar.

This hypothesis was tested in 1932, when a Milne-Shaw seismograph was borrowed from the Science Museum, South Kensington. The Milne-Shaw seismograph was placed, in the first instance, on the floor of the seismograph room in the basement of the Observatory, and a few feet from the pillar on which the Galitzin instruments stood. It was found that on windy days the Milne-Shaw seismograms showed disturbances comparable with those on the Galitzin horizontal component records. In September, 1932, the Milne-Shaw instrument was transferred to an underground building, which had just previously been made for use in atmospheric electrical observations and was situated about a hundred yards south-south-east of the main building. On later occasions when the wind disturbance was prominent in the Galitzin records the Milne-Shaw seismograms were not affected, showing that the yielding of the subsoil did not extend far from the main building.

In view of this demonstration that the efficiency of the seismographs could be improved a scheme was put forward for the provision of a second underground house especially for seismological recording. The new building was constructed in 1936, and was ready for occupation early in 1937. The removal of the seismographs presented a suitable opportunity for making a number of improvements to the instruments. The two Wood-Anderson seismographs, which were constructed in the Observatory workshop in 1933 and 1935, and which had been operating in the main building, were transferred in February to the new underground seismological house. The Galitzin horizontal seismographs were moved in April, and the vertical seismograph in September, 1937.

*The numbers in brackets refer to the bibliography on p. 20.

§ 2—THE NEW BUILDING

(*a*) *Details of construction.*—The new seismograph house is rectangular with the walls approximately north-south and east-west ; it is situated about a hundred yards south-west by south of the main Observatory building. The walls are of brick carried on a floor of reinforced concrete about 15 in. in thickness ; the main walls, of thickness $13\frac{1}{2}$ in., are separated by a 2 in. cavity from $4\frac{1}{2}$ in. inner walls. The surfaces are rendered waterproof by a thick coating of asphalt. The floor is about 5 ft. below the level of the surrounding paddock. The ceiling is covered by soil to a depth of about 2 ft. and turfed, the level of the turf being about 5 ft. above the surroundings. The entrance to the building is reached down a flight of steps ; the paddock in the vicinity is liable to flooding when the Thames is exceptionally high, and a barrier is provided at the top of the steps to prevent flood water from entering the building. Rainwater which drives beneath the concrete roof over the steps

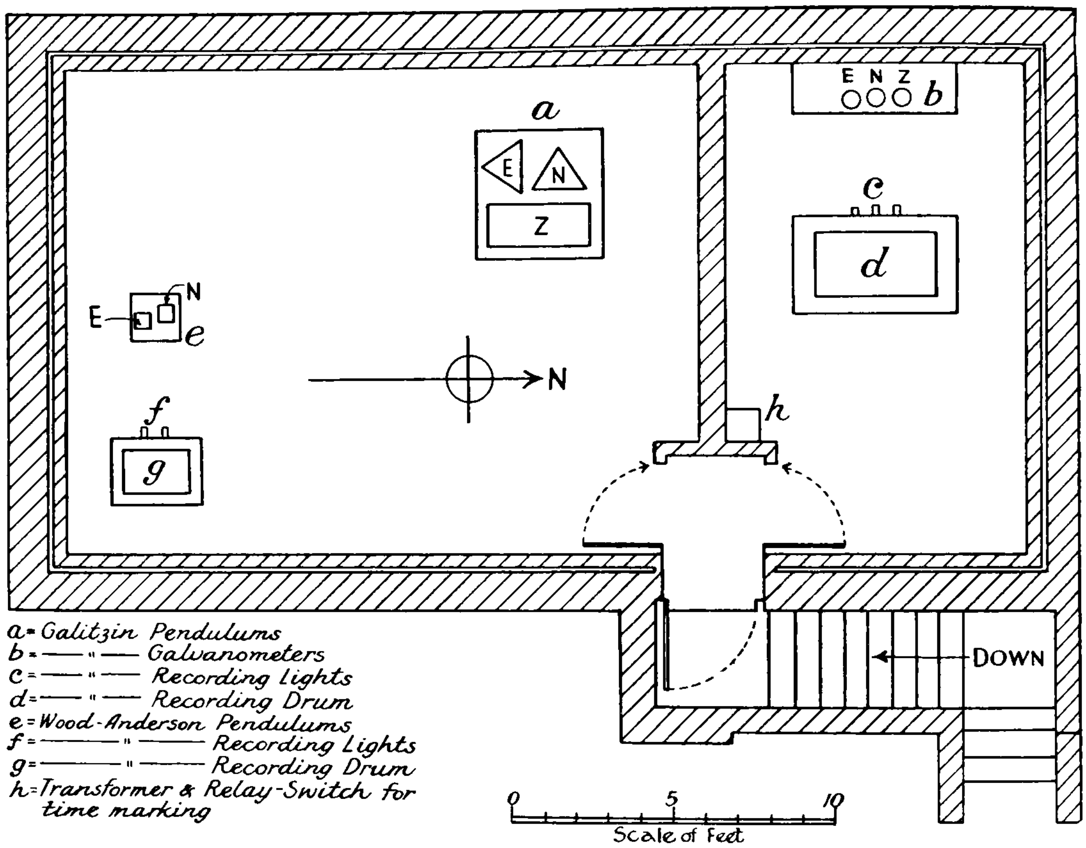

FIG. 2.—ARRANGEMENT OF SEISMOGRAPHS IN THE SEISMOGRAPH HOUSE.

collects at the bottom in a sump and is removed when necessary. A picture of the building taken from the west-south-west is given in Fig. 1, and a plan in Fig. 2 shows the disposition of the instruments.

The building contains two rooms opening from a small entrance lobby on the east side. The rooms are ventilated and they are heated by electric radiators which can be controlled by thermostats. The south room, 20 ft. by 15 ft., contains the Galitzin pendulums and the Wood-Anderson seismographs ; the galvanometers and recording drum for the Galitzin instruments are installed in the north room which is smaller, 10 ft. by 15 ft. There is ample room for additional seismographs if the number of instruments in operation should be increased.

Concrete pillars for the seismographs are built directly on the floor in the south room, and azimuth lines showing north-south and east-west have been scribed on the tops of the pillars. The pillar for the Galitzin pendulums is 4 ft. 6 in. by 4 ft. 6 in.

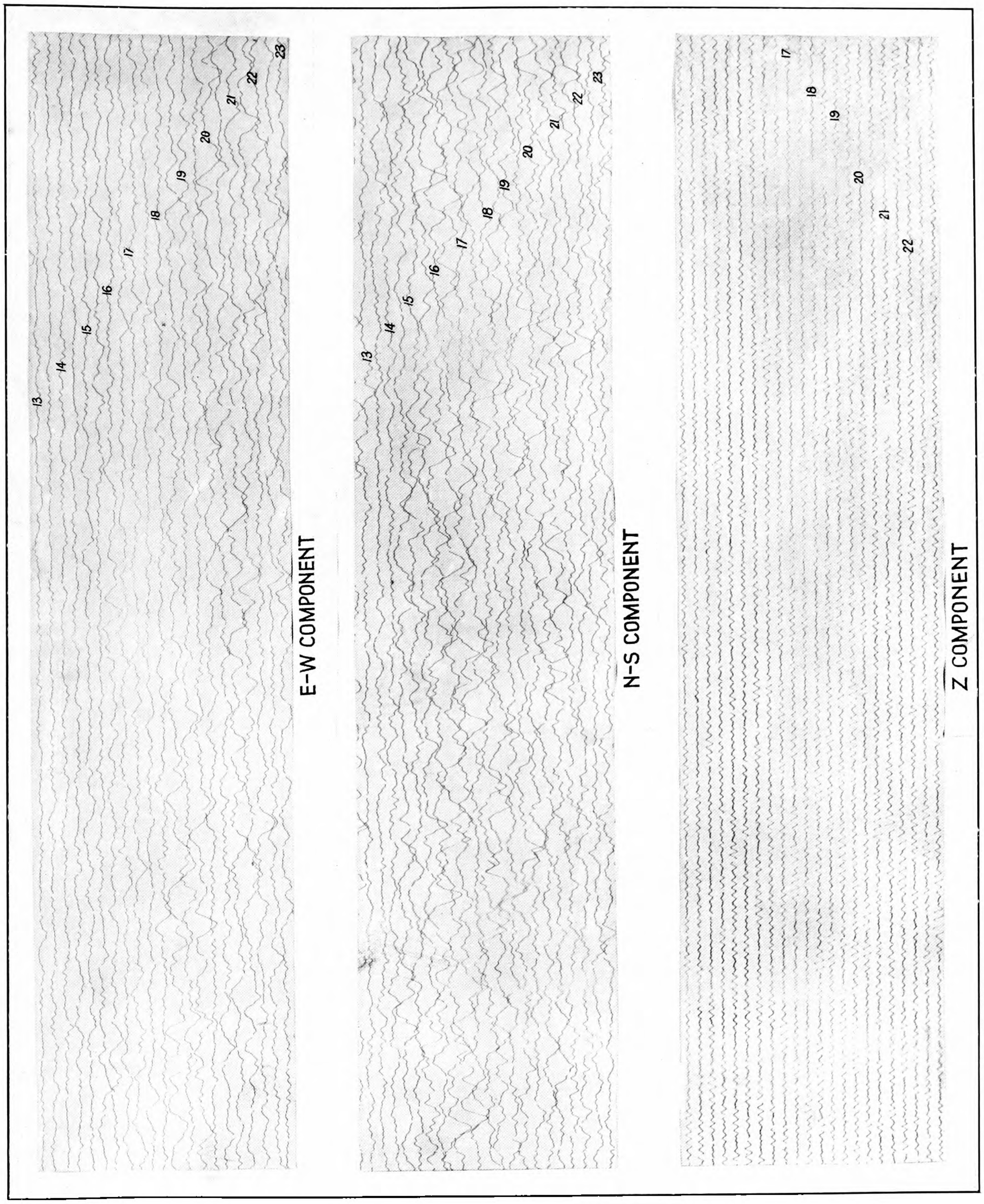

FIG. 3.—PORTIONS OF GALITZIN SEISMOGRAMS, KEW OBSERVATORY, FEBRUARY 16, 1935, SHOWING MICROSEISMS AND THE EFFECT OF VERY STRONG LOCAL WIND.

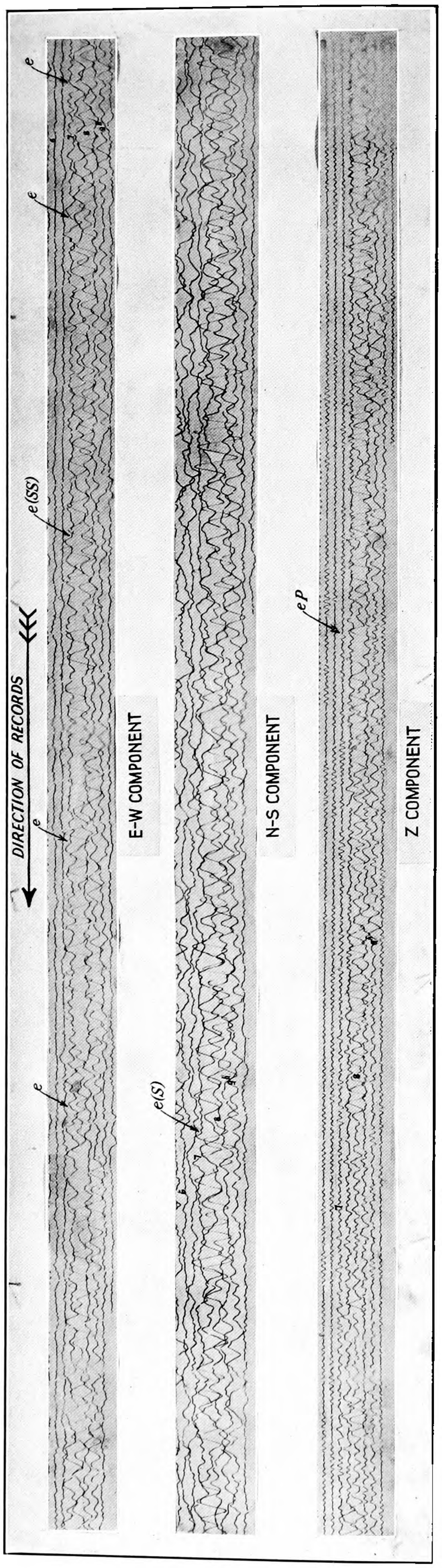

FIG. 4.—KEW SEISMOGRAMS FOR EARTHQUAKE SOUTH OF SUMATRA, FEBRUARY 10, 1931.

and of height 2 ft.; that for the Wood-Anderson instruments is 1 ft. 6 in. by 1 ft. 6 in. and 2 ft. 9 in. in height. The galvanometers and recording drum in the north room are placed on slate slabs cemented to concrete pillars.

Low tension electric current for recording with 6 volt bulbs is available in each room, the supply being taken from the 240 volt alternating current mains through a transformer of capacity 40 watts. The low tension circuit passes through a mercury switch operated by a solenoid connected to the Observatory standard clock (Hope-Jones Synchronome, No. 1901). The switch is an Isenthal Vertex, Type V.15.R, consisting of a sealed glass tube containing an armature floating on mercury. With no current in the solenoid the low tension circuit through the switch is complete, but when the solenoid is excited the armature is raised and the mercury level is lowered sufficiently to break the circuit. The time-breaks are of 2 sec. duration at the minute and 4 sec. at the hour. The timing is controlled from daily comparisons with the Greenwich time signals broadcast from Droitwich, and is accurate to within a few tenths of a second.

(*b*) *Freedom from wind disturbance.*—Since the Galitzin seismographs were moved to the underground seismological house the records have been examined closely; it was found that the seismograms obtained in the new building are not disturbed during strong winds.

Sections of the records obtained from 13h. to 23h. on February 16, 1935, with the instruments in the main building, are shown in Fig. 3. During the interval covered by the seismograms the mean hourly wind speed was from 9·0 m./sec. to 12·5 m./sec., the maximum occurring from 18h. to 19h.; the wind was south-westerly until about 18½ h., when it veered and became westerly. The horizontal component seismograms were badly disturbed by the wind, and the records show how the effect varied with the wind direction; before the wind veered the disturbance was greater on the N.-S. than on the E.-W. component, but afterwards the effects upon the two components were nearly equal. It is obvious that if an earthquake were recorded during such disturbance the records of the horizontal components would be of little value. In the analysis of such earthquake records the only phases recognisable would be those producing vertical displacements, and the phases characterised by horizontal movements of the ground would be lost in the wind disturbance.

The earthquake which occurred south of Sumatra on February 10, 1931 is of interest, being one of the shocks chosen for special study by B. Gutenberg and C. F. Richter in their investigation of travel-times (2). The Kew seismograms for this earthquake (Fig. 4) show how the difficulties of interpretation of the records were increased by the wind disturbance. The mean hourly wind speed was about 10 m./sec. and the direction south-westerly. The onsets marked in the records are those selected for tabulation in the Kew Seismological Bulletin:—

Phase	Component	Time on record	G.M.T.
eP	Z.	6h. 48m. 1s.	6h. 48m. 32s.
e	E.-W.	6h. 59m. 1s.	6h. 59m. 32s.
e(*S*)	N.-S.	6h. 59m. 33s.	7h. 0m. 4s.
e	E.-W.	7h. 1m. 42s.	7h. 2m. 13s.
e(*SS*)	E.-W.	7h. 8m. 8s.	7h. 8m. 39s.
e	E.-W.	7h. 14·2m.	7h. 14·7 m.
e	E.-W.	7h. 19·6m.	7h. 20·1m.

The phases *S* and *SS* were entered in brackets to indicate that the identifications were uncertain; later information has shown that these identifications were correct. The original analysis of these records was made before any information had been received regarding the epicentre of the earthquake or its distance from other observatories. Under these circumstances it was impossible to decide whether some of the movements shown in the records were due to the earthquake waves or to the wind disturbance.

Fig. 5 shows portions of the seismograms obtained during the storm of January 14-15, 1938, after the instruments were moved to the new building. The wind was southerly, the hourly mean speed being about 10 m./sec. before 5 h. on the 15th, increasing to more than 14 m./sec. from 8h. to 10h. Gusts exceeding 20 m./sec. were recorded frequently after 5h. Thus the wind was considerably stronger than on February 16, 1935, or on February 10, 1931. The records of Fig. 5 show that neither of the seismographs in the new building was affected by these strong winds, and it is clear that the difficulties due to wind disturbance have at last been overcome.

§ 3—THE GALITZIN SEISMOGRAPHS

The Galitzin seismographs now in operation at Kew are of the original pattern manufactured at St. Petersburg by H. Masing. The horizontal instruments were presented to Eskdalemuir Observatory in 1910 by the late Sir Arthur Schuster, who completed the installation two years later by adding the vertical seismograph. The instruments, which were transferred to Kew Observatory in 1925, are still the only complete set of seismographs in the British Isles recording the three components of earth movement.

In each horizontal pendulum the weight of about 7 Kg. is carried by a Zöllner suspension, stability being obtained in the usual way by inclining the axis slightly from the vertical. The boom is extended beyond the weight, and passes between the poles of two pairs of powerful horseshoe magnets which are attached to the framework of the instrument. Coils of fine wire, carried by the boom between the poles of the magnets nearer to the weight, are joined in series and connected to the recording galvanometer. A large copper plate, attached to the boom and moving between the poles of the outer magnets, acts as a magnetic damper, induced currents in the plate tending to oppose the free motion of the pendulum.

The mass of the vertical pendulum is attached to a robust framework ; the whole of the moving system is supported by a large spiral spring, and attached through crossed Cardan springs to pillars from the base of the instrument. To attain a long free period, the supporting spring is attached to a point below the centre of gravity of the pendulum. The damping magnets, coils and recording galvanometer are similar to those of the horizontal instruments. Illustrations of the horizontal and vertical Galitzin instruments are given in G. W. Walker's " Modern Seismology "(3), and in various other textbooks.

The chief defect of the vertical seismograph in earlier years was the drift of the pendulum, due to the effect of temperature changes on the elasticity coefficient of the steel spiral spring. The first important change to be made after the instruments came to Kew was the replacement in 1928 of this spring by one made of elinvar, an alloy which has a temperature coefficient of elasticity about one-tenth that of steel. Since the new spring was brought into use the difficulty of keeping the vertical instrument in operation has been greatly diminished. A detailed report on the behaviour of the new spring has been published in a paper by F. J. Scrase (4).

Galitzin (5) examined the relation between the movements of the galvanometer and those of the earth. He showed that the relation is simplified if the pendulum and galvanometer are both critically damped and have the same free periods, and recommended that the seismographs should be adjusted to conform approximately with these conditions. The damping of a galvanometer depends upon the electrical properties of the circuit, and critical damping can be attained by inserting an additional resistance in series with the pendulum coils ; the resistance required is determined by the method given by Galitzin (p. 290). When the adjustments of the pendulum are nearly correct, a graphical method can be used for rapid evaluation of the difference between the periods of pendulum and galvanometer and of the damping of the pendulum (6). Free periods of about 24 seconds were chosen by Galitzin for horizontal instruments, with a view to keeping the magnification as large as possible for the surface waves of distant earthquakes, which were then regarded as the most important features of the records ; on the other hand the longest period which could be obtained with his vertical pendulum, without the instrument becoming unstable, was 12 or 13 sec.

The difference between the free periods of the horizontal and vertical seismographs increases the difficulty of interpreting the records. One of the major problems when the Kew seismographs were moved was to alter the instruments

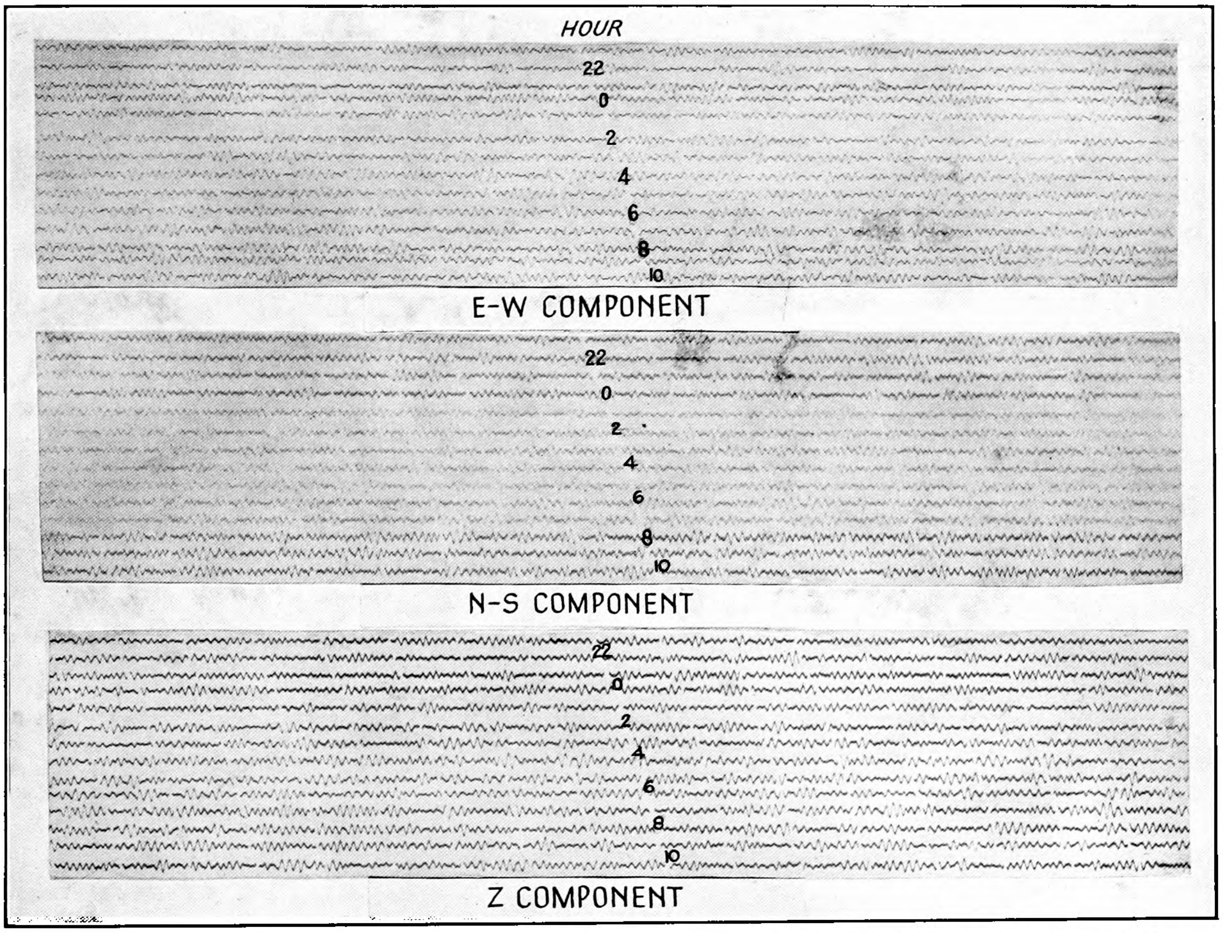

FIG. 5.—PORTIONS OF GALITZIN SEISMOGRAMS, KEW OBSERVATORY, JANUARY 14–15, 1938, SHOWING THAT THE RECORDS FROM THE NEW SEISMOGRAPH HOUSE ARE NOT DISTURBED DURING STRONG LOCAL WINDS.

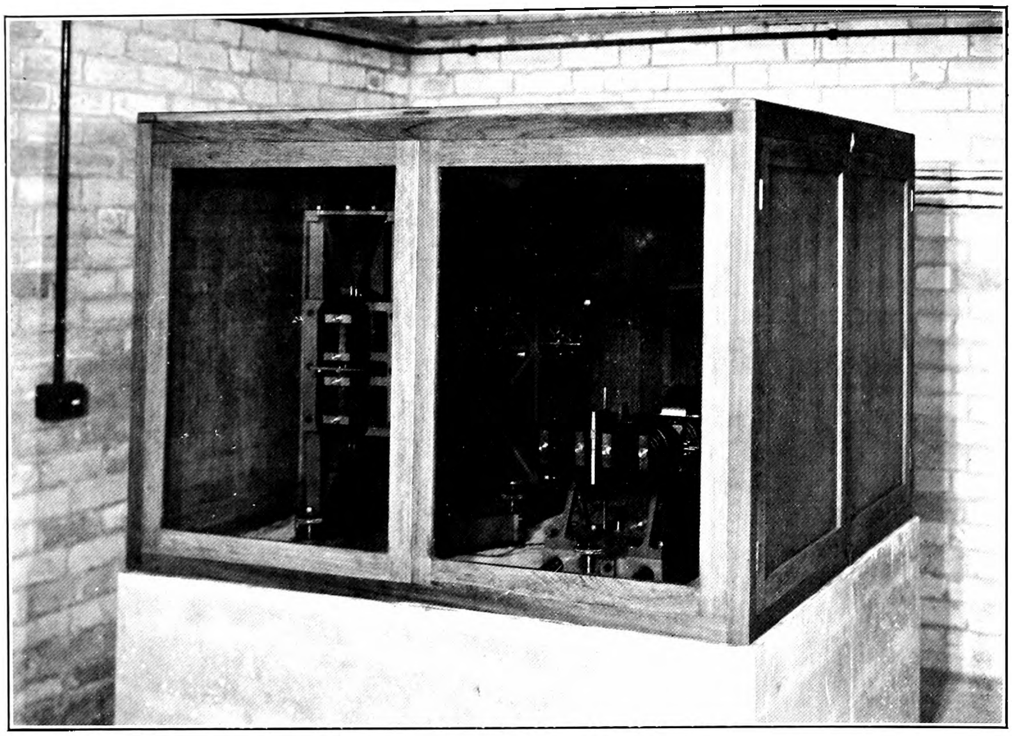

FIG. 6 (A).—SEISMOGRAPH PILLAR AND CASE CONTAINING PENDULUMS OF THE GALITZIN SEISMOGRAPHS.

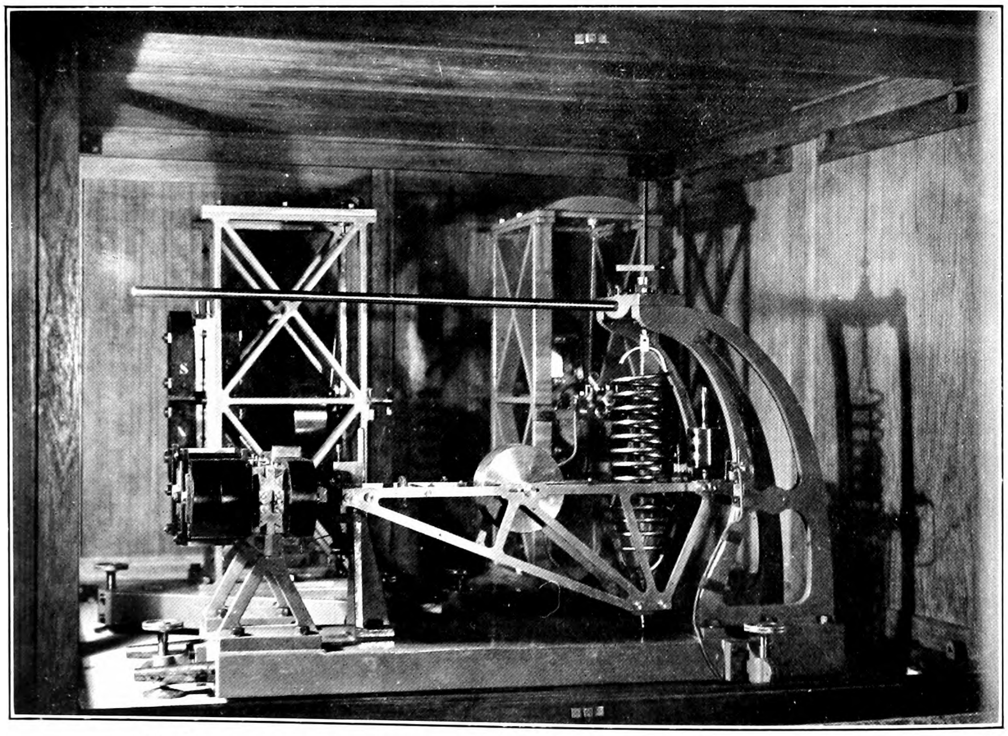

FIG. 6 (B).—GALITZIN PENDULUMS PHOTOGRAPHED FROM EAST SIDE OF CASE.

so that the records of the three components should be immediately comparable. The most direct method would have been to reduce the periods of the horizontal pendulums and galvanometers to 13 sec. in agreement with the vertical seismograph. New suspensions would have been required in the galvanometers, and it would not have been possible to recover the original adjustments if recording with the shorter periods proved unsatisfactory. An alternative method of securing close agreement between the three components without altering the galvanometers was therefore investigated. In this method each horizontal pendulum is adjusted to have a free period one-third of the galvanometer period, the pendulum and galvanometer both being critically damped. It is shown in Part II of this paper, that with the horizontal seismographs adjusted in this way their response is very nearly in agreement with that of the vertical.

Until 1937 three recording drums driven by clockwork were used with the Galitzin seismographs. A drum, large enough to take all three components and driven by an alternating current electric motor, was constructed in the Observatory workshop for use in the seismograph house. The new drum is of aluminium. A hard phosphor bronze driving rim screwed to one end of the drum rests on a small roller of stainless steel which is driven through a worm and large worm wheel from the synchronous motor. The motor, 200-250 volts and 60 kilocycles, is fitted with a device to ensure that it only rotates in one direction. Traversing is by a lead-screw and split-nut. A push button to cut off the electric supply is fitted as a precaution against damage, if the drum reaches the end of the traverse.

The one drum serves for all three components, the sheets of photographic paper being of size 36½ in. by 16¾ in. The drum rotates once an hour giving a time-scale on the records of 15 mm. per minute ; thus the time-scale is half that with the older drums which rotated twice an hour, and the confusion of the records due to overlapping of subsequent lines during large earthquakes (see Fig. 4) is reduced. The traverse is 4 mm. per hour. The motion of the recording sheet is much more uniform with the electrically driven drum than with the drums driven by clockwork. The complete specification and working drawings for the drum can be supplied to anyone interested. Apart from a difference in width, to allow for recording the three components instead of only two, the drum is similar to that used with the Wood-Anderson seismographs and shown in Fig. 7b.

Improvements in the Galitzin type of instrument covers were badly needed. Apart from the disadvantages of having the pendulums out of sight, the old metal covers were difficult to handle ; at times during adjustments they had to be removed and replaced many times in a day, and the risk of damage to the pendulums was considerable. A large new case to contain the three pendulums was constructed for use in the new building. The case consists of a heavy framework of teak bolted down to the concrete pillar, the joint at the bottom of the case being sealed with thin cement. Each of the four sides consists of two panels ; those on the south side are of plate glass, the others are of teak. The top is also panelled in teak. The panels on the east and west sides are hinged to the framework and can be opened for adjustments ; those on the north and south sides, being held by turnbuckles, can easily be removed if necessary. The case furnishes complete protection of the pendulums from draughts, and small variations of the room temperature do not affect the instruments. The photographs of Fig. 6 show (a) the pillar for the Galitzin instruments and the pendulums inside the case, and (b) the view of the pendulums with the east side of the case opened.

The Galitzin instruments now on the market (7) have been modified by Professor Wilip, a collaborator with Galitzin and at one time Director of the Seismic Central Station at Pulkovo. The main differences between the Galitzin and Galitzin-Wilip seismographs are :—

(a) Wilip discards the Zöllner suspension for the horizontal pendulums, the weight in his pendulums being carried by flat springs at the top and bottom of a rod perpendicular to the boom. The advantages claimed for this new suspension are reduction of size and the elimination of sideways displacements of short period which occur in the older instruments.

(b) The three components of the Galitzin-Wilip all operate with the same free periods.

(c) The new vertical seismograph is provided with an adjustable compensation for changes of temperature.

(d) Wilip introduced a modified type of recording drum driven by clockwork. The details need not be discussed since it is now generally agreed that the most satisfactory results are obtained from electrically driven motors.

(e) The metal covers of the Galitzin pendulums are replaced by airtight boxes of plate glass.

It will be noticed that the alterations in the Kew seismographs are similar to several of the improvements introduced by Wilip. In connexion with (a), the Zöllner suspensions could not have been replaced by spring hinges without complete reconstruction of the horizontal pendulums, and it was decided to retain the earlier form of suspension. The reduction to a smaller size would have been no great advantage, and, since the motion of the galvanometer follows the rotation of the pendulum in accordance with the theory (see § 8), there is no reason to believe that the short period movements of the pendulum interfere with the efficiency of the seismograph.

§ 4—THE WOOD-ANDERSON SEISMOGRAPHS

The Wood-Anderson seismograph (8) was developed in America as an instrument for recording the very rapid ground movements near the epicentre of an earthquake. The special feature of the design is the very small moving system ; the mass consists of a small copper cylinder, 25 mm. long and 2 mm. in diameter, which weighs 0·7 gm. The copper cylinder is carried longitudinally near the middle of a vertical tungsten fibre, 0·002 cm. in diameter and about 16 cm. long. The control is almost entirely due to the torsion of the fibre, and the magnification is very large owing to the small distance between the centre of gravity of the weight and the axis of rotation ; owing to the large magnification the instrument can be used with a very short free period, but instruments of this type with free periods of several seconds can be used for recording distant earthquakes. The mass is carried between the poles of a large magnet, and the amount of damping can be varied by raising or lowering the magnet. The registration is optical, a beam of light being reflected on to the photographic sheet by a small mirror at the top of the copper mass. The pendulum is subject to horizontal movements of very short period, termed " violin string " movements, in addition to the rotations of the copper cylinder around the fibre ; the " violin string " movements are damped out by passing the fibre above and below the weight through drops of oil carried in small cups.

The instruments, which have been installed at Kew Observatory to supplement the records of the Galitzin seismographs, have larger weights than those fitted to the original Wood-Anderson. The masses used are bars of copper, 0·3 cm. by 0·5 cm. by 2 cm., and weighing about 3 gm. The axis is tilted slightly away from the vertical, and the controlling force is chiefly due to gravity, the copper bar being supported by a Zöllner suspension in which the weight has been brought very close to the axis of rotation. The " violin string " movement occurs but does not disturb the recording, and oil cups were not fitted to the Kew instruments. The static magnification of these seismographs is about 700 : 1, and the instruments are adjusted to have a free period of 2·5 sec. with a damping ratio of approximately 20 : 1. The instruments are orientated to record the N-S and E-W components of the earth movements ; a single recording drum is used for both components, the light beam of the E-W component being deflected through a right angle as it enters and leaves the case of the instrument. The recording drum, which is electrically driven, is of the type described in the previous section.

Photographs of the Wood-Anderson pendulums and of the recording mechanism are given in Fig. 7 ; the upper photograph is a view of one of the pendulums with the cover removed, the other shows the general arrangement of the complete installation.

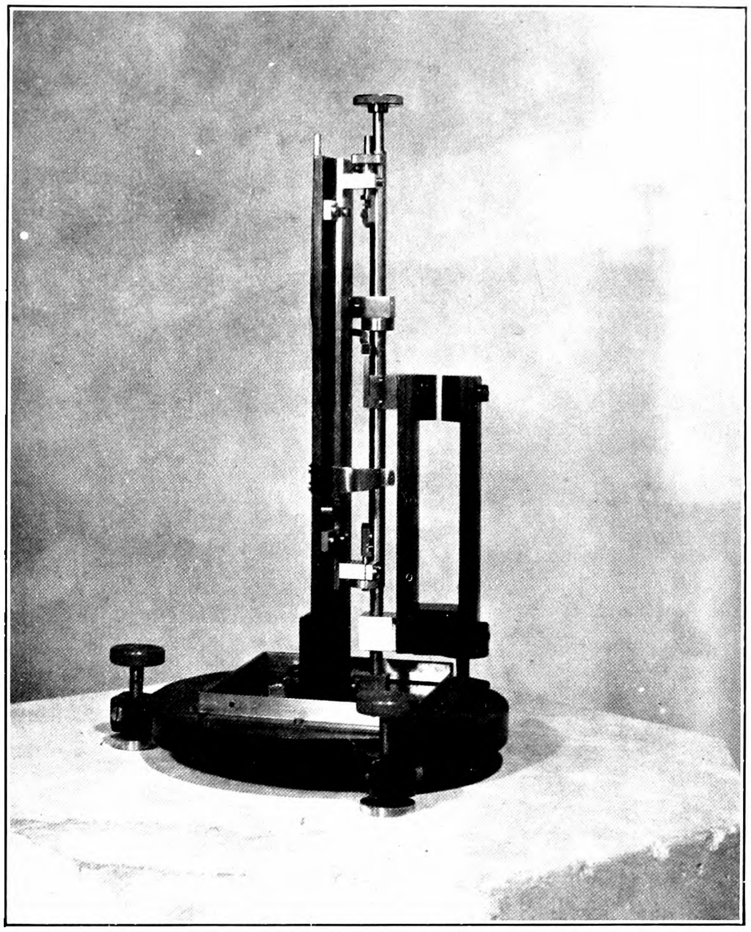

FIG. 7 (A).—WOOD-ANDERSON SEISMOGRAPH.

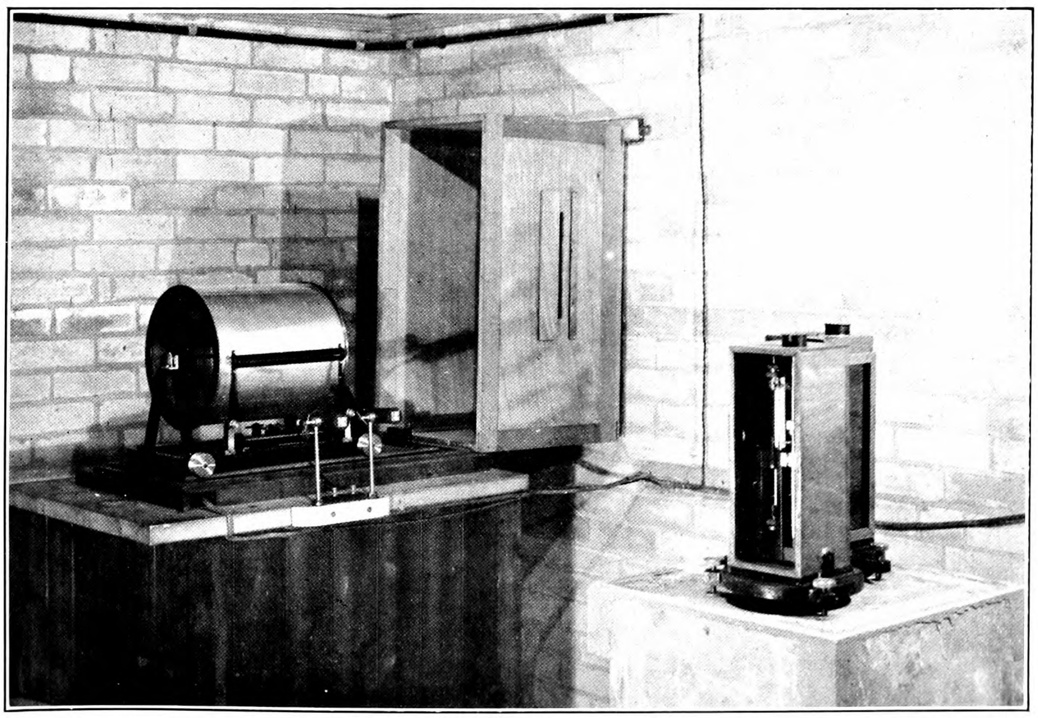

FIG. 7 (B).—ARRANGEMENT OF THE TWO WOOD-ANDERSON SEISMOGRAPHS WITH RECORDING LIGHTS AND ELECTRICALLY-DRIVEN DRUM.

PART II—THE OPERATION AND STANDARDIZATION OF GALITZIN SEISMOGRAPHS

§ 5—THEORY OF THE GALITZIN SEISMOGRAPH WITH SIMPLE HARMONIC EARTH MOVEMENTS

The notation adopted for this paper is based upon that given by Galitzin, but some modifications have been introduced. The symbols and their interpretations are :—

Earth Movement.	x = Displacement of the ground.
	T = Period of simple harmonic earth-waves.
Pendulum.	l = Length of the equivalent simple pendulum.
	T_0 = Free period of pendulum.
	ε_0 = Damping coefficient of pendulum.
	τ_0 = The " lag " correction of the pendulum for sinusoidal earth-waves.
	θ = Angular displacement of pendulum.
Galvanometer.	k = The " transmission factor " which depends upon the electrical coupling between the pendulum coils and the galvanometer.
	T_1 = Free period of galvanometer.
	ε_1 = Damping coefficient of galvanometer.
	τ_1 = The " lag " correction of the galvanometer for sinusoidal earth-waves.
	ϕ = Angular displacement of galvanometer coil.
	A = Distance of galvanometer mirror from recording drum.
	y = Displacement of light spot on recording drum.

The speeds, n, n_0 and n_1 ($n = 2\pi/T$, $n_0 = 2\pi/T_0$ and $n_1 = 2\pi/T_1$) are generally used in the equations instead of the corresponding periods. In Galitzin's notation, which has been used by other writers, the pendulum constants, T_0, n_0 and τ_0 were represented by the same letters without the suffixes, and the constants of earth movement, T and n, were designated as T_p and p. The modified notation has the advantage of uniformity.

Following Galitzin, the departure of the pendulum from aperiodicity is represented by the damping constant μ^2, where

$$\mu^2 = 1 - \frac{\varepsilon_0{}^2}{n_0{}^2}$$

The equation of motion of the pendulum under the influence of an earth movement may be expressed in the form

$$\theta'' + 2\,\varepsilon_0\,\theta' + n_0{}^2\,\theta + \frac{x''}{l} = 0 \qquad \ldots\ldots \text{(i)}$$

and the equation for the motion of the galvanometer coil is

$$\phi'' + 2\,\varepsilon_1\,\phi' + n_1{}^2\phi = k\theta' \qquad \ldots\ldots \text{(ii)}$$

where differentiations with respect to time are indicated by dashes.

Galitzin gives the solution of these equations for earth-movements of various types. In the case of simple harmonic motion the ground movement is represented by the equation

$$x = x_m \sin\,(pt + \delta) \qquad \ldots\ldots \text{(iii)}$$

where x_m is the amplitude and δ the phase at zero time. With critical damping of the pendulum and galvanometer the corresponding displacement on the record is given by the equation

$$y = x_m \frac{kA}{\pi l} \cdot T \frac{T_0^2}{T_0^2 + T^2} \cdot \frac{T_1^2}{T_1^2 + T^2} \cdot \sin\{n(t - \tau_0 - \tau_1) + \delta\} \quad \text{(iv)}$$

The " lag " corrections, τ_0 and τ_1, are given by the equations

$$\tau_0 = \frac{T}{\pi} \tan^{-1} \frac{T_0}{T} \quad \ldots\ldots \quad \text{(v)}$$

$$\text{and } \tau_1 = T \left\{ \frac{1}{4} + \frac{1}{\pi} \tan^{-1} \frac{T_1}{T} \right\} \quad \ldots\ldots \quad \text{(vi)}$$

The magnification, V, of simple harmonic earth-waves is

$$V = \frac{kA}{\pi l} \cdot T \cdot \frac{T_0^2}{T_0^2 + T^2} \cdot \frac{T_1^2}{T_1^2 + T^2} \quad \ldots \quad \text{(vii)}$$

For waves of very short period $V = T \cdot kA/\pi l$, and the factor $kA/\pi l$ may be expressed in the form $(V/T)_{T \to 0}$

The magnification is a maximum when

$$T^2 = \frac{1}{6} \left\{ \sqrt{(T_0^4 + 14\, T_0^2\, T_1^2 + T_1^4)} - (T_0^2 + T_1^2) \right\} \quad \ldots\ldots \quad \text{(viii)}$$

The solutions of equation (viii) for various ratios T_0/T_1, and the maximum magnifications obtained by substituting the roots of (viii) in (vii) are set out in the following table :—

$T_0\ T_1$	Period of earth-waves for maximum magnification	$\frac{V_{max}/T_1}{(V/T)_{T \to 0}}$
1	$0 \cdot 5773\ T_1$	$0 \cdot 3247$
$\frac{1}{2}$	$0 \cdot 3843\ T_1$	$0 \cdot 2106$
$\frac{1}{3}$	$0 \cdot 2862\ T_1$	$0 \cdot 1523$
$\frac{1}{4}$	$0 \cdot 2267\ T_1$	$0 \cdot 1183$

The values given below are computed for seismographs with pendulum and galvanometer periods of 12 sec. and of 24 sec., and for a 24 sec. galvanometer operating with pendulums of 12 sec., 8 sec., and 6 sec. respectively.

Galvanometer free period T_1	Pendulum free period T_0	Period of earth-waves for maximum magnification	$\frac{V_{max}}{(V/T)_{T \to 0}}$
sec.	sec.	sec.	sec.
12	12	6·93	3·896
24	24	13·86	7·793
24	12	9·22	5·054
24	8	6·87	3·655
24	6	5·44	2·839

Thus, for agreement between the periods of earth-waves giving the maximum magnification and for agreement between these magnifications, the values for an 8 sec. pendulum with a 24 sec. galvanometer are close to those for the combination in which the periods are both 12 sec. On this account it was decided to reduce the period of the horizontal pendulums at Kew to a third of the galvanometer period. The variations of magnification with period of the earth-waves, for the pendulum-galvanometer combinations examined above, are plotted in Fig. 8. In this diagram the magnifications are expressed as percentages of the maxima.

The " lag " corrections for seismographs of periods 24 sec. and 12 sec. with $T_0 = T_1$, and for a combination of a 24 sec. galvanometer with an 8 sec. pendulum, are given in Table I.

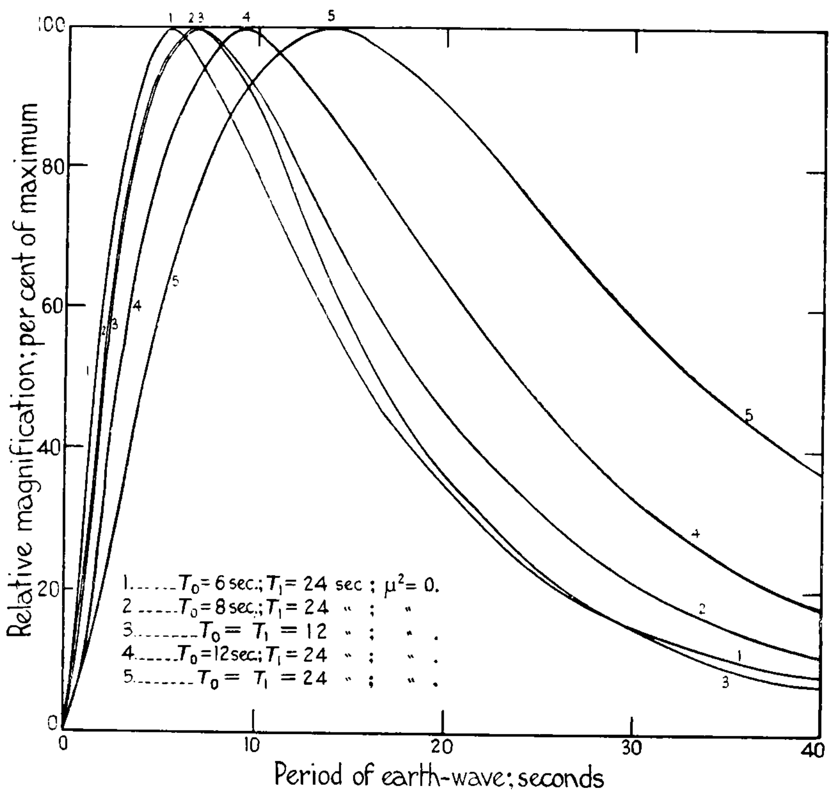

FIG. 8.—RELATIVE MAGNIFICATIONS OF GALITZIN SEISMOGRAPHS FOR SIMPLE HARMONIC EARTH-WAVES OF DIFFERENT PERIODS.

TABLE I—" LAG " CORRECTIONS ($\tau_0 + \tau_1$) FOR $\mu^2 = 0$

T_1	T_0	Period of earth-wave (sec.) 5	10	15	20	25	30	35	40
sec.	sec.	sec.	sec.	sec.	sec.	sec.	sec.	sec.	sec.
24	24	6	10	13	16	18	20	22	24
24	8	5	8	10	13	15	16	18	19
12	12	5	8	11	12	13	15	16	17

The corrections for $T_1 = 24$ sec., $T_0 = 8$ sec., are in very close agreement with those for $T_1 = T_0 = 12$ sec. for earth-waves of periods less than 20 sec., and for the longer periods the differences do not exceed 2 sec.

§ 6—MOTION OF THE PENDULUM AND GALVANOMETER WHEN THE PENDULUM IS DISPLACED BY A SMALL IMPULSE

A theoretical examination of the motion of the pendulum and galvanometer, following the displacement of the pendulum by a small impulse, is required in connexion with the determination of the constants.

There are three types of solution of equation (i).

Case 1. $\varepsilon_0 < n_0$.

In this case μ^2 is positive and the pendulum is underdamped. For equation (i) the solution vanishing when $t = o$ is

$$\theta = \frac{\theta_0'}{\mu n_0} \exp(-\varepsilon_0 t) \sin(\mu n_0 t) \quad . \quad . \quad . \quad . \quad (ix)$$

θ_0' being the initial angular velocity of the pendulum.

The maximum displacement, θ_M, occurs when t satisfies the equation

$$\mu n_0 t = \alpha \quad . \quad . \quad . \quad . \quad . \quad (x)$$

where α is such that $\tan \alpha = \mu n_0/\varepsilon_0$, $\sin \alpha = \mu$, $\cos \alpha = \varepsilon_0/n_0$. Accordingly

$$\theta_M = \frac{\theta_0'}{n_0} \exp(-\varepsilon_0\alpha/\mu n_0) \qquad \ldots\ldots \quad \text{(xi)}$$

Hence the ratio of the displacement at any time to the maximum displacement is given by

$$\frac{\theta}{\theta_M} = \frac{\exp(-\varepsilon_0 t)\sin \mu n_0 t}{\mu \exp(-\varepsilon_0\alpha/\mu n_0)} \qquad \ldots\ldots \quad \text{(xii)}$$

Case 2. $\varepsilon_0 = n_0$.

Here $\mu^2 = 0$ and the damping is "critical." The solution is

$$\frac{\theta}{\theta_M} = n_0 t \exp(1 - n_0 t) \qquad \ldots\ldots \quad \text{(xiii)}$$

Case 3. $\varepsilon_0 > n_0$.

In this case μ^2 is negative and the motion is overdamped. If $\mu = i\nu$, so that $\nu^2 = \varepsilon_0^2/n_0^2 - 1$, and if $\tanh \beta = \nu n_0/\varepsilon_0$, the solution of equation (i) is

$$\frac{\theta}{\theta_M} = \frac{\exp(-\varepsilon_0 t)\sinh \nu n_0 t}{\nu \exp(-\varepsilon_0\beta/\nu n_0)} \qquad \ldots\ldots \quad \text{(xiv)}$$

The values of θ/θ_M which correspond with given values of $n_0 t$ can be evaluated from equations (xii) to (xiv) if the ratio ε_0 to n_0 is specified. Such computations have been carried out for three cases :—

$\mu^2 = +0{\cdot}25$, corresponding with $\varepsilon_0 = 0{\cdot}866\, n_0$, (motion slightly underdamped),
$\mu^2 = 0$, ,, ,, $\varepsilon_0 = n_0$, (critically damped), and
$\mu^2 = -0{\cdot}25$, ,, ,, $\varepsilon_0 = 1{\cdot}118\, n_0$, (slightly overdamped).

The values are tabulated in Table II, and shown graphically in Fig. 9.

TABLE II—VALUES OF θ/θ_M CORRESPONDING WITH GIVEN VALUES OF $n_0 t$

$n_0 t$	θ/θ_M (per cent.)		
	$\mu^2 = +0{\cdot}25$	$\mu^2 = 0{\cdot}00$	$\mu^2 = -0{\cdot}25$
0·0	0·0	0·0	0·0
0·4	69·6	72·9	75·5
0·8	96·5	97·7	98·5
1·0	99·9	100·0	99·9
1·2	98·9	98·3	97·6
1·6	88·9	87·8	87·1
2·0	73·7	73·6	73·7
2·4	57·8	59·2	60·5
2·8	43·2	46·3	48·8
3·2	31·0	35·5	38·9
3·6	21·3	26·7	30·8
4·0	14·1	19·9	24·3
4·4	8·9	14·7	19·1
5·0	3·9	9·2	13·3
6·0	0·4	4·0	7·2
7·0	−0·4	1·7	3·9
8·0	−0·4	0·7	2·1
9·0	−0·2	0·3	1·1
10·0	−0·1	0·1	0·6

For $\mu^2 = +0{\cdot}25$, θ_M corresponds with $n_0 t = 1{\cdot}047$, and for $\mu^2 = -0{\cdot}25$, θ_M corresponds with $n_0 t = 0{\cdot}962$.

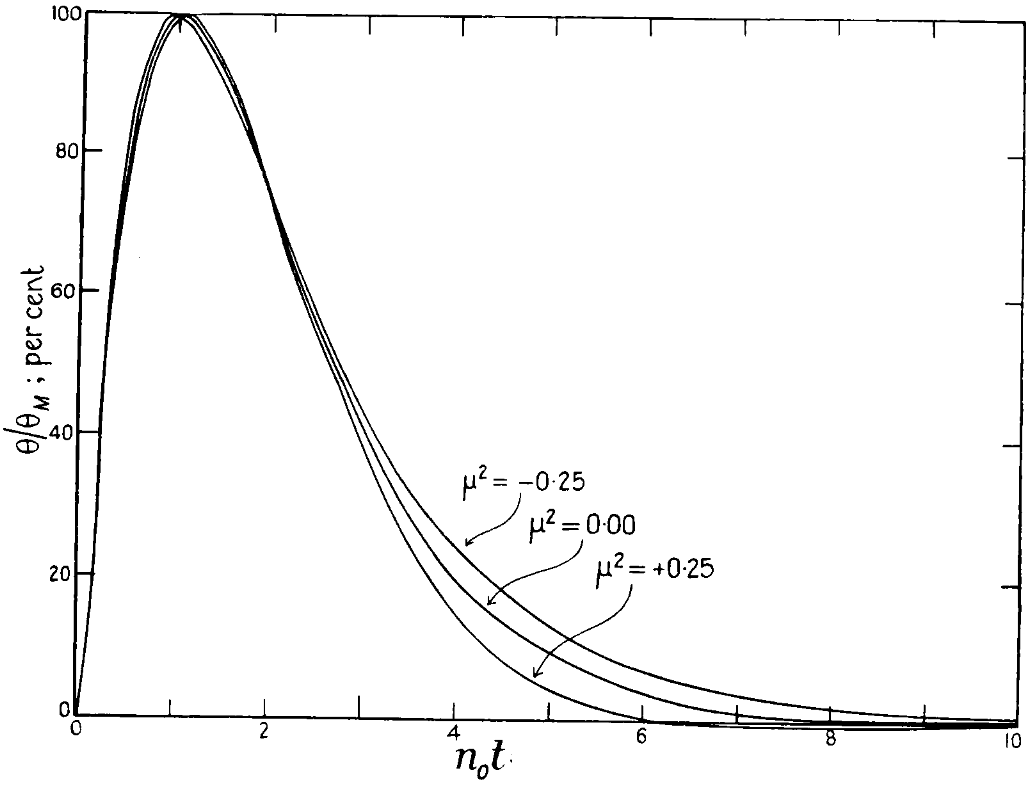

FIG. 9.—MOTION OF PENDULUM DUE TO AN IMPULSE.

The solution of the equation of motion of the galvanometer coil (ii) is only required for the simple case in which the pendulum and galvanometer are both critically damped. On substitution in (ii) of the value of θ' from (xiii), the equation becomes

$$\phi''+2n_1\,\phi'+n_1{}^2\,\phi = k\theta_M\,(n_0 - n_0{}^2t)\exp(1-n_0t) \quad \ldots\ldots \quad \text{(xv)}$$

The initial conditions are that $\phi = 0$ and $\phi' = 0$ when $t = 0$, and the solution is

$$\phi = \frac{n_0 k\theta_M}{(n_1-n_0)^2}\left[\left\{\frac{n_1+n_0}{n_1-n_0} - n_0t\right\}\exp(1-n_0t) - \left\{\frac{n_1+n_0}{n_1-n_0} + n_1t\right\}\exp(1-n_1t)\right] \text{(xvi)}$$

Thus ϕ, the deflexion of the galvanometer coil following an impulse applied to the pendulum at $t = 0$, is of the type shown in Fig. 10. The time when the coil crosses the zero after the first half of the oscillation is indicated as t_0, and the stationary values of ϕ on the positive and negative sides of the zero as ϕ_1 and $-\phi_2$ respectively.

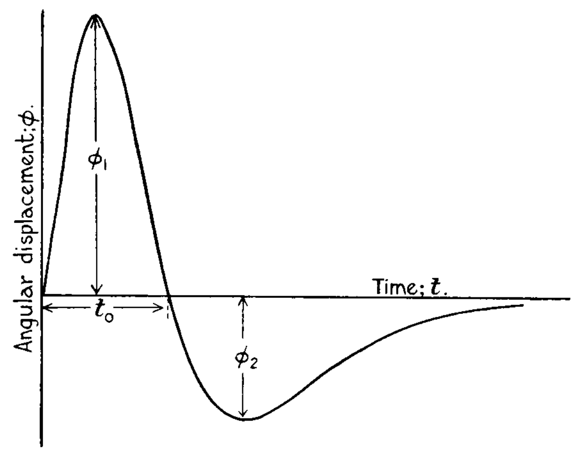

FIG. 10.—MOTION OF GALVANOMETER COIL DUE TO IMPULSIVE MOVEMENT OF THE PENDULUM.

The value of t_0 is given by

$$\exp\left[(n_1 - n_0)\, t_0\right] = \frac{\dfrac{n_1 + n_0}{n_1 - n_0} + n_1 t_0}{\dfrac{n_1 + n_0}{n_1 - n_0} - n_0 t_0} \qquad \ldots\ldots \quad \text{(xvii)}$$

and the values of t corresponding with the stationary values of ϕ on either side of the zero are the roots of the equation

$$\exp\left[(n_1 - n_0)\, t\right] = \frac{\dfrac{2\, n_1 n_0}{n_1 - n_0} + n_1^2 t}{\dfrac{2\, n_1\, n_0}{n_1 - n_0} - n_0^2 t} \qquad \ldots\ldots \quad \text{(xviii)}$$

If the periods of pendulum and galvanometer are equal (xvi) reduces to

$$\phi = \exp\,(1 - n_1 t)\; n_1\, k\theta_M \left(\frac{t^2}{2} - \frac{n_1 t^3}{6}\right) \qquad \ldots\ldots \quad \text{(xix)}$$

which agrees with the solution given by Galitzin. Between ϕ_1 and ϕ_2 the deflexion is zero when $n_1 t_0 = 3$, i.e., when

$$t_0 = \frac{3T_1}{2\pi} = 0\cdot477\; T_1 \qquad \ldots\ldots \quad \text{(xx)}$$

and the condition for ϕ to be stationary is that

$$n_1 t - n_1^2 t^2 + \frac{n_1^3 t^3}{6} = 0 \qquad \ldots\ldots \quad \text{(xxi)}$$

The stationary values of ϕ therefore occur when $n_1 t = 3 - \sqrt{3} = 1\cdot268$ and when $n_1 t = 3 + \sqrt{3} = 4\cdot732$. On substitution of these values for $n_1 t$ in (xix) the maximum displacements on either side of the zero are

$$\left.\begin{aligned} \phi_1 &= 0\cdot3550\; \frac{k\theta_M}{n_1} \\ \phi_2 &= 0\cdot1548\; \frac{k\theta_M}{n_1} \end{aligned}\right\} \qquad \ldots\ldots \quad \text{(xxii)}$$

and the ratio of these displacements is

$$\frac{\phi_1}{\phi_2} = 2\cdot294 \qquad \ldots\ldots \quad \text{(xxiii)}$$

Similar calculations have been made for various ratios of pendulum and galvanometer free periods using the more general equations given above. The solutions for $n_1 t_0$, and for $n_1 t$ corresponding with the stationary values of ϕ, are summarised in Table III, together with the values of $\phi_1 n_1/k\theta_M$, $\phi_2 n_1/k\theta_M$ and of the ratios t_0/T_1 and ϕ_1/ϕ_2.

TABLE III—SOLUTIONS OF THE EQUATIONS OF MOTION FOR THE GALVANOMETER WITH THE FREE PERIODS OF PENDULUM AND GALVANOMETER IN SPECIFIED RATIOS—PENDULUM AND GALVANOMETER BOTH CRITICALLY DAMPED

$\frac{n_0}{n_1}=\frac{T_1}{T_0}$	$n_1 t_0$	$\frac{t_0}{T_1}$	Stationary values of ϕ		$\frac{\phi_1 n_1}{k\theta_M}$	$\frac{\phi_2 n_1}{k\theta_M}$	$\frac{\phi_1}{\phi_2}$
			First $n_1 t$	Second $n_1 t$			
4	1·600	0·255	0·584	2·651	0·2618	0·0843	3·105
3	1·797	0·287	0·695	2·914	0·2925	0·1046	2·797
2	2·149	0·342	0·878	3·423	0·3284	0·1319	2·489
1	3·000	0·477	1·268	4·732	0·3550	0·1548	2·294
$\frac{3}{4}$	3·471	0·553	1·459	5·484	0·3503	0·1505	2·327
$\frac{1}{2}$	4·298	0·684	1·756	6·846	0·3284	0·1319	2·489
$\frac{1}{3}$	5·390	0·858	2·085	8·742	0·2925	0·1046	2·797

§ 7—STANDARDIZATION OF THE SEISMOGRAPH FROM OBSERVATIONS OF THE GALVANOMETER

The Galitzin method of standardization, for seismographs which are approximately in adjustment, is based upon observations of the pendulum and galvanometer when the former is given a small impulse. The deflexion of the pendulum is produced by a hammer controlled by an electromagnet. One observer using a telescope and scale notes the deflexion of the pendulum. A second observer follows the deflexions of the light spot from the galvanometer. The procedure is for the second observer to depress the key which operates the hammer and at the same time start a stop-watch ; the maximum deflexions of the light spot on either side of the zero are noted, and the watch is stopped as the light spot crosses the zero after the first maximum. The observations therefore give θ_M, ϕ_1, ϕ_2 and t_0.

The practice at Kew is to plot the values of ϕ_1/ϕ_2 and of t_0/T_1, obtained from a series of about 25 observations, on Scrase's isopleth diagram (6), and the departures from the ideal conditions ($T_0 = T_1$, $\mu^2 = 0$,) can be determined. The transmission factor is then computed from the approximate formulæ, due to O. Somville (9) :—

$$k = n_1 \frac{\phi_1}{\theta_M} (2 \cdot 817 + 0 \cdot 018\, \mu^2) = n_1 \frac{\phi_2}{\theta_M} (6 \cdot 461 - 2 \cdot 196\, \mu^2).$$

In this method the seismograph is adjusted approximately, and allowance is made in any later calculations for the departure from the optimum conditions. With different periods of pendulum and galvanometer the isopleth diagram cannot be used, and a modified procedure was introduced. The transmission factor can be found at once, if the pendulum and galvanometer are critically damped and the periods are in either of the ratios for which numerical results have been given in § 6. The adjustments are therefore continued until the ratios t_0/T_1 and ϕ_1/ϕ_2 are in as good agreement as possible with the theoretical ratios. For the horizontal instruments at Kew the free period of the pendulum is now one-third that of the galvanometer and the conditions are that

$$t_0/T_1 = 0 \cdot 287 \text{ and } \phi_1/\phi_2 = 2 \cdot 797.$$

The process of successive adjustments to the period of the pendulum and position of the damping magnets can generally be carried out in about an hour. On account of the greater stability the adjustments of the pendulum are much easier with the free period of about 8 sec. than they were with the longer free period.

When the adjustments are satisfactory a series of observations is taken and the medians of the values of t_0/T_1, ϕ_1/ϕ_2, ϕ_1/θ_M and ϕ_2/θ_M are computed. The results, given in Table III for critical damping with $T_0 = \frac{1}{3} T_1$, are that

$$\frac{\phi_1 n_1}{k\, \theta_M} = 0 \cdot 2925 \quad \text{and} \quad \frac{\phi_2 n_1}{k\, \theta_M} = 0 \cdot 1046$$

and the transmission factor is obtained from either of the formulæ :—

$$\left. \begin{aligned} k &= 21 \cdot 48\, \phi_1/T_1\theta_M \\ \text{or } k &= 60.07\, \phi_2/T_1\theta_M \end{aligned} \right\} \qquad \ldots\ldots \quad \text{(xxiv)}$$

The standardizations during December, 1937, of the horizontal Galitzin seismographs at Kew Observatory, given in Table IV, may be quoted as examples of the method.

The deviations which accompany the medians of the values of t_0/T_1, ϕ_1/ϕ_2, ϕ_1/θ_M and ϕ_2/θ_M are half the ranges between the first and third quartiles of the individual observations ; the ratios for half of the observations are therefore within the limits shown in the table.

For each component there is good agreement between the values of k computed from the formulæ involving ϕ_1 and ϕ_2.

TABLE IV—STANDARDIZATION OF HORIZONTAL GALITZIN SEISMOGRAPHS, DECEMBER, 1937

Component and date of standardization	N.—S. December 14, 1937	E.—W. December 15, 1937
T_1 (sec.)	24·2	24·8
Number of observations	25	25
Median and half interquartile range ; t_0/T_1 ...	0·285±0·001	0·287±0·001
,, ,, ,, ,, ; ϕ_1/ϕ_2 ...	2·80 ±0·02	2·79 ±0·01
,, ,, ,, ,, ; ϕ_1/θ_M ...	23·92 ±0·41	24·69 ±0·20
,, ,, ,, ,, ; ϕ_2/θ_M ...	8·54 ±0·14	8·84 ±0·14
$21 \cdot 48\ \phi_1\ T_1\theta_M$	21·20	21·38
$60 \cdot 07\ \phi_2\ T_1\theta_M$	21·17	21·41
k	21·2	21·4

§ 8—DIRECT OBSERVATIONS OF THE PENDULUM MOTION DUE TO AN IMPULSE

Galitzin found that observations of the free period of the pendulum, with the damping magnets removed, did not give the period appropriate for the seismograph in operation, and introduced the impulse method of standardization. The tests he devised are based upon the theoretical determination of the ratios of ϕ_1/ϕ_2 and of t_0/T_1, appropriate for a pendulum which is nearly critically damped. To check the new standardizations, experiments had to be devised to determine how closely the behaviour of a pendulum, adjusted by the impulse method, was in accordance with the theory. The method employed is applicable for measurements of the free period and damping of any type of pendulum having a fairly long free period. The procedure is simple, and can be carried out by a single observer reading pendulum deflexions with a telescope and scale, and timing with a stop watch.

The watch is started at the exact instant when the key operating the pendulum hammer is depressed. The observer notes the maximum deflexion, θ_M, and stops the watch at time t when the pendulum returns to a deflexion θ, the latter deflexion being chosen to be between 5 per cent. and 30 per cent. of θ_M (i.e. in the region where the curves of Fig. 9 for $\mu^2 = +0 \cdot 25$, $\mu^2 = 0$ and $\mu^2 = -0 \cdot 25$ are most widely spaced.) A number of observations are taken with different values of θ/θ_M and a curve is drawn to show the variation of θ/θ_M with t. To determine the damping and free period of the pendulum readings are taken of the times, measured from the impulse, in which the deflexion diminishes to two selected ratios of θ/θ_M ; the ratios chosen for this purpose are 20 per cent. and 10 per cent., and the corresponding times are designated t_{20} and t_{10}.

The values of nt_{20} and of nt_{10}, obtained from a large-scale graph of the three curves given in Fig. 9, together with the values of T_0/t_{20}, T_0/t_{10} and of t_{10}/t_{20}, are :—

μ^2	$\theta/\theta_M = 20$ per cent.		$\theta/\theta_M = 10$ per cent.		
	nt_{20}	T_0/t_{20}	nt_{10}	T_0/t_{10}	t_{10}/t_{20}
+0·25	3·667	1·713	4·300	1·461	1·173
0	3·993	1·574	4·878	1·288	1·222
−0·25	4·322	1·454	5·455	1·152	1·262

Hence, if the pendulum is adjusted so that the ratio t_{10}/t_{20} is between 1·17 and 1·26, the damping coefficient, μ^2, and the ratios T_0/t_{20} and T_0/t_{10}, can be determined approximately by interpolation from the computed values.

A number of these experiments were carried out with the Galitzin seismographs at Kew Observatory. Two series of observations were taken. In the first the instruments had been adjusted so that the ordinary standardization indicated critical damping with the periods of pendulum and galvanometer equal; in the second the adjustments gave critical damping with the pendulum period one-third that of the galvanometer. At first large deflexions of the pendulum were taken, with a view to increasing the accuracy of the ratios θ/θ_M; with these large deflexions the galvanometer was disconnected from the circuit. The pendulum motion under these conditions, both with $T_0 = T_1$ and with $T_0 = \frac{1}{3} T_1$, was overdamped. This result is discussed in § 9. With some experience in taking the observations it was possible to obtain satisfactory readings from much smaller deflexions of the pendulum, and the galvanometer could be kept in circuit without risk of damage. These pendulum observations were taken under the conditions which hold for the Galitzin method of standardization, and the results obtained by the two methods are practically identical. Subsidiary tests with the smaller deflexions showed no appreciable difference between the pendulum observations with the galvanometer in the circuit or disconnected, indicating that the reaction of the galvanometer on the pendulum may be neglected.

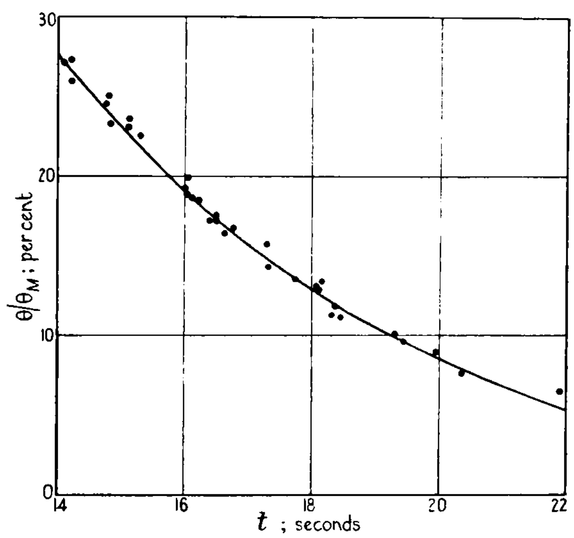

FIG. 11.—OBSERVATIONS OF PENDULUM MOTION. $T_0 = T_1 = 24 \cdot 8$ SEC.; $\mu^2 = 0$.

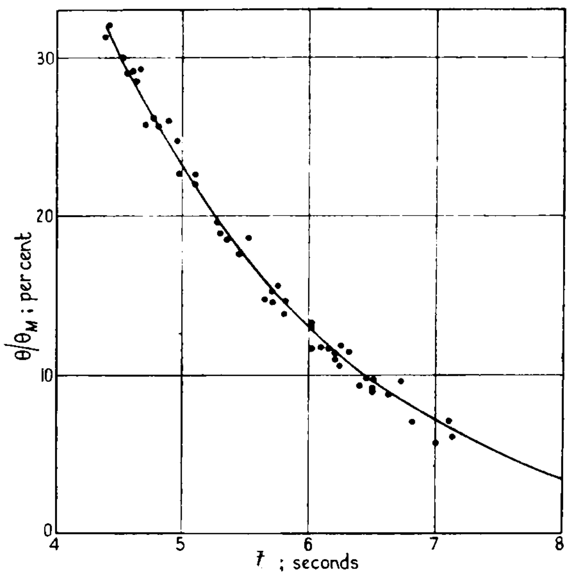

FIG. 12.—OBSERVATIONS OF PENDULUM MOTION. $T_1 = 24 \cdot 8$ SEC.; $T_0 = \frac{1}{3}T_1$; $\mu^2 = 0$.

The ratios of θ/θ_M are plotted against t in Figs. 11 and 12 for observations of the E-W pendulum standardised by the impulse method to the conditions $T_0 = T_1 = 24 \cdot 8$ sec., $\mu^2 = 0$, and $T_0 = \frac{1}{3}T_1$, $T_1 = 24 \cdot 8$ sec., $\mu^2 = 0$. The curves drawn in these figures are computed from the theoretical values for $\mu^2 = 0$, taking the appropriate free period of the galvanometer and the relations $T_0 = T_1$ and $T_0 = \frac{1}{3} T_1$; they represent the variations of θ/θ_M with t if the seismograph operates exactly in the manner required by the theory. The curves, which were originally plotted through the points to give the observed variations of θ/θ_M with t, are very close to the theoretical curves, and have not been reproduced. The results obtained from the experimental curves are :—

$T_0 = T_1 = 24 \cdot 8$ sec.; $\mu^2 = 0$.			$T_0 = \frac{1}{3}T_1$; $T_1 = 24 \cdot 8$ sec.; $\mu^2 = 0$		
t_{20}	t_{10}	t_{10}/t_{20}	t_{20}	t_{10}	t_{10}/t_{20}
sec. 15·8	sec. 19·25	1·22	sec. 5·25	sec. 6·45	1·23

The observed ratio of t_{10}/t_{20} in either case is very close to the theoretical value for $\mu^2 = 0$ (1·222), and the damping may be accepted as critical within the accuracy of the measurements.

According to the theory the ratios T_0/t_{20} and T_0/t_{10} are 1·574 and 1·288 respectively. For the first case ($T_0 = T_1$) the ratios of T_0 to the values of t_{20} and t_{10} obtained from the observations are 1·57 and 1·29 ; for the second case ($T_0 = \frac{1}{3}T_1$) the corresponding ratios are 1·57 and 1·28.

From these results it is clear that the behaviour of the seismograph agrees exceedingly well with the theory, and that if the adjustments are made to give the prescribed motion of the galvanometer the pendulum conforms with the corresponding conditions regarding its free period and damping.

§ 9—SOMVILLE'S EXPERIMENTS

The discrepancy found by Galitzin between the free period of the pendulum given by the impulse method and that obtained from direct measurements with the magnets removed, has been investigated by Somville (9). The experiments carried out by Somville for this investigation are divided into three series. The pendulum used was of the horizontal Galitzin type, but alterations were made, so that the damping and coil magnets could be removed from their usual positions and replaced without disturbing the tilt of the pendulum.

From the first series of measurements Somville found that with the pendulum adjusted by the Galitzin method to a period of 24·0 sec., the free period was diminished by 1·1 sec. when the damping magnets were removed, and by a further 1·4 sec. when the coil magnets were also removed. Further tests without the copper damping plate showed that with the damping magnets in position the period was 0·6 sec. greater than when these magnets were removed.

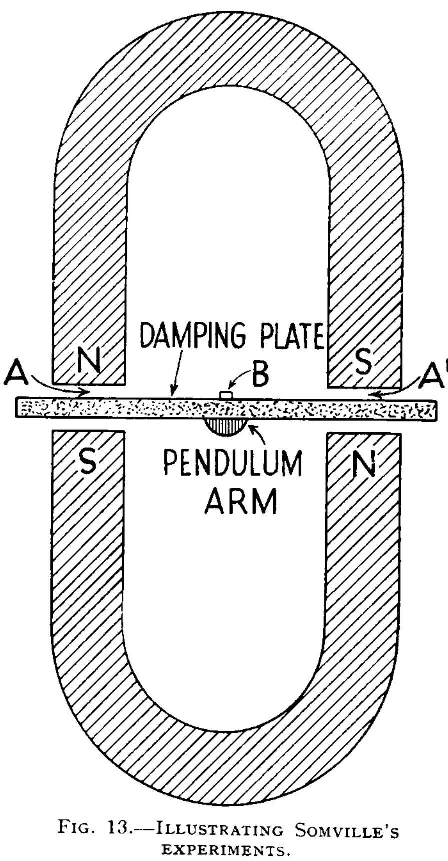

Fig. 13.—Illustrating Somville's experiments.

In the second series determinations were made of the free period and pendulum zero with various paramagnetic or diamagnetic materials carried on the damping plate in the positions shown as A A′ in Fig. 13.

The third series were measurements of the free period with and without nickel filings placed upon the end of the pendulum arm (position B, Fig. 13). The free period was increased by the addition of the filings showing that the brass arm was paramagnetic.

The experiments show that the period of the pendulum is diminished with paramagnetic material directly in the field between the poles of the magnet, or with diamagnetic material on the pendulum arm ; the period is increased with diamagnetic material in the field or with the arm paramagnetic.

Somville's explanation of these results is that as the pendulum oscillates the arm moves in a variable magnetic field ; being paramagnetic the arm is attracted towards the poles, and the period is lengthened. Paramagnetic material placed between the poles at A and A′ is constantly attracted to the strongest field and the period of oscillation is shortened. Somville concludes that " the presence of strong magnets in the immediate neighbourhood of the moving parts of very sensitive seismographs disturbs their normal behaviour, and it is essential that the effects produced by these magnets should be compensated." The method of compensation described is to insert nickel filings in cavities at A and A′ in the damping plate. Somville shows that the effect of placing the nickel filings in the field is to compensate for the paramagnetic pendulum arm, and not for the copper damping plate, which has a very low magnetic susceptibility but may be slightly para- or diamagnetic according to the purity of the copper.

These conclusions given by Somville have been completely misunderstood by Wilip, who states (7, p. 19) that " Somville . . . . has ascribed the variability of the period to the diamagnetic qualities of the copper plate used for damping.

By choosing a suitable alloy of copper and aluminium it has been managed to remove this defect in the new pendulums."

Somville's experiments demonstrate that the rod carrying the plate is paramagnetic, and there is no suggestion in his paper that the plate is diamagnetic. Somville's method of compensation depends upon the motion of a plate of variable susceptibility in a non-uniform magnetic field ; a uniform plate, whether paramagnetic, neutral or diamagnetic, cannot compensate for the paramagnetic pendulum arm.

The main result obtained from the Kew experiments is that with small deflexions, and the galvanometer in or out of circuit, the constants determined from the pendulum observations agree with those from the standardization through the galvanometer. The agreement breaks down for large deflexions with the galvanometer disconnected, when the pendulum observations indicate greater damping than that obtained from the galvanometric measurements. The discrepancy for larger throws is in accordance with Somville's deduction that the pendulum arm is paramagnetic, if we assume that the magnetic field is nearly uniform immediately around the zero position of the pendulum. There is then no appreciable change in the magnetic field for small deflexions, and the operation of the pendulum is undisturbed. For larger deflexions, however, the pendulum arm moves into a stronger field and is attracted towards the poles, the attraction being strongest when the displacement is greatest ; as a result the ratio t_{10}/t_{20} is too small and the damping is overestimated. The observations of the large pendulum deflexions, however, are made under conditions which differ from those when the seismograph is in operation. The results for smaller deflexions are directly comparable with the ordinary standardization experiments. For such deflexions the determinations by the two methods are in good agreement, and compensation for the magnetic properties of the moving parts of the Kew instruments is unnecessary.

§ 10—Summary

The seismographs at Kew Observatory were installed until 1937 in the basement of the main building. The Observatory is fully exposed, and the behaviour of the Galitzin instruments indicated that the building and the ground on which it stands are rocked whenever there is an appreciable wind. The seismographs were moved in 1937 to a new underground seismograph house, about a hundred yards away and outside the region affected by winds striking the main building. A full description is given of the new seismograph house and of the instruments.

The removal of the seismographs presented a suitable opportunity for making various improvements in the installation. The changes include an alteration in the tuning of the horizontal Galitzin pendulums to bring the response into approximate agreement with that of the vertical instrument, and the installation of electrically driven recording drums.

The theory of the Galitzin seismograph is examined with particular reference to the operation and standardization of a seismograph with the free period of the pendulum differing from that of the galvanometer. Some new experiments are described in which the free period and damping of a pendulum are obtained from observations of its motion following an impulse ; these observations are a valuable check on the determinations of the pendulum constants by the Galitzin method of standardization, which depends upon observations of the motion of the galvanometer coil. The results obtained by the two methods are in very good agreement, showing that the behaviour of the seismograph is in accordance with the theory.

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Mr. G. A. Herbert—the Galitzin recording drum.

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Mr. P. Thompson—case for Galitzin pendulums, cases for the Wood-Anderson seismographs, and the covers for the recording drums.

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