REPORTS ON THE STATE OF SCIENCE.

Seismological Investigations.—Nineteenth Report of the Committee, consisting of Professor H. H. TURNER (*Chairman*), Professor J. PERRY (*Secretary*), Mr. C. VERNON BOYS, Mr. HORACE DARWIN, Mr. F. W. DYSON, Dr. R. T. GLAZEBROOK, Mr. M. H. GRAY, Professor J. W. JUDD, Professor C. G. KNOTT, Sir J. LARMOR, Professor R. MELDOLA, Mr. W. E. PLUMMER, Dr. R. A. SAMPSON, Professor A. SCHUSTER, Mr. J. J. SHAW, *and* Dr. G. W. WALKER. (*Drawn up by the Chairman.*)

[PLATE I.]

CONTENTS.

I.—*General Notes.*

THE Committee asks to be reappointed with a grant of 60*l*.

The death of John Milne, in July 1913, creates a situation of some difficulty and anxiety. He organised a world-wide seismological service with very little financial help from others. In many of the outlying stations the instrumental equipment was provided either by himself or by one of his friends, and the care of it has been generously undertaken by a volunteer who is often busily engaged in other work. The collation of results was in the early years undertaken by Milne himself, with the able help of Shinobu Hirota. Of late years a subsidy of 200*l*. a year from the Government Grant Fund allowed of paid assistants; and Shinobu Hirota thus obtained a well-deserved official position; but for many years the only salary he received was paid from Milne's own pocket. It is by no means certain that the volunteer services at the stations, and the subsidy from the Government Grant Fund which makes it possible to keep running the central station at Shide, can be long continued; and it seems in any case very improbable that they can be rendered permanent. But a much more serious difficulty is the want of a salary for a Director or Superintendent of the whole British network of stations, who can give undivided attention to the valuable results which they have accumulated and to which they are daily adding. The salary of a competent Director, with the requisite mathematical knowledge, cannot be put lower than 500*l.* or 600*l.* a year, and there is at present no prospect of obtaining even this endowment. The superintendence has, of course, been hitherto provided voluntarily by Milne himself; and a certain amount of volunteer attention is available for the present. But seismology is developing so rapidly that the whole-hearted attention of at least one English mathematician should be devoted to it; and if an endowment for a British Director could be obtained this would surely be the most direct method of doing justice to a new and fascinating science which was nurtured by an Englishman. The negative result of previous appeals to the Government does not encourage the hope of their taking any action, and the chief hope thus lies in the direction of private benefaction. Is it too much to hope that some generous benefactor will provide a firm footing for seismology?

The present state of affairs is as follows:—The Shide Observatory is rented from Mrs. Milne at 20*l.* a year. The work of the Shide station and the collation of results from other stations is being done by Mr. J. H. Burgess, who assisted Professor Milne in the later years of his life, especially after the return of Shinobu Hirota to Japan. At the time of Professor Milne's death the work of collation was in arrear; and in order to bring it up to date assistance is being temporarily rendered by Mr. S. W. Pring (who had already considerable knowledge of the work) and his daughter. The general superintendence is undertaken by the Chairman of this Committee, partly by correspondence and partly by personal visits to Shide (on September 20-21, January 17-20, March 29-April 2, and May 9-11).

Registers. Card Catalogue System. Monthly Bulletins.—The form of the Circulars has been changed. Up to the present the information supplied by each individual station has been printed separately, thus leaving the formal collation of results to others. But since a good deal of collation was actually done at Shide in order to eliminate accidental tremors from the records, it seemed desirable to render this work generally available at the cost of a slight extension. The collation was formerly done in a large book with ruled columns, one double page being devoted to each month. In place of this a card catalogue system has been adopted. The information supplied by the stations is copied on to cards, a separate card for each day. A cabinet of twelve drawers (one for each calendar month) has been made, each drawer divided into 32 partitions (4×8) corresponding to the days of the month (with 1—4 over), and the cards are slipped into the proper partition as they are copied off. When all the records have been received for the month (and the stations have been asked kindly to send their records *each month*) it is easily seen by comparison of the different cards in any partition which are the important quakes and which are microseisms or accidental tremors. For the first few months of 1913 details were printed for all disturbances recorded at more than four stations; but experience quickly showed that much of this information was of comparatively little value, the records for small quakes being liable to errors of various kinds; and from April 1913 onwards a chart has been printed showing merely that such and such a quake has been observed at a particular station without further details, except in the case of a really large earthquake. It is, of course, difficult to draw a satisfactory line between large earthquakes and small, but a practical procedure was based on the following figures given in the April Bulletin:—

Month	Number of Stations recording an Earthquake:					
	5 to 10	11 to 20	21 to 30	31 to 40	41 to 50	Over 50
January	3	5	3	2	4	2
February . . .	5	5	5	1	0	1
March	6	9	7	3	2	3
April	9	13	6	10	4	3
Total . .	23	32	21	16	10	9

According to this table, if attention is confined to those earthquakes recorded at thirty-one stations at least, we should get a hundred of them in a year; and it was thought sufficient to give full details for these. It should be remarked that the stations are no longer Milne stations only—the list has been extended to include all those stations which send their records to Shide; and it is hoped that this comprehensive collation of results will be found useful. Undoubtedly a comparison with tabular theoretical results would increase its usefulness, and it is hoped to undertake such a comparison from January 1914; but to attempt this for 1913 would have seriously delayed publication (already considerably in arrear), and indeed was scarcely possible until a tentative discussion such as is given later in the present Report had been carried out.

Notation.—One other change will be made in January 1914. The symbols P_1, P_2, P_3, &c., were introduced by Milne, and have been used by him throughout his work, although he assented to the change to P, S, L, &c., as determined at the Manchester Meeting, 1911, of the International Seismological Association. It seemed only a proper mark of respect to complete the year of Milne's death (1913) in his notation; but the change to the adopted system will be made from the beginning of 1914.

Visitors.—The station at Shide continues to attract a number of visitors, many of them with only a limited knowledge of seismology; their visits naturally make inroads on the time of the assistant-in-charge, but it seems undesirable to discourage them at the present juncture. The visits of seismologists have naturally been affected by Milne's death; and in the consequent disorganisation the visitors' book was for a time not regularly posted; but we have had the pleasure of seeing at Shide Mr. J. J. Shaw of West Bromwich, Mr. E. F. Norris of Guildford, Mr. J. Round and Mr. S. B. Round of

Birmingham, Mr. L. F. Richardson of Eskdalemuir, and Mr. J. E. Crombie of Aberdeen.

II.—*Seismic Activity in* 1911.

The visit of the British Association to Australia makes it necessary to have the greater part of this Report in proof at an earlier date than usual. The list of origins for 1911, in continuation of those given in previous Reports, is not completed at this date; but it is hoped to add it at the end of the Report before it is finally printed off for distribution.

III.—*Distribution of Earthquake Centres.*

Study of the information collected by Milne in previous Reports has suggested a new form of the map which he has usually printed showing the distribution of large earthquakes. On some of these maps he has shown Libbey's Circle, and on others a cycle of his own running through the chief earthquake centres.

On scrutiny of the distribution of centres not thus accounted for, the existence of a curve of secondary disturbance was suggested, with the suggestive feature of enclosing most of the land on the earth's surface—skirting especially the Western coast of North America and the Eastern coast of Asia. Adjustments by trial and error of these two curves showed that it was not difficult to make them great circles cutting at right angles; but not easy to make them account for all the striking facts. More or less by accident, the third great circle cutting both at right angles was drawn, and immediately several striking *geographical* features fell into line. Further work on this system of three great circles suggested after many trials a system symmetrical with respect to the earth's axis, the points of intersection being at about 55° (accurately $\tan^{-1}\sqrt{2}$) from the poles; and there was little trouble in fixing the approximate longitudes at 25° ± 60° n East.

A system of three great circles cutting at right angles divides the surface of the sphere into eight equilateral right-angled triangles. If we project each of these on a tangent plane at its centre, we get an octahedron surrounding the sphere, and we can unwrap it into a plane in various ways. The particular plan of the accompanying map is adopted in order to bring out the striking symmetry, both seismological and geographical, of the earth as thus represented, a symmetry only slightly disguised by the one-sidedness of the water covering. [We can imagine the distribution made quite symmetrical, and then the upper right-hand corner dipped slightly more under the water; but we will neglect this point for a moment.]

Six of the triangles are easily recognised, the other two have been divided by their median lines in order to show the symmetry while keeping the figure compact; but ABC and CBD could be detached from AC and CD, and joined along CB placed in a vertical position, thus keeping the symmetry at the expense of a little detachment.

Let us consider the triangle EFK, which is chiefly Asia. India lies nearly on the median line, pointing to the apex of the triangle; and just

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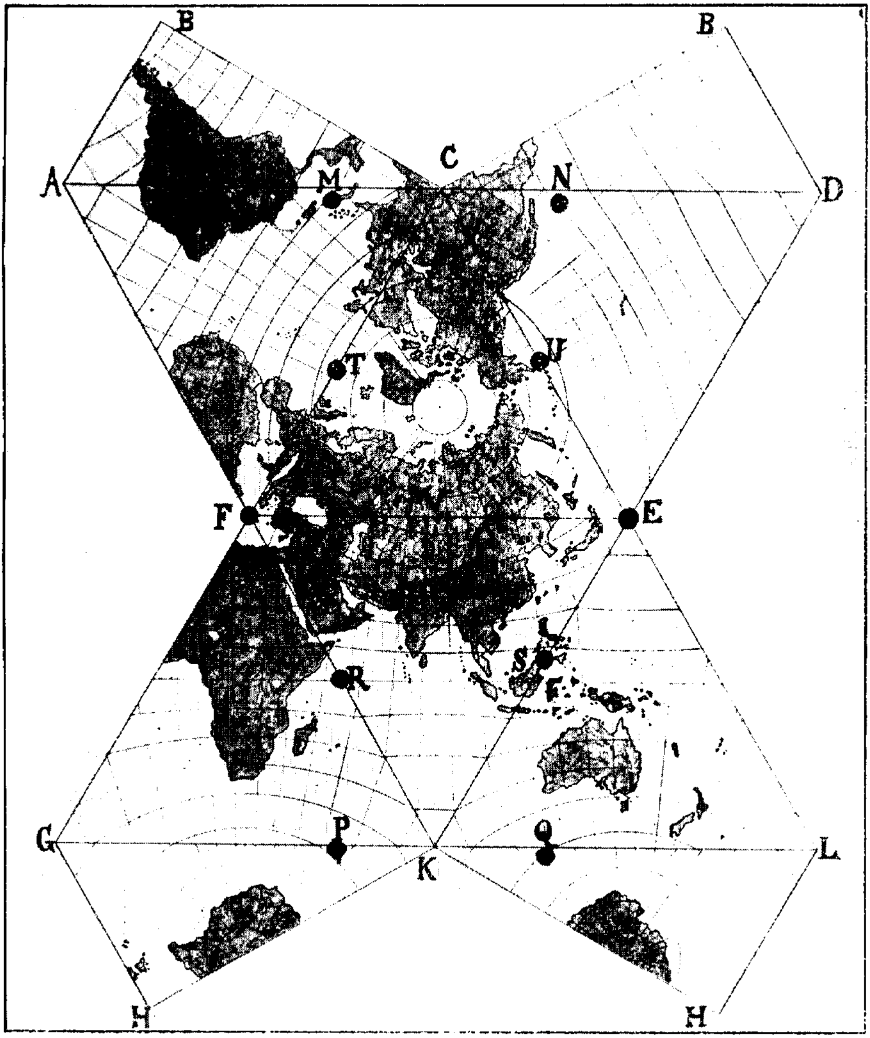

Illustrating the Report on Seismological Investigations.

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above India Tibet, the highest land in the world, occupies nearly the centre of the triangle. The side KE runs through a well-known series of earthquake centres skirting the coast, of which perhaps the most important are at E (Japan) and S (Borneo), one at the extremity and the other near the middle point. The continuation of KE is EC, since the angles FEK and FEC, though they are only 60° on the plane projections, are 90° on the sphere; and since there is a notable centre U (Alaska) near the middle of EC, we may perhaps consider S and U as corresponding points of strain.

The side KF is not so conspicuous a line of earthquakes at present, though the point F (Crete) is a familiar region, and corresponding to S we may take R, the middle point of FK, as representing earthquakes in the Indian Ocean. But apart from modern records, the geographical features of this line RF, viz., the Red Sea, the Grecian Archipelago, and the Adriatic, are strongly suggestive of crumpling into folds at some time in the past. Continuing the line along FC, there is an active centre near the middle point T which is not far from Iceland; so that S, E, V have corresponding points in R, F, T; the former are at present the stronger, but this may not have been always so.

The apex C is not an earthquake centre, but near it, and symmetrically disposed on the sides CD, CA, are the Californian and West Indian regions. The symmetry of the whole arrangement round the point V (close to Tomsk) will be complete if we may put two Antarctic centres at the points P and Q which are in latitude −53° and longitudes 55° and 115° East. Milne assigned two Antarctic regions near these as a result of observations made during the voyage of the 'Discovery' (March 14, 1902, to November 28, 1903), but it is doubtful whether the material is sufficient to locate them exactly.

As regards the remainder of the map, the symmetrical disposition of South Africa and Australia is noteworthy; but as we go northwards from them the symmetry disappears, the upper half of the African triangle being land, that of the Australian water (though much of it not very deep). Superposed on the arrangement symmetrical about the line CK there is at least one unsymmetrical character which may be roughly described as a division into land and water hemispheres, and as such has been often noted. In the present diagram the salient points of this contrast are:—

(*a*) Land in the triangle FGK, water in the triangle CDE.

(*b*) Water in the middle of land in the triangle ACF, land in the middle of water in EKL.

(*c*) The absence of land corresponding to South America, on the line CD. If a bathy-orographical map be consulted it will, however, be found that there is a shallow in this part of the ocean, not very different from South America in shape. It is conceivable that a mere shift of the earth's centre of gravity might uncover this 'image' of South America.

In a future Report it is hoped to show the actual distribution of observed earthquakes on this map; but this will take some little time.

IV.—*Discussion of Results from Different Seismographs.*

The card catalogue system introduced at Shide for records from January 1913 onwards facilitates the comparison of results from different instruments. The following discussion is only preliminary, and the unit of time adopted (0·1 m. or 6 sec.) is not small enough to do justice to the best instruments. But it is as small as can reasonably be adopted for the Milne instruments, and the main object of the discussion is to bring out the comparative attainments of the Milne seismographs as compared with modern and much more sensitive apparatus.

From the beginning of 1912, the weekly Bulletins issued from Pulkovo give epicentres for the large earthquakes, determined by Galitzin's method for a single station. Adopting these as correct and using the table printed by G. W. Walker on p. 54 of his monograph on 'Modern Seismology,' or by Galitzin in his 'Vorlesungen über Seismometrie,' p. 137, we can deduce from the times recorded at Pulkovo for either P or S, the time of the earthquake itself. Re-applying the table we can deduce the theoretical times of arrival of P and S at other stations, for comparison with their records. For this purpose the distances of the stations from the epicentre were read to whole degrees from a globe, which again is a method unsuitable to refined investigation, but sufficiently accurate for the present preliminary examination.

As an example, the times recorded for the earthquake of 1913, January 11, were as follows:—

	P			S		
	h.	m.	s.	h.	m.	s.
	13	29	45	13	40	9
Subtract		12	36		22	54
Time at epicentre	13	17	9	13	17	15

The distance of Florence from the adopted epicentre (6° N., 117° E.) was read off as 98°, and the calculated and observed times were:

For P					For S				
C		O		O—C	C		O		O—C
h.	m.	h.	m.	m.	h.	m.	h.	m.	m.
13	31·1	13	30·2	−0·9	13	42·7	13	35	−7·7

These differences O—C were collected and discussed for the following five earthquakes:—

Date	Adopted Epicentre	Δ for Pulkovo	Adopted Time	
	° °	°	h.	m.
1913, January 11	6·0 N., 117·0 E.	83	13	17·2
1913, March 23	26·3 N., 143·3 E.	78	20	47·2
1913, April 30	50·2 N., 176·3 E.	67	13	34·4
1913, May 18	26·3 N., 143·7 E.	79	2	9·7
1913, June 22	50·1 N., 178·1 E.	66	13	50·3

TABLE I.

134 *Errors of P for Seismographs other than Milne's.*

	Distance from Epicentre 0° – 40°	40° – 80°	80° – 90°	90° – 100°	100° – 130°	Summary (Corrected)
Large Errors .	—	—	m. +10·3	m. +10·6	—	—
			+10·1	+10·4	—	—
			+ 9·2	—	—	—
m. m.						
+5·5 to 5·1	—	—	—	—	1	—
5·0 to 4·6	—	—	—	2	1	—
4·5 to 4·1	—	—	—	7	—	—
4·0 to 3·6	—	—	2	14	—	—
3·5 to 3·1	—	—	—	4	2	—
3·0 to 2·6	—	—	—	1	—	—
2·5 to 2·1	—	—	—	1	—	—
2·0 to 1·6	1	—	—	2	—	—
+1·5 to 1·1	1	—	—	—	1	—
+1·0	—	—	—	—		—
0·9	—	1	—	—		2
0·8	1	1	—	—		2
0·7	1	1	1	—		3
0·6	—	1	—	1		3
0·5	1	—	—	—		1
0·4	2	2	1	1		4
0·3	—	3	—	1		6
0·2	1	2	—	—		8
+0·1	2	6	3	1		11
0·0	—	4	2	1		14
−0·1	—	4	4	3	None	9
0·2	—	3	5	2		5
0·3	2	2	2	4		4
0·4	1	1	—	—		4
0·5	—	1	1	—		3
0·6	1	1	—	2		3
0·7	—	—	—	—		1
0·8	—	—	—	1		0
0·9	—	1	—	2		2
−1·0	—	—	—	—		1
−1·1	—	—	1	—		0
−1·2	—	1	—	1		1
Large Errors .	—	− 3·3	−2·3	—	—	—
		− 4·2	−3·3	−3·4	—	—
		−14·2	−5·0	—	—	—
		−24·8	—	—	—	—

In Table I. the differences are grouped under distances from epicentre, all instruments *other than Milne* being grouped together.

Errors greater than 6 *m.*—The five large positive residuals are as follows:—

Observatory	Instrument	Date	Errors P	Errors S	Dist. from Epicentre
			m.	m.	°
Triest	W	1913, Jan. 11	+10·6	+7·4	95
Triest	W	1913, May 18	+10·4	—	96
Triest	W	1913, June 22	+10·3	—	83
Czernowitz	Ma.	1913, May 23	+10·1	+9·5	89
Pompeii	O.A.	1913, June 22	+ 9·2	—	88

The difference between the times of arrival of P and S being near 10 m. it is possible that some of these are mistakes of P for S. But in the case of Czernowitz, a mistake of 10 m. in both P and S seems probable. It is safer to omit these cases as anomalies than to attempt to correct them.

Errors. <6 *m. and* >1 *m.*—With the exception of a couple near the epicentre these do not develop until near 90°. Between 90° and 100°, however, they outnumber the normal errors given in the body of the table. They are doubtless due to the fact that a reflected wave has been mistaken for the direct wave. The fact that the first reflected effect PR is often more pronounced than P in the case of distant earthquakes is duly noted in Walker's monograph (p. 41); it may not, however, be realised that it is so often mistaken for P in the published records of sensitive instruments. Beyond 100° from the epicentre *no* times for P were correctly given at all for the five earthquakes here examined. It is not intended to ignore the fact that these differences will change with distance from epicentre, but for the present rough review we will neglect this change. The *median* is 3·75 m. or 3 m. 45 s. The mean of the differences from this is ± 0·53 *m.* But it does not seem clear that some of the differences which *may* be faulty P readings should be included. If these are excluded the median is 3·8 m.; the mean is 3·87 m.; and the mean of the differences from the mean is ± 0·35 m.

Normal Errors.—Coming now to the main part of Table I., if we take the errors as they stand (assuming the time-table for P correct throughout) the mean of the 87 differences is – 0·07 m. or – 4 s. But there is a systematic run about the differences as may be seen from the following means for the separate columns:—

0° — 40°	— 80°	— 90°	— 100°
m.	m.	m.	m.
+0·13	+0·01	−0·11	−0·27

The process adopted in the previous work does not justify any great refinement of correction; but we may fairly correct the different columns by the quantities

0° — 40°	— 80°	— 90°	— 100°
m.	m.	m.	m.
−0·1	0·0	+0·1	+0·3

and then the errors are distributed as in the last column. The mean is now +0·014 m. or +0·8 s. and the mean of the errors is ± 0·31 m., very close to the mean of the errors 0·35 m. obtained above for the reflected wave. A considerable part of this mean error may be due to the errors of reading distances from the epicentre, and to the error of assumed position of the epicentre itself.

Large Negative Readings.—The eight negative readings are probably due to accidental air tremors just preceding the quake; these call for no special remark here except that they seem to be pretty clearly separated off from the normal readings; even making a generous allowance for accidental error in the latter. It will be seen that the numerically smallest (– 2·3 m.) is a full minute away from the outside error (– 1·2 m.) included among possible normal readings. The details may be given here in case the observatories care to examine the records:—

Observatory	Instrument	Date	Errors P	Errors S	Dist. from Epicentre
			m.	m.	°
Lemberg . . .	B.O.	Jan. 11, 1913	– 3·3	—	88
Lemberg . . .	B.O.	Mar. 23, 1913	– 5·0	—	87
Lemberg . . .	B.O.	April 30, 1913	–14·2	—	79
Lemberg . . .	B.O.	June 22, 1913	– 4·2	–3·9	78
Aachen	W.	April 30, 1913	–24·8	—	80
Paris	—	Mar. 23, 1913	– 3·4	–0·7	98
Ksara	—	Mar. 23, 1913	– 2·3	—	90
Batavia . . .	W.	Mar. 23, 1913	– 3·3	—	47

Coming now to S, two large positive errors have already been mentioned as associated with large positive errors in P, viz., +9·5 m. at Czernowitz on 1913, March 23, and +7·4 m. at Triest on 1913, January 11, as also one considerable negative error of – 3·9 m. at Lemberg on June 22, 1913. These are omitted from further notice. Two large negative errors are

Observatory	Machine	Date	P	S	Δ
Tiflis	G	1913, Jan. 11	+0·2	–8·1	73°
Florence . . .	A	1913, Jan. 11	–0·9	–7·7	98°

The former is due to some unknown mistake; the latter is probably a mistake of S for PR_1. These are also omitted from further notice. Two positive errors of smaller amount as follows:—

Observatory	Date	P	S	Δ
Riverview	1913, June 22	–0·3	+4·5	94°
Heidelberg	1913, June 22	+0·1	+4·7	80°

are omitted as quite anomalous. The remaining errors are grouped in Table II.

TABLE II.

Errors of S for Seismographs other than Milne's.
(Unit 0·1 m. or 6 s.)

Errors	Distance from Epicentre 0°	40°	80°	130°
+2·1 to +2·5	—	—	1	—
+1·6 to +2·0	1	—	3	—
+1·1 to +1·5	2	3	1	—
+0·6 to +1·0	1	3	1	—
+0·1 to +0·5	1	4	3	—
−0·4 to 0·0	2	10	9	—
−0·9 to −0·5	1	4	12	—
−1·4 to −1·0	—	3	12	—
−1·9 to −1·5	—	2	7	—
−2·4 to −2·0	—	1		—
−2·9 to −2·5	—	—		—
Mean . .	+0·5	−0·2	−0·5	—

It would hereby appear that while the tables for P are fairly accurate, those for S are sensibly in error. The amount of error cannot be assigned more than very roughly by the present method, because the error for Pulkovo comes differently into the various earthquakes. But it would appear that the times of arrival of S at 20° distance and at 100° distance from the epicentre are relatively erroneous by something like a whole minute. The error is apparently not complicated in the case of S by any reflection phenomenon; the residuals for P are definitely grouped about two separate maxima, but for S this is not so. The first group (0° – 40°) is too small to show a decided maximum; but the position of the maximum is clearly marked in the other two by the numbers given in the table. As a rough expedient the following corrections have been applied:—

	Distance from Epicentre 15°	25°	35°	45°	55°	65°	75°	85°	95°	105°
Correction .	−0·3	−0·2	−0·1	0·0	+0·1	+0·2	+0·3	+0·4	+0·5	+0·6

the correction for 15° being applied to distances between 10° and 20°, and so on. The corrected errors are then distributed as follows:—

	Distance from Epicentre 0° – 40°	40° – 80°	80° – 130°	All
+2·8 to +3·2	—	—	1	1
+2·3 to +2·7	—	—	3	3
+1·8 to +2·2	—	—	—	0
+1·3 to +1·7	1	1	2	4
+0·8 to +1·2	2	6	—	8
+0·3 to +0·7	2	4	6	12
−0·2 to +0·2	—	11	13	24
−0·7 to −0·3	2	2	12	16
−1·2 to −0·8	1	4	10	15
−1·7 to −1·3	—	2	1	3
−2·2 to −1·8	—	1	—	1
Totals	8	31	48	87

The mean of the errors is ± 0·73 m., and though there is a slight tendency to increase from the second group to the third, the material is fairly homogeneous. Now, comparing this with the mean for P, viz. ± 0·31 m., it is clear that we are dealing with a much less definitely marked phenomenon, as is indeed well known. Part of each of these mean errors is due to errors of reading, &c.; and this part should be approximately the same in both. If we were to calculate and remove it, the ratio between the two, already greater than 2 to 1, would be sensibly increased.

In determining Δ from P and S, the superior accuracy of P is therefore rendered more or less useless by the uncertainty of S. Galitzin's azimuthal method of determining the epicentre has thus obvious advantages; if the epicentre is well determined from the azimuths at several stations, and if the time of the catastrophe is determined from the Ps at these stations, we should appear to have the material in the best shape for improving the tables of P and S, especially the latter.

But this is a digression from the present investigation, which is primarily concerned with the performance of the Milne instruments.

Putting aside for the present any question of correcting the tables for S, and therefore the position of the epicentre (as determined from Pulkovo), and consequent correction of the calculated times, it is clear that we can compare the performance of the Milne pendulums with other instruments on a common basis (though not the ultimate basis) by collecting their records for the same earthquakes in the same way. This is done in the following Table III., which corresponds to Table I.

It will be seen—

(*a*) That there are 5 large positive errors and 8 large negative errors, for which no special explanation can be given. In Table I. there are 8 negative errors, no positive.

(*b*) That in 6 + 5 + 10 + 5 = 26 cases, S has presumably been read in place of P. With other instruments there were only 5 such cases.

(*c*) That in at least 17 cases a reading has been made which can be attributed to a reflected wave. There are, moreover, 9 readings intermediate between these and the normal readings, which are extreme cases of one or the other. The line of demarcation is not so sharp as before. Similarly there are 5 doubtful negative readings.

(*d*) In the middle part of the table have been collected within the same limits as before what may be fairly regarded as normal readings.

They number 25 in all. They do not of themselves suggest any corrections to the table for P, but we might use the same corrections as before. It is simpler, however, to restrict attention to the second and largest group, the mean of the errors for which is ± 0·4 m. If, however, we include in this the 'doubtful' + 1·8 m., + 1·4 m., + 1·2 m., and − 1·0 m., − 1·2 m., the mean of the errors rises to ± 0·6 m. For other instruments this mean was ± 0·31 m.

The most significant fact is perhaps that of the whole 95 readings only 25 at a severe scrutiny, and at most (*i.e.*, including

TABLE III.

95 *Errors of P for Milne Seismographs in* 1913.

Error	0°—40°	40°—80°	80°—90°	90°—100°	100°—130°	130°—
Large Positive	—	+18·7	+39·4	+40·7	—	—
	—	+15·3	—	+25·0	—	—
Transferred to S	—	(6)	(5)	(10)	(5)	—
PR$_1$	—	+4·3	—	(9)	(6)	—
	—	+3·3	—	—	—	—
Doubtful	—	+2·9	—	+2·8	+2·0	—
	—	+2·7	—	+2·0	—	—
	—	+1·8	—	+1·4	—	—
	—	+1·4	—	—	—	—
	—	+1·2	—	—	—	—
m.						
+0·9	—	1	—	—	1	—
+0·8	—	1	—	—	—	—
+0·7	—	—	1	—	—	—
+0·6	—	—	1	—	1	—
+0·5	1	1	—	—	—	—
+0·4	—	1	—	—	—	—
+0·3	1	3	—	—	—	—
+0·2	—	2	—	—	—	—
+0·1	—	2	—	—	—	—
0·0	—	1	—	—	—	—
−0·1	—	—	—	—	—	—
−0·2	2	1	1	—	—	—
−0·3	—	1	—	—	—	—
−0·4	—	—	—	—	—	—
−0·5	—	—	—	—	—	—
−0·6	—	—	—	—	—	—
−0·7	—	1	—	—	—	—
−0·8	—	—	—	—	—	—
−0·9	—	1	—	1	—	—
Doubtful	−1·2	−1·0	—	−1·9	−1·0	—
	—	−1·2	—	—	—	—
Large Negative	—	− 3·4	—	−5·4	−12·4	—
	—	− 5·8	—	—	−17·5	—
	—	−10·1	—	—	−25·4	—
	—	−35·3	—	—	—	—

all those marked doubtful) only 39, can be regarded as true readings of P; say 40 per cent. at most. With the other machines there are 87 out of 134, or 65 per cent.

Coming now to S, and correcting the results (which include those transferred from P) as for other instruments, we find 12 large errors; the others are distributed as below:—

TABLE IV.

38 Errors for S in Milne Seismographs in 1913.

	Distance from Epicentre			
	0° — 40°	40° — 80°	80° — 130°	All
m. m.				
+3·3 to +3·7	—	1	1	2
+2·8 to +3·2	—	—	—	—
+2·3 to +2·7	—	—	3	3
+1·8 to +2·2	—	1	1	2
+1·3 to +1·7	—	—	1	1
+0·8 to +1·2	—	1	2	3
+0·3 to +0·7	2	2	2	6
−0·2 to +0·2	—	3	3	6
−0·7 to −0·3	—	2	5	7
−1·2 to −0·8	—	—	2	2
−1·7 to −1·3	—	2	2	4
−2·2 to −1·8	—	—	1	1
−2·7 to −2·3	—	1	—	1

The mean of the errors is ± 1·1 m.; for other instruments it was ± 0·73 m. The ratio of these is about the same as in the case of P. But it will be seen that there are acceptable readings of S in 38 cases, whereas for the same earthquakes there are only 39 of P at most. It is usually considered that the Milne instruments show P but not S. The evidence here tabulated points to the conclusion that S is shown at least as well as P. It is true that the five earthquakes considered are large ones; but it might reasonably be argued that P should therefore have the better chance of asserting itself. It seems probable that in some cases P could be recovered from the records when it was realised that the reading formerly given was that of S. The important point is that without any great difficulty it can be settled when we have an S reading, for the cases of doubt are few. We may now give the 12 large errors excluded as mistakes; they are +35·2 m., +11·9 m., +10·3 m., +9·1 m., +8·7 m., +8·6 m., the smallest of which exceeds the maximum error (+3·5 m.) accepted as S by over 5 m.; and on the negative side we have −4·4 m., −4·4 m., −5·1 m., −8·0 m., +11·8 m., and −14·2 m. Here the separation is not so marked; but there is a full 2 m. interval. Some or all of these negative errors may be readings of PR_1, but the two largest, which both occur on January 11 (Toronto −11·8 m. and Stonyhurst −14·2 m.), are supported by several other readings and probably refer to a preliminary shock. As the performance of the Milne pendulums is the main point under investigation, not only were the above five earthquakes used, but also five others in 1911 as follows:—

—	Date	Adopted Epicentre	Adopted Time		
		° °	h.	m.	s.
I.	1911, July 4	39·0 N., 71·4 E.	13	33	33
II.	1911, July 12	27·0 N., 116·0 E.	4	9	7
III.	1911, Aug. 16	19·0 S., 140·0 E.	22	38	51
IV.	1911, Oct. 14	33·5 N., 82·5 E.	23	24	1
V.	1911, Dec. 16	12·0 N., 101·8 W.	19	13	51

For these earthquakes Pulkovo epicentre determinations were not available, but the results from Galitzin instruments at Eskdalemuir are published in the 'Geophysical Journal,' and have been adopted for use. The computations were kindly made by Mr. A. E. Young, formerly Deputy Surveyor-General of the Malay Survey, who is at present working at the Oxford University Observatory; and in this instance greater care was taken, Mr. Young calculating the distances trigonometrically (instead of reading them from a globe) and using the times and tables to seconds of time in the computations, though in giving the results the unit 0·1m. has been considered sufficient.

V.—*Comparison of Films for* 1911.

The chief object in using this additional material was as follows. It was thought that some of the errors of the Milne instruments might be due to faulty readings of the records, susceptible of correction. To test the general accuracy of such readings the different stations were invited to send their films for the year 1911 to Shide, and many of them have responded. Some had bound up their films in such a way that transmission was undesirable; but films for 1911 have been received at Shide from Cape Town, Cork, Toronto, San Fernando, Sydney, Helwan (Egypt), Victoria, Ascension, Perth, Seychelles, Eskdale, Guildford, and Colombo, and have been systematically examined at Shide by Mr. Burgess and Mr. Pring, who have had much experience in reading the Shide films. It was thought advisable to make this examination quite independently, before knowing whether the revised readings would suit the calculated facts better; and indeed the calculations were made at Oxford, so that the Shide readings were made in ignorance of the tabular result either before or after. On comparing the old and new readings with expectation, it does not appear that the new afford any systematic improvement on the old. The actual figures for the above five earthquakes are as follows (the quantities given being differences from expectation, calculated as already indicated). They apply entirely to the phase P, the phase S being seldom read from the Milne records.

TABLE V.

Comparison of Original and Revised Readings of Various Films for the Phase P.

Ascension.

Quake.	Orig.	Rev.
II.	−5·5	Not read
III.	+5·1	+5·1

Cape Town

Quake.	Orig.	Rev.
I.	−0·9	+0·2
II.	+2·3	+2·9
III.	+6·3	+5·8
V.	+5·5	+5·1

Helwan.

Readings for Jan. and Feb. confirmed former results so consistently that the scrutiny was discontinued as superfluous.

Perth.

Quake.	Orig.	Rev.
III.	+3·5	+3·5
V.	+2·4	+2·5

San Fernando.

Quake.	Orig.	Rev.
I.	−0·2	−3·0
III.	+5·9	+6·6
IV.	+6·5	+21·7
V.	−0·3	−0·7

Seychelles.

Quake.	Orig.	Rev.
I.	+6·0	Not read
II.	+0·0	−1·0
III.	+1·5	+1·5
V.	(37·0)	(34·0)

For V. epicentre is so distant that tables fail.

Sydney.

Quake.	Orig.	Rev.
I.	+2·8	−14·4
II.	−4·5	−41·9
III.	+1·7	−13·2
IV.	+9·6	+ 9·2

For II. an earlier quake is confirmed by Alipore. For III. see Toronto.

Toronto.

Quake.	Orig.	Rev.
I.	+10·1	−14·4
II.	+ 4·9	+ 4·1
III.	+ 9·7	−14·3
V.	− 0·3	− 1·1

For III. see Sydney.

Victoria.

Quake.	Orig.	Rev.
V.	− 0·1	− 0·1

Films not sent for other earthquakes.

After consideration of the above figures, it was decided to apply no corrections at all, but to accept the original readings as they stand, and in Table VI. these are compared with calculated values. The table corresponds to Table III. except that Δ was now used in km., and the grouping is therefore a little different.

There is room for some difference of opinion as to the 17 records marked doubtful; but the $12+13+15+3+4=47$ readings in the body of the table are probably normal. We thus get at least 47 but not more than 64 normal readings out of 108. These figures are better than the 1913 figures and encourage the hope that on the whole 50 per cent. of the recorded readings for P may be normal; but the percentage cannot be higher than this.

One feature of the records seems to demand further investigation. There is a suggestion that the readings are divisible into two groups separated by about a whole minute; and this applies also to the results for 1913, though they are scarcely numerous enough to declare it independently. It will be seen that the records −0·4 m. and −0·5 m. are not represented in either table, thus creating an appearance of separation. But this may be purely accidental.

Coming now to S, Table VII. has been formed in the same manner as before, adopting the same corrections to the tables for time of S. There are three consistent observations of S at Δ =15,000 kms. for which the tables are scarcely available but were

Table VI.

108 *Errors of P for Milne Seismographs in* 1911.

	Distance from Epicentre in kms. 0 — 5000	5000 — 9000	9000 — 10000	10000 — 11000	11000 — 13000	13000 — over	
Large Errors .	m. +17·2 —	m. +22·1 +16·1	— —	— —	— —	— —	
S	(2) — —	(6) — —	(1) — —	(3) — —	(0) — —	— — —	+10·8? + 9·7? + 8·5?
PR_1 . . .	— — — —	+4·5 +3·3 +2·6 +2·6	+4·4 +4·3 +4·2 —	+6·1 — — —	+6·3 +5·2 +4·9 —	+5·9 +5·7 +5·5 +5·3	+5·2 +5·1 +4·4 +3·9
Doubtful . .	+1·7 +1·2 +1·0 +1·0	+1·7 +1·7 +1·5 +1·5	+1·5 +1·5 +1·0 —	— — — —	+2·8 +2·3 +1·0 —	+3·0 +2·4 +1·4 —	— — — —
+0·9	—	—	—	—	1	—	
+0·8	—	—	—	—	—	—	
+0·7	—	—	—	—	—	—	
+0·6	1	—	—	—	—	—	
+0·5	—	1	—	—	1	—	
+0·4	—	—	1	—	—	—	
+0·3	—	1	1	—	—	—	
+0·2	1	1	2	—	—	—	
+0·1	—	—	—	—	1	1	
0·0	—	1	1	—	—	—	
−0·1	1	—	2	—	—	1	
−0·2	—	2	—	—	—	—	
−0·3	1	1	2	—	—	1	
−0·4	—	—	—	—	—	—	
−0·5	—	—	—	—	—	—	
−0·6	2	3	—	—	—	—	
−0·7	1	—	—	—	—	—	
−0·8	2	1	2	—	—	—	
−0·9	1	1	2	—	—	—	
−1·0	1	—	—	—	—	—	
−1·1	1	—	—	—	—	—	
−1·2	—	—	1	—	—	—	
−1·3	—	—	1	—	—	—	
−1·4	—	—	—	—	—	—	
−1·5	—	1	—	—	—	—	
Large Errors .	−43·0 — —	−3·6 −4·5 −4·7	−4·8 — —	−3·7 — —	— — —	−5·5 — —	

provisionally extended. It seems clear that an even larger correction is necessary at this distance than has been assumed. In calculating the mean error these observations have been omitted, and the mean error is then ± 1·1 m. as before. Including them as they stand raises it to ± 1·2 m.

TABLE VII.

36 Errors for S for Milne Seismographs in 1911.

	Distance from Epicentre in kms. 0 — 5000	5000 — 9000	9000 — 10000	10000 — 11000	11000 — 16000	All
+2·8 to +3·2	—	—	1	—	—	1
+2·3 to +2·7	—	1	1	—	—	2
+1·8 to +2·2	1	1	—	—	—	2
+1·3 to +1·7	—	—	—	—	—	0
+0·8 to +1·2	—	—	2	1	—	3
+0·3 to +0·7	—	3	2	1	—	6
−0·2 to +0·2	—	1	3	—	—	4
−0·7 to −0·3	—	3	—	1	—	4
−1·2 to −0·8	4	2	—	1	—	7
−1·7 to −1·3	—	1	1	—	(1)	2
−2·2 to −1·8	—	1	—	—	(2)	1
−2·7 to −2·3	—	1	—	—	—	1

In addition there are three large positive errors (+9·9 m., +7·8 m. and +7·8 m.) and four large negative (−5·2 m., −5·8 m., −6·7 m. and −8·1 m.), which may be reflected waves. The percentage is slightly less than before, but, putting 1911 and 1913 together, we have 36+39=75 tolerably certain S readings as against 47+25=72, or possibly 64+39=103 P readings. The fact that S is as often readable as P on Milne seismograms, at any rate for large earthquakes, seems to be thus fairly well established.

VI.—*Comparison of Milne and Galitzin Instruments.*

To the information conveyed by the above discussion the following may be added. At Eskdalemuir Observatory various seismographs have been mounted side by side for comparison, and Mr. G. W. Walker made very careful and thorough comparisons of the relative advantages as indicated in his book already referred to. It seemed desirable at the present juncture to have a formal report on the comparison of the Milne instrument with at least one other; and the Galitzin seemed the best to select as standard of comparison. Application was therefore made to the Superintendent of the Meteorological Office, and he kindly sent the following report, to which the names of L. F. Richardson and L. H. G. Dines are attached.

Comparison between the Milne and the Galitzin types of Seismographs.

It is convenient to treat the question under several different aspects, and a brief description of the two instruments may usefully precede the rest.

It is unnecessary to say much about the Milne instrument. Extreme lightness and compactness characterise it, and no simpler method of optical registration could well be devised. No expensive lenses are needed, and, with the exception of a few parts of the mechanism, no specially high-class work is required in manufacture. The whole of the apparatus is self-contained and does not take up much floor-space. It does not require a continuously darkened room in which to work. Two pendulums to record both N.S. and E.W. movements can be installed in the same case and record on the same drum.

The Galitzin instrument, on the other hand, is a very much more complicated affair. It is designed to follow a somewhat elaborate mathematical theory, and high-class workmanship and accuracy are needed in its construction. Its pendulum is shorter than the Milne and much heavier—say, seven kilograms. It is hung by two steel wires (Zollner system), and has no pivot at all in some cases. Provision, however, is made on the pendulum and frame for a steel point and cup to be inserted if required. The supporting wires might, with advantage, be made of tungsten if corrosion were feared. At the outer end of the boom are fixed to the frame four powerful horseshoe magnets. Between the poles of one pair of these moves a set of wire coils fixed to the boom and coupled in series with a delicate galvanometer placed in any convenient position elsewhere. Between the other pair is a large copper plate, also fixed to the boom, and this last acts as a magnetic damper. The magnets can be adjusted as desired to vary the magnetic field between the poles.

The galvanometer is of the moving coil type, and has a long period of oscillation when undamped. This galvanometer is an excellent piece of work and is electrically damped so that it can be rendered just aperiodic. With the whole instrument in normal working it is necessary that the undamped periods of both pendulum and galvanometer should be the same, and that they both should be damped just to the limit of aperiodicity.

The optical registration consists of a collimator with a fine slit powerfully illuminated. The beam is reflected from a mirror on the galvanometer and thence to the recording drum, where a cylindrical lens condenses the line of light into a point on the paper.

The two pendulums for recording N.S. and E.W. movements are under entirely separate covers, and in a more refined installation two separate drums are also used; but it is possible to use one drum only and arrange the spots of light from the two galvanometers side by side.

A good deal of floor space is required, and the room in which the recording parts are placed must be kept dark.

The galvanometers and recording drum may be placed in a separate room altogether; and, in fact, are better so placed. The presence of the attendant is likely to disturb the pendulum if he brings his weight near the pillar on which it stands. The recording part of the apparatus is quite unaffected by disturbances in the room in which it is placed.

For a further description of the Galitzin instrument see (1) 'Modern Seismology,' by G. W. Walker, F.R.S., chapters 2 and 3.

(2) The catalogue supplied by H. Masing, St. Petersburg, the makers of the pendulum and recording part of the instrument. (3) 'Ueber ein neues Aperiodisches Horizontalpendel mit galvanometrischer Fernregistrierung,' by Prince B. Galitzin. (4) 'Ueber einen neuen Seismographen für die Vertikalkomponente der Bodenbewegung,' by Prince B. Galitzin. (5) 'Die electromagnetische Registriermethode,' by Prince B. Galitzin, Academy of Sciences, St. Petersburg.

The Galitzin recorder for vertical movements operates electrically in exactly the same manner as the horizontal instrument, and a similar magnetic damper is fitted to it. The room in which the pendulum is placed must be maintained as far as possible at a uniform temperature, as the change in the elasticity of the spring which supports the pendulum causes excessive wandering if the temperature changes by even as little as 0.5 per cent.

Comparative cost.—A Galitzin installation is much more expensive than a corresponding Milne one. Two horizontal pendulums complete with galvanometer and one recording drum cost at least 148*l.*, while the pendulum for vertical movements with galvanometer and drum costs at least 110*l.*

This does not exhaust the expensiveness of the instruments, since about six times as much sensitive paper is required for one Galitzin recording drum as for one modern Milne drum for two pendulums. It is customary to run the paper at three centimetres per minute, and unless the optical arrangements were improved it would be hardly feasible to run it at much less speed without losing a good deal. Under these circumstances the cost in paper alone of one recorder is about 33*l.* per annum.

Attention required.—The Milne instrument does not require more than ordinary skilled attention. If the operator be used to handling delicate instruments little more is required. Of the Galitzin instrument the same may be said as far as the ordinary routine is concerned, but the greater complexity of the apparatus means a greater number of things liable to go wrong, and sooner or later it is almost certain to happen that highly skilled attention is necessary. Both types of instrument require periodical standardisation, but while in the Milne type this is quite a simple process, in the Galitzin it is quite otherwise. A certain amount of auxiliary apparatus is required, such as telescopes and scales, and two persons are necessary to make simultaneous observations of the pendulum and galvanometer; when these have been made the constants of the instrument can be determined. Prince Galitzin has worked out formulæ for this purpose.

The whole process has in general to be gone through twice for each instrument, and it is a lengthy operation, taking probably about two working days. A certain measure of observational skill is required to take the necessary readings accurately, as well as a fair working knowledge of mathematics to deal with the results when obtained.

It would be possible to simplify the process somewhat more than has at present been done, and reduce it largely to routine; but a Galitzin installation must always require a greater measure of skilled attention to run it successfully than is the case with the simpler types of instruments.

It is difficult to estimate what is the minimum of mathematical and physical knowledge that must be possessed by an assistant in order to maintain successfully a Galitzin installation. A working knowledge of algebra is essential, and probably with this as a basis an intelligent operator could learn the rest of the routine with the aid of computing-forms. But without a knowledge of higher mathematics, and particularly elementary differential equations, it is impossible to understand the meaning of the formulæ by which the constants are determined.

Results obtainable.—The Milne type of instrument is very sensitive as a mere seismoscope. With the exception of very faint movements indeed, some record of a distant quake can always be obtained by it; this is due to the absence of damping and almost entire absence of solid friction; by altering the period of oscillation of the boom it can be made particularly sensitive to any wave-period desired. The instrument at Eskdalemuir Observatory has at present a period of about eighteen seconds, and this corresponds approximately with the wave periods from very faint and remote shocks. For waves of this type the Milne instrument leaves some record of almost any earthquake that affects the Galitzin instrument; but whereas the latter gives a trace that approximately follows the actual movements of the ground, the trace from the former has little resemblance to it. Maximum movements on the Milne record may or may not coincide with the maximum movements of the ground: it depends on the type of the earth movements and on the period of the pendulum. By damping slightly, a more faithful record can be obtained, and by making the pendulum actually dead beat a moderately close agreement will prevail between the actual earth movements and those worked out from the record. This can be established theoretically, but Prince Galitzin has also conducted experiments which show that theory and practice are in close agreement. See Professor C. G. Knott's book on 'The Physics of Earthquake Phenomena,' chapter 5, Unfortunately the reduction in the scale of the record which accompanies damping renders the Milne pendulum very insensitive when damped. For some months an oil damper has been fitted to one of the Milne pendulums at Eskdalemuir; the ratio of successive elongations is approximately 2:4. The results obtained are disappointing for the reason given above.

If any satisfactory means could be found of increasing the magnification optically even by a moderate amount, the damped Milne pendulum should be capable of yielding good results, and the greater simplicity of standardisation should be another point in its favour.

Turning to the Galitzin type of machine, as an instrument of precision it may safely be said to be ahead of all others. The interpretation of its records is not a very simple matter, but by those prepared to spend the time a vast amount of information can be obtained. The scale of magnification varies widely with different wave-periods, being in general approximately 800 as a maximum and for periods of about fourteen seconds, and falling off for either longer or shorter periods.

The preliminary tremors of a distant earthquake can be examined particularly well, and individual impulses analysed. An experienced observer can analyse these preliminary phases from the shape and general appearance of the record far more easily than can be done in the case of the undamped Milne record. See 'Modern Seismology,' by G. W. Walker, F.R.S., chapter 7, for fuller information on this point.

It is probably safe to say that a full and rigid investigation into the theory of these instruments has not yet been published, and the possibilities of deducing complicated formulæ in that direction are vast. The high degree of accuracy that in favourable circumstances has been obtained in locating epicentres, using the records from a single station only, is sufficient to demonstrate the excellence of the instrument as at present used. It would be well to state here that, though the Galitzin record does not represent the ground motion accurately in many cases, yet in the case of the first movement of the first phase P of an earthquake the movements on the N.S. and E.W. records will be proportional to the actual earth movements provided that the two pendulums and galvanometers are in correct adjustment and have the same undamped period. Hence the azimuth can in favourable circumstances be accurately and easily determined, though to work out the actual earth movements would be a complicated matter.

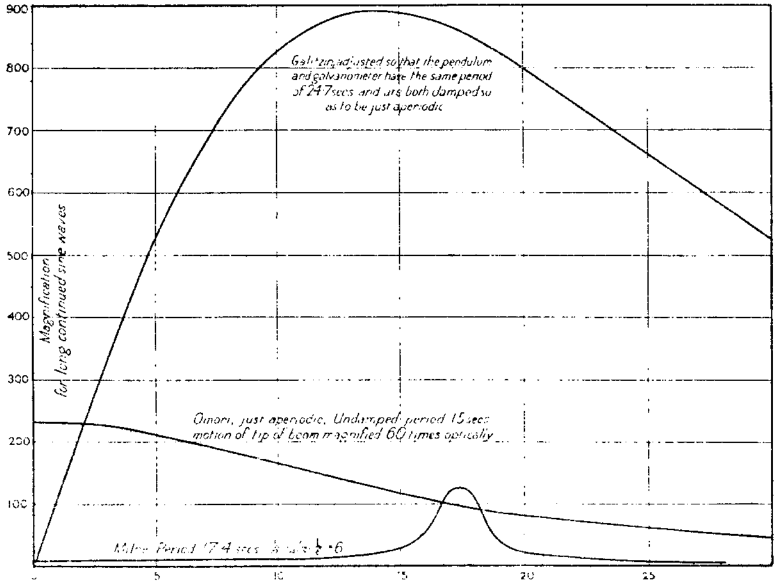
One point worthy of mention in which the Galitzin instrument differs from most or perhaps all others is the absence of trouble arising from the wandering of the pendulum. However the latter may wander, the zero of the galvanometer is unaffected. The scale value may be altered slightly if the pendulum be far from the middle position, but this can easily be corrected from time to time. This quality renders the instrument useless for determining slow changes in tilt, as can be done with other types.

Mention has been made above of varying scale value; this introduces another limitation. For very short periods the magnification is very small, being about 110 for one-second period and varying directly as the period for lesser values.

Hence rapid vibrations will leave no record, and this may be the explanation of the fact that small local earthquakes are not recorded on this type of instrument.

Owing to the high degree of magnification and great sensitivity, some trouble is experienced from disturbances due to high winds, and from experience at Eskdalemuir it would seem desirable to house the pendulum in a small sheltered building rather than a large exposed one. Heavy weights moving in the vicinity cause trouble, as with any other sensitive instruments; but the records so produced being of definite character can be readily traced to their origin, and are immaterial if not too frequent. Occasional traffic along a neighbouring road would not cause much confusion on the record.

A curve is shown attached giving the magnification of movement in both the Milne and Galitzin types. It refers solely to the case



of a long-continued series of uniform waves; but it is noteworthy that in the Milne type it cannot be applied to any other kind of motion and may be considerably in error even one or two minutes after the commencement of the series.

In the Galitzin type, however, the free motion dies away much more rapidly.

VII.—*Present Value of the Milne Instrument.*

We may summarise the present situation as follows:—

(*a*) The Milne instrument is undamped, but for one purpose—viz., the determination of times of arrival of P and S—this does not matter. There has been an idea that S (or P_2) is not easy to read on Milne records; but S has often been read in mistake for P, and when these readings are counted properly S seems to be identifiable as often as P. On the other hand, the absence of damping makes the readings of maximum of uncertain significance.

(*b*) The time scale of the Milne instrument is small and its magnification is also small. Both might be increased with advantage, and it seems probable that then the times of arrival of P and S could be read as well as on most other instruments.

(*c*) The present wide dispersion of Milne stations makes the records of great value. Most of the modern instruments are in Europe. For an earthquake in Europe they are distributed in various azimuths (not quite a complete circuit even then), but for distant quakes they cluster in the same azimuth and give no material for discussion in azimuth (see Section VIII.). The Milne stations, however, especially those in Australia, can supply this information.

It is clear, then, that the usefulness of the Milne instruments is by no means at an end, as the perfection of modern seismographs (especially the Galitzin instrument) might at first suggest. And it should not be difficult to extend it considerably.

(*a*) It can be *damped* effectually. Mr. J. J. Shaw, of West Bromwich, has done this electro-magnetically with an aluminium plate in place of the Galitzin copper plate, which is too heavy for the light Milne boom. At present, however, he has not obtained simultaneously sufficient magnification to give the damping effect: damping is chiefly of use for following the movements of the long waves, and the scale should be big enough to show them clearly. Mr. Shaw is still at work on the instrument, and hopes to obtain the requisite magnification.

(*b*) There should be little difficulty in increasing the magnification moderately both in movement and in time scale, though it may not be easy to settle which is the very best way of doing it. The experiments being made by various observers should at least give us a feasible plan.

(*c*) Meanwhile *if special attention is paid to getting good time determinations*, and if the films are carefully read with a lens, the times of arrival of P and S for Milne stations should enable us to correct the tables for considerable distances from the epicentre where the European stations all agree and are all in error owing to their congestion in azimuth. (See next Section.)

VIII.—*Correction of the Tables for P and S.*

Recurring to the discussion of Section IV., it was shown that the tables for both P and S were sensibly in error, and the question arises how far they can be corrected. The main facts are these :—

(α) The tables for small values of Δ are sensibly correct. This is shown by the agreement of determinations of epicentres from Pulkovo and Eskdalemuir, quoted by G. W. Walker in his monograph (p. 65). From each station the azimuth a and the distance Δ can be determined ; and from the two azimuths a and a_2 the epicentre can be determined without reference to Δ at all.[1] This is a modern advance, the importance of which is not easily over-estimated. If then the values of Δ determined from the P and S tables agree (to a fraction of a degree) with those found from the azimuths, the tables must be fairly correct. The value of Δ is about 20°.

(β) But this single example may give quite a wrong impression of the accuracy with which an epicentre is at present determined. At greater distances we gradually lose the accordance between these stations. Thus, on January 4, 1912, Pulkovo gives 175° E., 49°·5 N., and Eskdale-

[1] See letter of Galitzin and Walker in *Nature* for September 5, 1912.

muir 177° E., 51° N.; on July 9 Pulkovo gives 30°·3 E., 2°·1 N., and Eskdalemuir 33°·9 E. and 5°·3 N.; and at greater distances still the discordance may be 5° or even 10°. The azimuths may still be good, though as the azimuthal lines do not meet so sharply, the determination becomes less definite; and, moreover, it must be remembered that actual errors in the adjustment of the booms become of greater importance. We have nothing to set against the clear evidence offered in Section IV. that the tables for S are in error, though since the errors there found are only *relative*, we may add a constant to them all, substituting, for instance, for

Error at 15°	35°	55°	75°	95°	115°
m.	m.	m.	m.	m.	m.
−0·3	−0·1	+0·1	+0·3	+0·5	+0·7

the revised values

0·0	+0·2	+0·4	+0·6	+0·8	+1·0

so that the error is small near the epicentre.

Similarly the errors for P might be written—

Error at 15°	35°	55°	75°	95°	115°
m.	m.	m.	m.	m.	m.
0·0	0·0	+0·1	+0·2	+0·4	+0·6

if we determine to keep the error small near the epicentre. In this case it seems possible that the revised tables just published by the K.G. Landesantalt für Meteorologie und Geodynamik in Zagreb (Agram) might supply information which would determine the unknown arbitrary constant. The errors of the Galitzin tables indicated by Zagreb at the above points are

	m.	m.	m	m.	m.	m.
	+0·1	+0·1	0·0	+0·1	+0·2	+0·3
Difference	+0·1	+0·1	−0·1	−0·1	−0·2	−0·3

The differences do not, however, remain constant, even approximately. The present comparison indicates larger errors for values of Δ greater than 75° than the Zagreb tables admit.

It thus appears that the moment is not yet come to suggest corrections to the tables which are likely to meet with general acceptance. It seems better to retain the old tables until a much greater mass of material has been discussed, and the old tables will accordingly be used for the comparisons made at Shide at any rate for the observations of 1914. The discussion of some 100 earthquakes should provide corrections approximating to definitive ones. Meanwhile, the best available corrections to the tables from the material above discussed, incorporating the information derived from the next section, are given at the end of the next section.

IX.—*Discussion in Azimuth.*

If the receiving stations are arranged in azimuth (A) round the epicentre, then

(*a*) Assuming the velocity of transmission constant in all azimuths, any error (δ) of position of the epicentre will give rise to an error

$$c + e \cos (A - A_0)$$

in the observed times at the stations: where A_0 is the azimuth in which the epicentre is erroneously displaced; A is the azimuth of the receiving station; e is the effect of the displacement (δ) on P or S, as the case may be, at the distance of the receiving station; and c is a constant depending on the position of Pulkovo, or other station from which the epicentre is determined.

(b) If the velocity of transmission varies with the azimuth, then, if the velocity in azimuth A is not the same as in azimuth A + 180°, there will be a first-order harmonic which will be mixed up with that just written, due to the error in position of epicentre; and it may be difficult to separate the two. If, however, the velocity is the same for A and A + 180°, then we may look for a second-order harmonic to represent the variation. It will be seen from what follows that there are no trustworthy indications of such terms from the material now discussed. The material is insufficient to pronounce definitely against the existence of such terms, especially with small coefficients; but it is apparently sufficient to discredit any large term of the kind. For instance, Milne suggested a velocity N. and S. sensibly less, in the case of the large waves, from the velocity E. and W. (Eighteenth Report, § v). No such difference can be detected in the velocities for P and S.

We will first give in some detail the results for a single earthquake, that of 1913, January 11, adopted epicentre 6° N., 117° E. The residuals for P, when corrected for distance from epicentre as in Section IV., and arranged in azimuth measured from the N. point round the epicentre in the direction N., E., S., W., are as shown in Table VIII.

We see at a glance the better distribution of the Milne pendulums; most of the modern pendulums are in Europe and appear in the same azimuth-class 300°—330°. Were it not for the Milne instruments we should have very scanty material for an azimuth discussion; and yet this is one of the most favourable cases. The inferiority of the Milne instrument suggests giving a smaller weight to its records, but it will be seen that we should gain very little thereby. Taking the simple means as in the last column and filling in vacant terms by simple interpolation (in brackets), we can make a very rough harmonic analysis, obtaining

$$-1{\cdot}6 + 7{\cdot}5 \cos (A-330°) + 2{\cdot}7 \cos 2 (A - 70°).$$

Treating the S observations in the same way, we get Table IX.

The material for discussion in azimuth is even more scanty and uncertain than before; but, analysing it for what it is worth, we get

$$-1{\cdot}2 + 8{\cdot}0 \cos (A - 332°) + 4{\cdot}7 \cos 2 (A - 177°).$$

Now, considering the nature of the material and of the process used, it is somewhat remarkable that the results from P and S should accord so well in indicating a correction to the epicentre. The direction is in azimuth 331° say, and as the azimuth of Pulkovo is 330°, it is pretty clear that the estimated Δ for Pulkovo is in error, owing doubtless to the errors of the tables. The *amount* of displacement is not so easy to assess. In the above simple process we have treated all stations, at whatever distance from the epicentre, alike. A displacement of the epicentre of 1° will, however, alter the times of arrival of P by 16 s. near the epicentre, by 5½ s. at 90°, and by less still at greater distances. Nevertheless, on calculating the alterations for the actual distances, the mean

TABLE VIII.

Distribution of errors of P in azimuth round epicentre, 1913, *January* 11.

(The unit is 0·1 m. or 6 secs.)

(*a*) *Instruments other than Milne.*

0° — 30°	— 60°	— 90°	— 120°	— 150°	— 180°	— 210°	— 240°	— 270°	— 300°	— 330°	— 360°
+ 4 + 3 − 4				− 12	+ 1		0			+ 17 + 7 + 7 + 6 + 4 + 4 + 4 + 3 + 2 + 2 + 1 − 5 − 6	+ 3

(*b*) *Milne Instruments.*

0° — 30°	— 60°	— 90°	— 120°	— 150°	— 180°	— 210°	— 240°	— 270°	— 300°	— 330°	— 360°
+ 11		− 1		− 9 − 12	− 16	− 13	0	+ 3	+ 9 + 5 + 2	+ 14 − 9	
+ 4	(+ 2)	− 1	(− 6)	− 11	− 8	− 13	0	+ 3	+ 5	+ 3	+ 3

TABLE IX.

Distribution of errors of S in azimuth round epicentre, 1913, *January* 11.

(The unit is 0·1 m. or 6 secs.)

	0°—30°	—60°	—90°	—120°	—150°	—180°	—210°	—240°	—270°	—300°	—330°	330°—360°
(a) Instruments other than Milne.												
	+ 15 + 5					+ 3		− 16 − 5 − 5			+ 13 + 11 + 4 + 4 − 1 − 1 − 3 − 5 − 7 − 8	+ 11
(b) Milne Instruments.												
	− 5				− 10 − 16 − 20					+ 6	+ 23 − 8 − 18	+ 22
Mean	+ 5	(0)	(−5)	(−10)	− 15	+ 3	(−3)	− 9	(−2)	+ 6	0	+ 16

for the different groups was found to be nearly constant at about 8 s. Since the coefficient (8 units of 0·1 m.) means 48 s., we may take it that the epicentre is about 6° wrong. As regards direction, note that the observed times for receiving stations on the side of the epicentre remote from Pulkovo are too small; so that the epicentre must be moved nearer to them and further from Pulkovo. The observed S–P at Pulkovo, viz. 10 m. 24 s., does not correspond (as indicated by the present tables) to an epicentral distance of 83°·5, but to a distance of 89°·5.

Turning to S, we find the average value of 1° to be about 13 s. The first harmonic of S thus indicates a displacement of 48°/13 or 3°·7. We may regard this as a satisfactory confirmation of the magnitude of the error, which may be put at about 5°.

The second harmonics in both cases are small, and the phases are quite discordant. We may fairly say that there is no evidence of a variation in velocity of an elliptic type.

As regards other earthquakes analysed for azimuth the following notes will suffice:—

1913, *March* 14. *Epicentre* 11° *N.*, 123° *E.*, *distant* 82° *from Pulkovo.*

Of nearly same type as that of 1913, January 11, but distribution of stations not so good. The numbers in the 30° divisions for P are

1 1 0 0 1 2 1 1 1 4 33 5

and the harmonic expression is (in units of 0·1 m.)

$$+ 0{\cdot}2 + 5{\cdot}0 \cos (A - 302°) + 4{\cdot}0 \cos 2 (A - 36°).$$

For S the number of stations are

1 1 0 0 0 6 0 0 0 2 24 3

and the harmonic expression is

$$- 7{\cdot}8 + 14{\cdot}5 \cos (A - 345°) - 4{\cdot}2 \cos 2 (A - 7°).$$

In spite of the broken nature of the series, the indication of an error of about 4° or 5° in Δ is tolerably plain. The azimuth of Pulkovo is 330°, and the magnitudes of the displacement assigned by the P observations may be put at 30°/8 = 3°·8.
,, S ,, ,, ,, 87°/13 = 6°·7.

There is some indication of a second order term, but it cannot be regarded very seriously.

1913, *March* 23. *Epicentre* 26° *N.*, 143° *E.*, *distant* 78° *from Pulkovo.*

The only available observations between azimuths 0° and 210° are two Milne observations of P and one Milne of S. There seems no advantage in making even a rough estimate.

1913, *April* 30. *Epicentre* 50° *N.*, 176° *E.*, *distant* 67° *from Pulkovo.*

Number of observations in the separate groups

for P	4	2	0	0	1	0	0	0	3	1	3	14
for S	4	3	1	0	0	1	0	0	1	2	1	10

Harmonic expressions

from P $+ 2\cdot1 + 2\cdot7 \cos (A - 207°) + 3\cdot6 \cos 2 (A - 73°)$
from S $+ 0\cdot5 + 11\cdot0 \cos (A - 235°) + 2\cdot6 \cos 2 (A - 160°)$

Azimuth of Pulkovo being 342°, the mean direction of displacement (azimuth 220° say) is nearly at right angles to the direction of Pulkovo, and cannot be wholly explained by an error of tables. The small component in the line joining epicentre to Pulkovo is in the opposite direction to that previously noted.

1913, *June* 14. *Epicentre* 43° *N.*, 26° *E.*, *distant* 17° *from Pulkovo.*

There are unfortunately no observations of S from azimuth 90° to 270°, so that we cannot make any analysis. The mean results for the other azimuths are

Azimuth	270°—300°	—330°	—0°	—30°	—60°	—90°
Mean	+1	−4	−2	−4	+4	0
No observations	4	4	11	2	2	1

which suggest a displacement in the opposite direction to that of January 11 and March 14, and in the same direction as the component of April 30.

The numbers for P are

1 4 1 2 0 0 1 0 4 3 11 2

and the harmonic expression is

$$+ 2\cdot1 + 2\cdot8 \cos (\theta - 165°) + 1\cdot6 \cos 2 (\theta - 111°)$$

The azimuth of Pulkovo being 7°, the small displacement indicated is nearly radial and in the opposite direction to those of January 11 and March 14.

Hence, so far as this evidence goes, the error of S–P is about 30 s. at 85°, diminishes at lesser distances, and changes to a small negative value. The corrections needed by the Galitzin tables would seem to be approximately as follows :—

	Δ = 15°	25°	35°	45°	55°	65°	75°	85°	95°	105°
	s.	s.	s.	s.	s.	s.	s.	s.	s.	s.
Correction P =	0	0	0	0	0	−1	−3	−8	−15	−24
Correction S =	+5	0	−4	−8	−11	−14	−17	−24	−35	−50
Correction (S–P) =	+5	0	−4	−8	−11	−13	−14	−16	−20	−26
Correction Δ =	−5	0	+6	+13	+18	+24	+28	+31	+42	+52

the correction to Δ being expressed in units of 0°·1.