THE EFFECTS OF THUNDERSTORMS AND LIGHTNING DISCHARGES ON THE EARTH'S ELECTRIC FIELD

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(*Communicated by C. T. R. Wilson, F.R.S.—Received* 29 *June* 1938—*Revised* 18 *February* 1939)

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1. Introduction

This paper discusses the results of a series of observations of the potential gradient near the ground during thunderstorms. The recording instrument is intermediate in speed between the ordinary methods used for recording the potential gradient in fine weather and the high-speed oscillographs employed for detailed study of the variation of the field during short intervals of time. It yields a continuous record of the potential gradient and will also follow fairly rapid changes, the limit being set by the time of response of the electrometer which is less than 0·05 sec. The records thus yield information which would be missed by slower or by very rapid recording instruments. The observations extended over the years 1926–36 and were mostly made during the summer months.

2. Apparatus and methods of observation

The observing station is situated in an open and approximately level field near the Solar Physics Observatory, Cambridge. The site has been described in detail by Wilson (1916, 1920).

The method of observation consists effectively in obtaining a continuous photographic record of the induced charge on a conductor exposed to the electric field and maintained always at zero potential. The measuring instrument is a type of capillary electrometer in which the position of the meniscus indicates the quantity of electric charge which has passed through the instrument. The quantity actually recorded is the sum of the induced charge on the conductor, at the moment, and of the integrated current which has flowed into the conductor since it was exposed to the field. The latter includes the ordinary ionization current into the conductor and may include also the effect of charged rain. When rain is falling in appreciable intensity, it is necessary to take special precautions either to prevent the rain from reaching the insulated conductor or, if it be allowed to fall on the conductor, to avoid spurious effects due to splashing. The nature of these precautions is discussed in detail later. When no rain is reaching the conductor, the conduction current into it is usually sufficiently small for its effect to be separated from the true induced charge by screening the conductor from the field for a few seconds at fairly frequent intervals (every few minutes say), and thus determining the actual value of the induced charge on the conductor at each moment when it is screened or exposed.

The technique employed is essentially that devised and employed by Wilson for observations on thunderstorm electricity. Various modifications have been made, however, during the course of the observations, and it therefore seems desirable to describe briefly the apparatus and technique as they have been used in the last few years.

The electric field produced at the surface of the earth by a thunderstorm may vary rapidly through a great range of intensities. When the storm is about 20 km. distant the effects are of the same order of magnitude as the fine-weather potential gradient (say 100 V/m.); immediately after a close lightning discharge, on the other hand, the potential gradient may exceed 50,000 V/m. It is therefore desirable to arrange a series of conductors which can be rapidly interchanged and any one of which can be exposed to the influence of the field and connected to the electrometer, according to the intensity of the field prevailing at the moment. The conductors consist of an elevated metal sphere which can be fixed at either of two different heights above the ground, a "test-plate" level with the surface of the ground (effectively a sample area of the ground), and finally, for use in very intense fields and during heavy rain, an "inverted test-plate".

The sphere, which has already been described in detail by Wilson (1920), is a hollow copper ball, 30 cm. in diameter, carried on an earthed metal pipe from which it is insulated. A bare copper wire stretched along the axis of the pipe connects the sphere to the recording apparatus. When the pipe carrying the sphere is in its vertical position, the centre of the sphere is at a height of 4·80 m. above the ground. The pipe may be swung about its lower end and thus lowered to a horizontal position; the sphere then descends into a box with an earthed metal lining. When the lid is placed on the box the sphere is completely screened from the field and carries no charge. When the sphere is raised to a height h, its potential being maintained at zero, an induced charge Q appears on it, where Q is given, to a sufficient degree of approximation, by the equation

$$Q/r - Q/2h + V = 0,$$

where r is the radius of the sphere and V is the potential at a height h if the sphere be removed. V differs from the potential at a height h over level ground owing to the distortion of the field by the hut containing the recording apparatus. The small correction is estimated by imagining the hut replaced by a conducting hemisphere. The correction amounts to 6 %. A measurement of Q thus determines the absolute value of V, the potential at a height h above level ground, and hence the value of the potential gradient, assuming it to be uniform for the first 5 m. above the ground. With the actual apparatus employed, an induced charge of 22·9 e.s.u. on the sphere corresponds to a potential gradient over level ground of 100 V/m.

Provision is also made for fixing the sphere at a lower height of about 1·5 m. in order to reduce the sensitivity when necessary. The relation between the induced charge and the potential gradient in this case is determined experimentally by comparing the induced charge on the sphere in its two positions in the same potential gradient. The observed ratio in the two positions is 3·40.

The test-plate consists of a shallow square wooden tray, of area 1·07 m.^{2}, supported, with its upper surface at the same level as the surrounding ground, in a brick-lined pit slightly larger than the tray. The tray is filled with earth in which is buried a sheet of wire netting connected by a wire through an underground pipe to the recording apparatus in the hut. The tray rests on a second deeper receptacle which is supported on sulphur-ebonite insulators on four iron pipes driven into the ground at the base of the pit. The area of the opening of the pit is 1·16 m.^{2}; there is thus an air-gap of about 2 cm. between the test-plate and the walls of the pit. The test-plate was designed to simulate natural conditions as far as was practicable, in order that measurements of both the field at its surface and also of the current into it might be of significance. The base of the pit and the surface of the plate exposed to the field are of ordinary earth. When rain is falling on the plate, it is falling on a natural earth surface except for a narrow region near the wooden edge. Moreover, the effects of any splashing from the edges of the plate to the walls of the pit should be approximately neutralized by splashing from the pit to the plate. The current into the plate should thus, under all ordinary conditions, approximate closely to that into an equal area of undisturbed ground. During a short exposure to rain, the moisture is absorbed by the soil in the test-plate; in order to make possible a long continuous exposure to rain, a vent covered with metal gauze is provided in the base of the test-plate, the containing tray of which is waterproof. When the soil has become saturated, the excess water thus drains into the receptacle below it and there is no possibility of water running off the upper surface and carrying with it electric charge. The test-plate can be screened from the electric field by means of a large earthed cover constructed of galvanized iron sheet on a wooden framework. The cover is so shaped that while, when in position, no portion of it is within 15 cm. of the insulated test-plate, any effects due to contact differences of potential being therefore of negligible proportions, yet it completely screens the test-plate from the field and also shields it from rain. The cover is mounted on wheels running on small iron rails which are fixed flush with the ground. It can thus be slid away to a considerable distance where its effect on the field at the surface of the test-plate is completely negligible. The charge Q on the test-plate when exposed in a field F is $AF/4\pi$, where A is taken as the mean of the areas of the plate and of the opening in the pit. A small correction is again applied for the disturbing effect of the hut on the field at the surface of the test-plate. The value of the correction in this case is estimated to be $2{\cdot}5\,\%$. The charge on the plate in a potential gradient of 100 V/m. is thus $2{\cdot}90$ e.s.u.

The sphere, at its greatest height, and the test-plate thus afford two independent measures of the absolute value of the potential gradient over level ground, assuming there is no variation in the gradient through the first 5 m. While no very accurate comparison has been attempted, measurements of fields by the two methods are in agreement within the accuracy of the observations.

When highly charged rain is falling, the current into the test-plate is so large that it is impossible to expose it continuously while connected to an electrometer of suitable sensitivity for measuring the electric field. This difficulty is avoided by the use of a form of inverted test-plate, which prevents rain from reaching the insulated conductor. This apparatus may thus be used to obtain a continuous record of the field when a storm is overhead. It has the further advantage that the cover necessary to screen off the field when desired is small and light and the operation of covering and uncovering at regular intervals can readily be made automatic. The insulated conductor is, in this case, part of the under-surface of a shallow vertical cylinder carried on a horizontal arm projecting, at some distance from the ground, from a vertical support. This form of exposed conductor was first devised and used by Wilson. The inverted test-plate in its present form, a gibbet-like structure, is shown diagrammatically in section in fig. 1. The circular brass plate A, $17{\cdot}5$ cm. in diameter, is carried on the sulphur-ebonite insulator B, to form part of the base of the vertical brass cylinder C which is soldered to the end of the horizontal brass tube D, 70 cm. in length. This tube projects from a vertical iron pipe at a height of $1{\cdot}5$ m. from the ground. An aluminium cover E carried on a light brass framework remains normally in the position shown in full line in the diagram, when the plate A is exposed to the field. The cover may, however, be swung into a position to screen A from the field; this position is indicated by dotted lines in the diagram. A simple mechanical device, actuated by a weight, moves the cover from either position to the alternative position whenever a trigger is released. This is done by actuating a small electromagnet and the necessary electric circuit is conveniently closed by a clock, which is arranged to make two contacts, separated by a few seconds, at 1 min. intervals. The plate A is thus exposed to the field for most of the time but is screened for about 4 sec. at 1 min. intervals. A metal shield protects the mechanism to some extent from the weather and prevents the accumulation of water in E which is also provided with drainage holes.

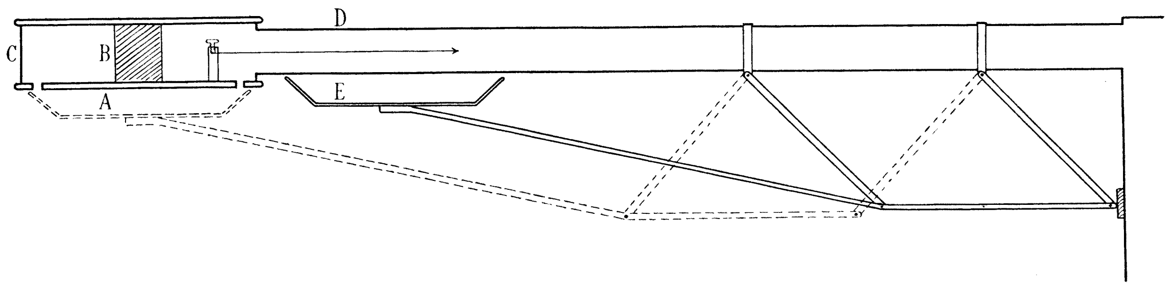


FIG. 1

The charge on the inverted test-plate, maintained at zero potential, will be proportional to the value of the potential gradient. No attempt is made to estimate the value of the constant of proportionality which is determined by direct comparison with the large test-plate. The inverted test-plate actually in use was thus found to carry a charge of 0·264 e.s.u. in a potential gradient of 100 V/m.

The inverted test-plate is intended primarily for observations during heavy rainfall and in very intense fields. In its construction, sharp edges and corners were avoided to reduce the risk of brush discharges. It is clear that such precautions are necessary. Thus, in a potential gradient of 50,000 V/m. (which has been observed immediately after a close lightning discharge) the electric charge on the insulated plate is 132 e.s.u., the average density of electrification 0·55 e.s.u. per cm.^{2} and the average potential gradient at the surface of the flat plate more than 2000 V/cm. The field at the edges of the plate must exceed this value, and it is clear that any sharp protuberances would probably cause brush discharge with consequent disturbance of the field. Moreover, it would not be safe to attempt to increase sensitivity by increasing the height of the plate above the ground considerably without modifying the other dimensions. No evidence has been obtained of the occurrence of brushing with the apparatus as actually employed in these observations.

The electrometer and recording apparatus are mounted on a brick-pier and protected by a hut. This is a substantial building of wood 14×10 ft.^{2} ($4{\cdot}26 \times 3{\cdot}05$ m.^{2}) with a concrete floor. The brick pier is independent of the floor of the hut in order to minimize mechanical vibration to which the electrometer is very sensitive. The wooden hut is completely encased by an outer covering of galvanized iron which penetrates the ground to a depth of 38 cm. and is used as the main earth connexion. The supporting pipe for the sphere, the large test-plate and the inverted test-plate are distant 8·5, 13·2 and 5·5 m. respectively from the centre of the hut.

The lead-in wires from the various conductors to the electrometer consist of bare copper wires mounted axially in earthed iron pipes of 5 cm. external diameter. The wires are kept taut by a spring near one end of each pipe. At bends they pass over small brass guides mounted on quartz rods. Where necessary the wire is kept near the axis by passing it through short quartz tubes fixed axially in the pipe, and at the ends of the pipe it is sealed through quartz or sulphur-ebonite insulators. The various leads are brought to a junction box inside the hut containing a number of small switches mounted on quartz. By this means it is possible quickly to connect any one of the conductors to the electrometer.

The instrument employed to measure electric charge is a capillary electrometer* of the symmetrical type discussed by Wilson (1916). It is constructed of ordinary soda glass and consists of a horizontal thick-walled capillary tube of uniform bore (0·1–0·2 mm.) joining two vertical glass tubes open at the top. A short column of dilute sulphuric acid in the capillary tube divides the mercury which fills the instrument into two halves. Connexion from an external circuit may be made to the mercury in each half by a platinum wire sealed through the glass wall. The essential property of the electrometer for the present purpose is that if one end be connected to earth and the other to a conductor exposed to the electric field, the electrometer maintains the conductor always at zero potential and, further, the displacement of the acid column from its initial position is always a measure of the total electric charge which has passed through the instrument since the observations commenced. The electrometer is dead-beat and quite rapid; if a condenser be discharged through it the meniscus reaches sensibly its final position in less than 0·05 sec.

One end of the electrometer is permanently connected to earth; the other is connected to the switch box, already referred to, into which are brought the leads from the different exposed conductors. The insulated end of the electrometer is also provided with a simple earthing key, an insulated cup of mercury into which an earthed wire may be inserted. It is necessary to short circuit the electrometer whenever any connexions to it are being changed, or any of the conductors connected to it being touched. There are also grouped round the switch box arrangements for making various routine tests. These include, the determination of the electrometer constant by charging a condenser of known capacity (about 100 e.s.u.) through the electrometer to a known difference of potential (say 100 V), and also an arrangement for applying directly to the electrometer, in either direction, a known variable potential difference of a few

* It is hoped shortly to publish elsewhere a full account of the construction and behaviour of this type of electrometer.

millivolts in order to be certain that the acid bubble is moving freely and behaving symmetrically. Finally, there is provision for testing the insulation of the various conductors and leads. All insulators consist of quartz or sulphur-coated ebonite, and provision is made, as far as possible, for maintaining a dry atmosphere about them. It has not been found necessary to keep the insulators warm, though this would be necessary if it was desired to use the apparatus regularly throughout the year. The main insulation difficulty is caused by spiders' webs. They insulate almost perfectly in dry weather and are thus liable to escape detection. With the onset of damper conditions not only does the insulation become poor, but the damp thread may probably be bridging two different metals, the whole system constituting in fact a voltaic cell, and the result is a rapid creep of the electrometer bubble making observations impossible.

It is necessary to record the displacements of the electrometer under considerable magnification. In order to obtain a sharp image, the top of the capillary tube is ground flat and a strip of thin glass is cemented on to it with Canada balsam. The electrometer is mounted on a glass plate and fixed on the stage of a microscope which projects a real image of the acid column, magnified 40 times, on to a slit of about 0·02 mm. width, parallel to the axis of the capillary tube. The motion of the image along the slit is recorded on a photographic plate whose sensitive emulsion is just above the slit and in uniform horizontal motion at right angles to it. The illumination is provided by a 100 W projector lamp and simple condensing system. The records are obtained on Ilford Ordinary 15×4 in.^{2} (38×10 cm.^{2}) plates, two 15 in. records being secured on each plate. The plate rests in a wooden carriage moved by a weight, the speed being controlled by an oil clepsydra with a series of interchangeable holes of different sizes. Most of the records discussed in this paper have been obtained with a velocity of the moving plate of about 0·6 mm./sec. The limit of resolution set by the width of the slit is thus about 0·03 sec. The time of response of the electrometer sets a limit of about the same value or rather less. The sharp boundary in the image between the brightly illuminated acid column and the dark mercury gives a sharp edge on the records, and the magnified displacements of the electrometer can be measured to an accuracy of about 0·05 mm.

TABLE I

Conductor	Potential gradient corresponding to 1 mm. displacement V/m.	Smallest measurable potential gradient V/m.
Sphere: Full height	44	2
Lower height	150	7·5
Test-plate	350	18
Inverted test-plate	3800	200

In a typical case a determination of the electrometer constant showed that a displacement of 1 mm. on the negative corresponded to the passage through the electrometer of 10·1 e.s.u. of charge. The values of the potential gradient causing a displacement of 1 mm. when any one of the various conductors is exposed to, or shielded from, the electric field and the smallest potential gradient which could be measured were then those given in Table I.

3. Results of observations: (1) General remarks

During a lightning discharge the electric field at the surface of the ground is changing rapidly. It is clear that the comparatively slow electrometer used in this series of observations cannot yield information as to the fine details of the behaviour of the electric field during a lightning flash, such as has been studied, for example, in the recent work of Appleton and Chapman (1937) with a cathode-ray oscillograph. Nevertheless, the record does frequently show a certain amount of detail during the discharge, i.e. it yields more information than merely the values of the potential gradient immediately before and immediately after the discharge. The rapid variation in the potential gradient is conveniently termed a field-change, and is said to be positive when its direction is such as would increase a positive potential gradient.

Two types of complication will be considered briefly. First, in a considerable proportion of cases, the recorded change in the potential gradient includes displacements of both signs. This is clearly not, in general, a case of the chance occurrence of two or more discharges almost simultaneously. The frequency with which the phenomenon occurs shows that, while we are presumably observing the effects of several discharges, there is a physical connexion between them although they may undoubtedly be, in some cases, a considerable distance apart. Two or more discharges in or from different parts of a cloud are not infrequently seen to occur apparently simultaneously or in very rapid succession. Flashes which cause a field-change, including changes of both signs, will be termed *complex discharges*, and their effects on the potential gradient *complex field changes*. Complex field-changes are recorded not infrequently, however, when an observer, watching the storm in daylight, only sees a single flash. Secondly, even when the whole change of electric field is of one sign, it may take place in a series of steps. Again, whether the variation of field is apparently smooth or stepped the whole change not infrequently lasts considerably longer than the time of response of the recording system. The stepped field-changes are clearly due in some cases to successive strokes down the same channel, although it would appear from the recent work of Schonland, Malan and Collens (1935) that the time interval between such successive strokes is often too small to be separated in these records. In other cases, the stepped appearance of the field-change is doubtless due to successive discharges along quite different paths. When the components of a field-change are all of the same sign it will be described as a *simple field-change* whether it occurs in one or more steps.

After a field-change the electric field usually varies rapidly, tending to return to its value before the discharge. This variation has been called the "recovery curve" of the field by Wilson who has pointed out its significance. In a great many cases the rate of variation of the field in the recovery is greatest immediately after the discharge and thereafter continually decreases. Such cases will be termed simple recovery curves. On other occasions the phenomena are more complicated, the rate of variation being comparatively small immediately after the discharge, and then increasing to a maximum value before finally dying away. If F be the magnitude of a field-change, and dF/dt the rate of variation of the field immediately after the completion of the field-change, the value of the important quantity $1/F \, . \, dF/dt$ sec.$^{-1}$ is termed the *initial rate of recovery*.

Records of the potential gradient, obtained during various storms, are reproduced in Plates 2–17. The time scale is indicated below the records, and the vertical scale of potential gradient, in volts per metre, at the left of each record. The vertical dark lines across the records indicate the times of commencement of peals of thunder. All times are given in U.T. (and not B.S.T.). The process of shielding or exposing the conductor, in order to determine the sign and magnitude of the potential gradient, is marked on the records by a cross; this may indicate the exposing of a conductor near the beginning of a record, the shielding near the end, or the double process of shielding for a few seconds and then exposing. This last process causes a hump on the record if the gradient is negative, a depression if the gradient is positive. Its effects are usually immediately recognizable unless a field-change has occurred during the few seconds for which the conductor was shielded; in such a case considerable care is necessary in interpreting the records. Several examples of this difficulty occur in the records of Plate 6 when field-changes were rather frequent.

In order to illustrate the method of making the observations, the records of three storms will be discussed in some detail. Points of interest from the other storms of which records are reproduced are briefly summarized in Table III.

4. Results of observations: (2) Examples of individual storms

20 *May* 1928. When observations commenced, at about 15 h. 30 m., distant thunder was audible from two storm centres, to the east and to the south-west respectively, the former being apparently the nearer of the two. During the next $2\frac{1}{2}$ hr. the cloud in the east receded and the large thunder-cloud originally in the south-west passed right overhead. Heavy rain was falling from 16 h. 11 m. until about 17 h. 45 m.; the intensity of rainfall was noted as particularly great for a few minutes after 16 h. 47 m., the potential gradient being then negative and of considerable magnitude. The storm caused prolonged and heavy rainfall and intense potential gradients, but the number of lightning discharges was not very great.

Portions of the records obtained during this storm are reproduced in figs. 12–20, Plates 4 and 5. Fig. 12 was obtained with the sphere in its lower position; it shows a negative potential gradient of −2500 V/m. at 15 h. 44·2 m. when the sphere was first exposed to the field. The gradient was increasing in intensity. Fairly frequent field-changes were due to flashes in both the active clouds in the vicinity. A considerable proportion of the field-changes on this first record were very complicated. The complex field-changes at 15 h. 44·4 m. and at 15 h. 48 m. are also reproduced on a larger scale in fig. 20, Plate 5. A little later, the potential gradient became positive and the second record (fig. 13) shows, when the sphere was raised at 16 h. 7·5 m., a potential gradient of +2160 V/m. The storm in the east was now distant, and its effect on the potential gradient can be neglected. The first few field-changes on this record were small, but at 16 h. 10·4 m. a discharge, only 3·2 km. away in the west, caused a double field-change whose net effect was to increase the positive gradient of potential by 7500 V/m. A little later, at 16 h. 11 m., it was necessary to lower and shield the sphere owing to heavy rain; the potential gradient was then, just after a negative field-change, +3320 V/m. Recording of the potential gradient was continued with the inverted test-plate (figs. 14–19). At 16 h. 34 m. the potential gradient became negative once more; the lightning discharges were now very close. The effects of shielding the inverted test-plate for a few seconds at 1 min. intervals can be clearly seen on the records and the actual values of the potential gradient deduced. Thus, for example, in fig. 15 the values of the potential gradient were at 16 h. 45 m. −6000 V/m., at 16 h. 46 m. about +8000 V/m. in a recovery curve, and at 16 h. 47 m. −4000 V/m. Some large field-changes of both signs were recorded, thirteen being due to discharges within 5 km. The largest of these are on the records reproduced. At 16 h. 10·4 m., when the pre-discharge gradient was positive, a discharge 3·2 km. away caused a positive field-change. During the period of negative potential gradient from 16 h. 34 m. to 17 h. 15 m., four large positive field-changes were recorded, the mean distance of the discharges being 1·8 km., and six rather smaller negative field-changes from discharges at a mean distance of 2·9 km. During the ensuing period of positive gradient three large negative field-changes occurred, the mean distance of the discharges being 1·6 km. These were the last discharges of the storm. Several of the close flashes which produced large negative field-changes in the last phase of the storm were seen. They were all in the cloud, no discharge to earth being visible. The brightly illuminated portion of the cloud was, however, in each case very low down, of the order of 1 km. only from the ground. The closest flash of the storm, about 0·8 km. away, caused a positive field-change of 46,000 V/m. (fig. 15), apparently preceded by a small negative change of about −1000 V/m. Data concerning all the big field-changes of this storm (exceeding 5000 V/m. in magnitude) are collected in Table II.

It is noticeable that each of the two very large positive field-changes is apparently immediately preceded by a quite small negative change, and each of the two biggest negative changes immediately followed by a small positive change.

The behaviour of the recovery curves is interesting. It is fairly clear that when a flash creates a very big electric field, i.e. greater than is ever observed to exist as a steady field, this dies away very rapidly. It is surprising, however, that there is no sign of a rapid recovery after the biggest negative discharge at 17 h. 27·4 m.

Finally, it may be pointed out that after each very big field-change, the zero line for the potential gradient appears to have been shifted through an appreciable amount. This suggests a sudden rush of intense ionization current into the ground during and immediately after the discharge. Whatever the cause of this effect may be, it makes the exact value of the biggest field-changes here observed rather uncertain.

TABLE II

Approximate time	Magnitude V/m.	Distance in km.	Potential gradient immediately after discharge V/m.	Initial rate of recovery sec.$^{-1}$
16 h. 10·4 m.	+ 9,500 − 2,000	3·2	+10,500	0·07
16 h. 40·7 m.	− 5,000 +13,000	1·4	+ 4,000	0·08
16 h. 43·4 m.	− 6,000	3·3	−11,000	0·33
16 h. 45·9 m.	− 1,000 +46,000	0·8	+40,000	>1
16 h. 50·3 m.	− 7,000	4·1	−16,500	0·50
17 h. 2 m.	− 1,000 +30,000	1·6	+17,000	0·30
17 h. 13·6 m.	−14,500 + 5,000	1·8	−13,000	0·14
17 h. 27·4 m.	−25,000 + 2,500	2·0	−17,000	0·07
17 h. 31·2 m.	−16,500 + 1,500	1·6	−12,000	0
17 h. 40·8 m.	− 6,000 − 6,000	1·2	− 7,000	0

4 *June* 1929. A fairly complete record was obtained of the potential gradient during a thunderstorm on the afternoon of this day. Typical samples from the records are reproduced in figs. 35–41, Plate 7. Fig. 35 was obtained with the sphere at its full height, fig. 36 with the sphere at its lower position and figs. 37–41 with the inverted test-plate. When observations commenced at 13 h. 40 m., the storm was approaching from the south-west, distant thunder being audible from it. A very small positive gradient of potential was recorded when the sphere was raised at 13 h. 40 m. (fig. 35); it increased to a maximum value of about +1500 V/m. and then diminished and reversed in sign at about 13 h. 52 m., when the edge of the approaching storm was almost directly overhead. The sign of the potential gradient reversed several times during the storm and finally, when the rear edge of the storm was overhead, at 15 h., a moderately intense positive gradient of potential was observed which diminished steadily to a small value as the active cloud receded. Rain was falling from 14 h. 4 m. until 14 h. 35 m. and from 14 h. 50 m. until 15 h. From 13 h. 40 m. until 13 h.

43·5 m. (fig. 35), the field-changes were all negative, the flashes being apparently about 20 km. away; some positive field-changes then occurred, and after 13 h. 50 m. (fig. 36), when the discharges were considerably closer, the field-changes were predominantly positive for some time. Between 14 h. 2 m. and 14 h. 14 m. (figs. 37 and 38), six field-changes were observed, due to fairly close discharges, all being of positive sign; the three biggest were due to discharges about 3 km. away, but the effects were not very large, the biggest field-change being only +5500 V/m. From 14 h. 23 m. to 14 h. 40 m. (figs. 39–41), six close discharges were recorded, all the field-changes being negative; these were larger than the earlier positive ones, the biggest due to a flash 2 km. away, being of −17,500 V/m. In both these periods the field reversed so that some of the large field-changes were of the same sign as the pre-discharge potential gradient. After 14 h. 45 m. only one small field-change was observed.

The discharges during this storm were rather infrequent, and the initial rate of recovery after the field-changes was usually slow. Of the distant discharges observed while the storm was approaching, four simple negative field-changes were followed by a mean initial rate of recovery of 0·07 sec.$^{-1}$, while four simple positive field-changes had a mean initial rate of 0·04 sec.$^{-1}$. The recovery of the field after the close discharges was very slow in nearly every case, the one exception being after the field-change of −11,000 V/m. at 14 h. 24·8 m. (fig. 39), with a pre-discharge gradient of −4000 V/m. In this case the initial rate of recovery was 0·16 sec.$^{-1}$, but the recovery rapidly slowed down.

19 *June* 1933. During the morning many active cumulo-nimbus clouds were visible. From 10 h. 50 m. until 11 h. 16 m. a small positive potential gradient was observed, the maximum value of +250 V/m. being reached at about 10 h. 55 m. In this period, twenty-eight very distant discharges were detected; twenty-two of these field-changes were simple, fourteen being positive, and eight negative while six were complex, the net effect being negative in each case. During this period a cumulo-nimbus cloud was approaching from the north-west. From 11 h. 16 m. until 11 h. 38 m. a steadily increasing negative gradient of potential was observed with the sphere (fig. 53, Plate 9). The records showed numerous small field-changes, those of positive and negative sign being about equally numerous. The main part of the cloud was now to the west of the observing hut, but one edge reached beyond the zenith. The gradient became positive again from 11 h. 40 m. until 11 h. 50 m., attaining a maximum value of +4500 V/m. (fig. 54, Plate 9, obtained with the sphere in its lower position). No field-changes were recorded in this interval, but the field was fluctuating rapidly. At 11 h. 51 m. rain commenced to fall and the gradient rapidly reached big negative values. There followed a brief period of rather intense positive gradient (12 h. 1 m. to 12 h. 6 m.), another period of negative gradient (12 h. 6 m. to 12 h. 18 m.), and then a moderate, slowly decreasing, positive gradient. In the central part of the storm, 11 h. 50 m. to 12 h. 18 m., only one field-change was recorded. At 11 h. 57·5 m. the pre-discharge gradient being about −10,000 V/m., a discharge 3·5 km. away caused a very large

simple field-change of $-37{,}500$ V/m. (fig. 55, obtained with the inverted test-plate). The negative gradient immediately after this discharge was thus very intense and the initial rate of recovery was high, about 0·7 sec.^{-1}. In the final period of positive potential gradient (12 h. 19 m. to 12 h. 35 m.), several field-changes were observed, due to discharges beyond 10 km.

In the afternoon a second and much more active storm was observed; records of potential gradient are reproduced in figs. 56–63, Plate 10. Fig. 56*a* was recorded with the sphere in its lower position, fig. 56*b* with the test-plate, figs. 57–59 with the inverted test-plate, fig. 60 with the test-plate, figs. 61–62 with the sphere in its lowest position, and fig. 63 with the sphere at its full height. From 14 h. 50 m. until 15 h. 24 m. the pre-discharge gradient was negative, its biggest value being about $-10{,}000$ V/m. at 15 h. 16 m. (fig. 58). Rain was falling from 14 h. 57 m. until 15 h. 17 m. Many close discharges occurred in this period, most of them at distances between 3·5 and 6 km., although one was within 2 km. Two flashes to earth were noted, each causing a simple positive change of field. The storm caused an interruption in the electric supply (fig. 57); there was a momentary failure immediately after the positive field-change at 15 h. 3·4 m. and an interruption for several minutes after 15 h. 4 m. In the period when the storm was close, twenty-four large field-changes were recorded, twenty-one being simple and three complex; they were all positive in sign. The mean initial rate of recovery after the simple field-changes was 0·05 sec.^{-1}, the individual values ranging from 0·00 to 0·11. From 15 h. 25 m. onwards the pre-discharge gradient remained positive, reaching a maximum value of just over $+4000$ V/m. at 15 h. 28 m.; the storm was now becoming distant. In this final phase of the storm, simple field-changes of $+2450$ V/m. (distance 7·9 km.), and $+290$ V/m. were recorded at 15 h. 27·2 m. (fig. 60) and 15 h. 44·8 m. (fig. 63) respectively. A complex field-change at 15 h. 25·7 m. (fig. 60), due to a discharge 6·3 km. away, caused a positive net change of field and five later complex discharges (figs. 61 and 62) at distances between 8·5 and 12·6 km. all caused negative changes of field. During the same period some very small field-changes also occurred, most of them being of positive sign.

The records reproduced in the remaining plates are briefly discussed in Table III.

5. The electric field at the ground during a thunderstorm

In considering the electric field as distinct from the sudden changes produced by lightning discharges it is necessary first to define more accurately what is meant by the electric field of a thunderstorm. There is inevitably a certain arbitrariness in deciding what value should be assigned to this quantity which may be varying rapidly, but it would seem that the quantity most appropriate to our present purpose is the value of the potential gradient immediately before a lightning discharge. We use for this quantity the convenient and more precise designation of the pre-discharge potential gradient.

TABLE III

24 June 1927	Figs. 1 and 2, Plate 2	Receding shower-cloud had just developed into a thunderstorm. Distance of discharges 11–20 km. Pre-discharge gradient was at first negative but becoming increasingly positive. Most of the discharges were in the cloud and there was a preponderance of negative field-changes. Several flashes to earth caused positive field-changes. Initial rate of recovery noticeably more rapid after negative than after positive field-changes
11 July 1927	Figs. 3–11, Plates 2 and 3	Portions of records considerably enlarged; approximate times are indicated. Large, almost stationary, thundercloud on a very warm afternoon. Distance of the discharges about 25–35 km. Pre-discharge gradient was always small. The first few flashes caused positive field-changes but, in the first hour of the storm, 16 h. to 17 h., 80 % of the numerous field-changes recorded were negative. After this, positive and negative changes were about equally frequent. The discharge process was now, in many cases, very slow and many of the field-changes very complex. Many of the simple field-changes were clearly resolved into steps, a striking example occurring in fig. 9 *b*, Plate 3. This positive field-change of 150 V./m., in six steps, with a total duration of 1·3 sec., was due to a flash, 24·3 km. away, visible as a flickering streak between the cloud-base and the ground, the luminosity lasting for more than a second. Some simple field-changes, with no sign of a stepped structure, had durations up to 0·5 sec. The complex changes showed great diversity and in some cases very long durations, up to 2 sec.
20 May 1928	Figs. 12–20, Plates 4 and 5	Records discussed in detail
24 May 1929	Figs. 21–34, Plates 5 and 6	Violent storm. Discharges were occurring close to the observing hut for nearly 3 hr. From 17 h. 10 m. to 17 h. 45 m. the field-changes were mostly simple with a big preponderance of positive changes, the flashes being mostly in the cloud. Three flashes to earth in this period, one with clear downward branching, caused simple positive field-changes. From 17 h. 45 m. to 18 h. 20 m., discharges were very frequent, at times more than 20 per min. Most of these frequent field-changes were small (figs. 25–30, Plate 6); the bigger ones were often very complex and slow. (Details are better shown in figs. 21–24, Plate 5.) Positive changes were again the more frequent. From 18 h. 20 m. to 18 h. 45 m. discharges were less frequent; they mostly caused complex field-changes with a big positive net effect (figs. 31–33, Plate 6). From 18 h. 45 m. onwards, occasional close discharges were causing mainly negative field-changes (fig. 34). Most of these last discharges were low down but in the cloud. It should be noted that the time-scale in fig. 34 is different from that of the preceding records
4 June 1929	Figs. 35–41, Plate 7	Records discussed in detail
6 June 1931	Figs. 42–44, Plate 8	Small brief storm. Pre-discharge gradient was negative, while the storm was close except for the brief period of positive gradient from 14 h. 13·2 m. to 14 h. 14·6 m. (fig. 42, Plate 8), initiated and ended by close discharges. The large positive field-change at 14 h. 14·2 m. with a big positive pre-discharge gradient is of interest. The closer discharges produced a great preponderance of positive field-changes. Later (fig. 44), with the storm receding, negative changes appeared with increasing frequency. The rapid initial

TABLE III (*continued*)

		recovery after the big field-changes of fig. 42 is noteworthy, and the slow initial recovery after several of the later discharges (figs. 43 and 44)
26 July 1932	Figs. 45 and 46, Plate 8	Clear sky overhead but a cumulo-nimbus cloud with rain falling from it was passing in the distance. No discharges could be detected but the positive potential gradient showed rapid fluctuations
29 April 1933	Fig. 47, Plate 8	Record of the potential gradient during a very violent rain and hail-storm with some very close discharges. The first complex discharge caused a net change of field of −23,000 V/m., the flash being within 1 km. The next flash caused a net change of −6000 V/m.; the detail is lost, due to a momentary failure in the electric supply; the discharge apparently struck a transmission line 2·4 km. away. The fluctuations in density of the remainder of the record are due to variations in the voltage of the supply. A simple positive change of +33,000 V/m. was recorded at 12 h. 54 m. and the supply failed completely just after a big double field-change at 12 h. 54·5 m.
9 May 1933	Fig. 48, Plate 9	Records of the potential gradient during the approach of a shower. No discharges occurred but the field was fluctuating violently. Rain commenced at the observing hut at 14 h. 42 m. Fluctuations of smaller amplitude persisted for some time after this
17 June 1933	Figs. 49–52, Plate 9	From 13 h. 38 m. to 13 h. 54 m. (figs. 49–51), numerous small cumulo-nimbus clouds were developing. One passed near the observing hut, the "false-cirrus" top reaching almost to the zenith. The records show a fluctuating field and some very small field-changes. Later (fig. 52), a thunderstorm occurred. The complex field-change at 14 h. 30·7 m. was followed by a "recovery" in the opposite direction to the normal one
19 June 1933	Figs. 53–63, Plates 9 and 10	Records discussed in detail
22 June 1933	Figs. 64–88, Plates 11–13	A line of cumulo-nimbus clouds slowly approached and finally passed over the observing hut. Up to 14 h. 44 m. fairly frequent field-changes of gradually increasing magnitude were observed, with a slight preponderance of changes of positive sign. At 14 h. 44 m. (fig. 65), considerably bigger field-changes suddenly appeared; the nearest discharges were now about 10 km. distant. From 14 h. 50 m. onwards there was an enormous preponderance of field-changes of positive sign. Until 15 h. 40 m. (figs. 64–74), the pre-discharge gradient was fairly small and mainly positive; discharges were slowly getting nearer. From 15 h. 40 m. until 17 h. (figs. 75–88), a rather intense negative pre-discharge gradient developed. Clouds were now passing overhead and some rain fell. After 16 h. 20 m. discharges were infrequent, but occasional ones occurred within 3 km. (figs. 85–87). The field-changes were still nearly all of positive sign. After 17 h. no further discharges were observed but a very intense positive gradient of potential (exceeding 12,000 V/m.) developed during moderate rainfall for about 30 min., followed by a persistent negative gradient of moderate intensity with an overcast sky. Of the field-changes observed in the whole storm, 126 exceeded 500 V/m. in magnitude, 122 being positive; sixty-seven were between 100 and 500 V/m., fifty-four being positive and 114 were less than 100 V/m., seventy-eight being positive

TABLE III (*continued*)

15 July 1933	Figs. 89–96, Plate 14	Samples from records as a fairly brief storm passed overhead. In fig. 89 the storm was distant and occasional small field-changes were recorded, several of them being complex; the potential gradient was small. When the storm came overhead (figs. 90 onwards) the pre-discharge gradient was mainly negative and most of the big field-changes positive. The large field-change at 16 h. 49·7 m. (fig. 93), with very rapid initial recovery, is noteworthy. There appear to be numerous small field-changes on this record; they were all of positive sign immediately before the big positive field-change and all negative immediately after it. The fairly large field-changes of the last records (figs. 94–96), have small initial recovery rates
13 July 1934	Figs. 97–105, Plate 15	Records of a distant storm. All discharges were beyond 18 km. The pre-discharge gradient was small and negative. Examples of complex field-changes may be noted at 14 h. 16 m. (fig. 99), 14 h. 35·2 m. (fig. 101), 14 h. 37·4 m. (fig. 102), and 14 h. 48·2 m. and 14 h. 50·5 m. (fig. 104). In the day's observations, 191 simple field-changes were recorded. Of these, thirty-three exceeded 100 V/m., twenty-six being positive and 158 were less than 100 V/m., 114 being positive. Of the complex field-changes, nine exceeded 100 V/m., seven being of positive sign and twelve were less than 100 V/m., five being positive
18 July 1934	Figs. 106–114, Plate 16	Distant storm observed in the morning (figs. 106–110). Pre-discharge gradient small and positive. Field-changes mostly simple but examples of complex ones may be noted at 11 h. 14·7 m. and 11 h. 16·2 m. (fig. 107), 11 h. 17·6 m. (fig. 108), 11 h. 32·3 m. and 11 h. 35·2 m. (fig. 110). Of the field-changes observed in this storm, twenty-one exceeded 100 V/m. in magnitude, two being positive and nineteen negative; 110 were less than 100 V/m., forty-eight being positive, fifty-eight negative, while in four cases the net effect was zero. In the later storm (figs. 111–114), which was rather closer, the gradient was more variable but still mainly positive and some rain fell. A fine complex field-change may be noted at 13 h. 32·3 m. (fig. 111). Six field-changes exceeded 500 V/m., one being positive and five negative. Fifty-eight were between 100 and 500 V/m., thirty-eight being positive, eighteen negative, while in two cases the net effect was zero. The seventy-two small field-changes (less than 100 V/m.) were equally divided between positive and negative sign. The behaviour of the field-changes in these storms was thus very complicated; the diversity was still more marked if the history of the storms be followed in detail
15 Sept. 1934	Figs. 115–122, Plate 17	A violent storm. A period of large positive potential gradient (fig. 118) accompanied hail of exceptional severity, the hailstones being very large. During this period large negative field-changes were being recorded from very close discharges. Before (figs. 115–117), and after (figs. 119, 120), this period of violent precipitation there occurred periods of negative pre-discharge gradient with discharges at moderate distances; in these periods the bigger field changes were mostly positive. Finally, as the storm receded (figs. 121, 122), there was a small pre-discharge gradient of variable sign and an excess of negative field-changes from distant discharges. Some of the field-changes of this storm were very complex and slow

The field-change due to a lightning discharge may be much bigger than the pre-discharge gradient, so that a field-change frequently causes a temporary reversal of the potential gradient. It is clear, therefore, that beneath a storm which is producing frequent discharges, the pre-discharge gradient, even in a period when it remains approximately constant, will be quite different in magnitude from the average value of the potential gradient and may conceivably be of opposite sign to the average gradient. Moreover, in order to obtain reliable values of the pre-discharge gradient, a recording system of fairly rapid response is essential. The speed of response of the capillary electrometer is ample for this purpose, and it therefore seems desirable to investigate the behaviour of the pre-discharge gradient in some detail. The records of potential gradient during thunderstorms have therefore been analysed with a view to determining the variation of the relative frequency of positive and negative pre-discharge gradient with first, the magnitude of the gradient and, secondly, the distance from the nearest active storm centre, i.e. the nearest region where lightning discharges are occurring. For this purpose each record (lasting on the average for about 12 min.) was first classified according to the distance of the nearest lightning flash whose field-change was recorded on it, and then the durations of positive and negative pre-discharge gradient on the record in three ranges of magnitude of potential gradient were determined. There was generally no ambiguity in this determination, but in a few cases the pre-discharge gradient was fluctuating so rapidly that no definite value could be assigned to it. Such cases are omitted from the table which follows. The total duration of the records on which the pre-discharge gradient was thus classed as indeterminate was just over 100 min.

The results of this analysis are given in Table IV. The principal entries in each column are the durations, in minutes, of positive and negative pre-discharge gradients of the relevant magnitudes and in the relevant range of distances from the nearest storm centre. The ratio of the durations of positive and negative gradient is also given in each case. The gradients are classified in three ranges of magnitude, <1000 V/m., 1000–5000 V/m., and >5000 V/m. The pre-discharge gradient very rarely exceeded 10,000 V/m., and for about 93 % of the duration in the last class was below this value. The classification, according to the distance of the nearest discharge, is divided into four ranges of distance and a fifth class when the record showed no field-changes. Records in this last column represent occasions when the cloud had for the time being ceased to discharge or, alternatively, the potential gradient was so much greater than the field-changes that the latter could not be detected. All the records included, however, refer to thundery conditions; occasions of rain or showers which produced no lightning discharges have been excluded.

Before discussing in detail the figures given in Table IV, one difficulty must be considered. The observed value of the potential gradient at the ground near a thunderstorm is made up of the direct effect of the charges in active clouds in the vicinity, together with a contribution due to other causes. This latter contribution is negligible when the storm is close but is probably the cause, to some extent, of the large preponderance of positive gradients when the gradient is small and the nearest storm more than 15 km. away. In such cases it is not possible to determine separately the direct effect of the storm. Even if the fine-weather gradient for the same time and vicinity were known, it might well be modified indirectly by the storm in various ways and, in particular, by the storm's effect on the electrical properties of the upper atmosphere. The fine-weather gradient itself may, of course, be largely due indirectly to still more distant storms. It would seem then, that the only quantity which can justifiably be tabulated is the observed potential gradient at a definite distance from the nearest thunderstorm. The ratios (of durations of positive and negative gradient) which are probably seriously disturbed by these secondary effects, together with those where the observations are too scanty for the figures to have any significance, are enclosed in brackets in Table IV.

TABLE IV. DURATIONS, IN MINUTES, OF POSITIVE AND NEGATIVE PRE-DISCHARGE POTENTIAL GRADIENTS

Magnitude of pre-discharge potential gradient V/m.	<5 +	<5 −	5–10 +	5–10 −	10–15 +	10–15 −	>15 +	>15 −	No field-changes recorded +	No field-changes recorded −	Totals +	Totals −
	Distance of nearest active storm centre in km.											
<1000	73	121	115	120	179	104	1051	275	196	93	1614	713
Ratios	1/1·7		1/1·0		1·7/1		(3·8/1)		2·1/1		(2·3/1)	
1000–5000	114	224	106	200	66	33	82	65	107	101	475	623
Ratios	1/2·0		1/1·9		2·0/1		1·3/1		1·1/1		1/1·3	
>5000	37	99	4	14	19	49	3	6	6	10	69	178
	1/2·7		(1/3·5)		1/2·6		(1/2)		(1/1·7)		1/2·6	
Totals	224	444	225	334	264	186	1136	346	309	204		
Ratios	1/2·0		1/1·5		1·4/1		(3·3/1)		1·5/1			

The data of Table IV may be summed up fairly accurately in the statement that the proportion of negative pre-discharge gradients is higher, the bigger the value of the gradient and the closer the active storm centre. There is one apparent exception to this general tendency among the figures in the table. If we confine ourselves to the consideration of potential gradients between 1000 and 5000 V/m., the frequency of occurrence of positive pre-discharge gradient rises to a maximum at distances between 10 and 15 km. from the storm centre and then falls again at greater distances. The data are not sufficiently extensive for it to be certain whether this effect is real or not, but in any case the proportion of negative gradients of these intensities is rather surprisingly high when the storm is distant. It must be remembered, however, that the occurrence of such large potential gradients when the nearest lightning discharges are more than 15 km. away will, in many cases, be due to the presence nearer the observer of other highly charged clouds which are not producing lightning discharges. A thunderstorm not infrequently leaves behind it an overcast sky with a rather persistent and fairly large negative gradient of potential.

Simpson and Scrase (1937) have recently stated that while there is a marked preponderance of negative potential gradient beneath a thunderstorm, this preponderance is much smaller very close to the storm centre than at some distance away from it. Storm centre, in their analysis, is defined merely as the mid-point, in time, of the period during which the potential gradient was appreciably disturbed from its fine-weather value. A search has been made for such an effect in these records by re-analysing the records of close storms and confining attention to records which include the effects of discharges within 3 km. of the observer. The data available consists of the relevant parts of the records of potential gradient of the sixteen storms of the whole series which produced flashes within this distance. The following figures resulted for the durations of positive and negative pre-discharge gradients:

TABLE V

Magnitude of pre-discharge gradient, V/m.

Distance of discharges	< 1000		1000–5000		> 5000		Totals	
	+	−	+	−	+	−	+	−
< 3 km.	46	52	64	99	27	75	137	226
Ratios	1/1·1		1/1·5		1/2·8		1/1·65	
< 5 km. from Table IV Ratios	1/1·7		1/2·0		1/2·7		1/2·0	

There is a trace in these figures of an effect such as Simpson and Scrase suggested, i.e. the preponderance of duration of negative gradient in these storms was slightly less when the storm centre was very close than when it was slightly more distant. It must be noted, however, that the effect is only found here when the pre-discharge gradient is rather small; when the gradient exceeds 5000 V/m. the preponderance of negative gradients is as high as ever when the storm centre is very close.

An attempt will now be made to sum up the facts which have definitely emerged for this group of storms from the study of the pre-discharge gradient.

The pre-discharge potential gradient beneath a storm may have any value from zero to 10,000 V/m. The latter value is occasionally but only rarely exceeded. Quite small pre-discharge gradients (less than 1000 V/m.) are not uncommon even when the storm centre is very close. The pre-discharge gradient may be of either sign up to any distance from the storm at which it can be detected. When, however, the storm centre is within 10 km. of the observer there is a definite preponderance of negative pre-discharge gradients. When the distance of the storm centre is between 5 and 10 km., the duration of negative gradient is 1·5 times that of positive; when the distance is less than 5 km. the corresponding ratio is 2·0, and when less than 3 km. 1·65. On the other hand, when the storm centre is at a greater distance than 10 km., there is a definite preponderance of positive pre-discharge gradients. When the distance of the centre is between 10 and 15 km. the duration of positive gradients is about 1·4 times that of negative gradients. At still greater distances the ratio would probably be still higher, but it is then often impossible to separate the gradient due directly to the cloud from other effects. When large pre-discharge gradient occurs (greater than 5000 V/m.), there is a large excess of negative gradients whatever the distance of the storm centre, the relative durations of negative and positive gradients being about 2·6. Very close to the storm centre this ratio is slightly higher.

These results may be compared briefly with those of some earlier investigations. Observations for two years at Cambridge with an earthed metal point (Wormell 1930) gave for the ratio of the amounts of negative and positive electricity discharged in disturbed weather conditions the value 2·0. This is just about the value one would have guessed from Table IV for the effect of thunderstorms. Similar observations at Kew, with a point of different dimensions and exposure, gave the value 1·7 for all types of disturbed weather (Whipple and Scrase 1936) and 1·5 for thunderstorms (Simpson and Scrase 1937). Such observations are clearly concerned with the average potential gradient rather than the pre-discharge gradient. Simpson and Scrase (1937), from a study of twenty storms at Kew, found that, in the middle period of 30 min., negative gradient was twice as frequent as positive gradient. This is in excellent agreement with the first column of Table IV. Schonland (1928), in observations of South African storms, found an excess of positive pre-discharge gradient when the storms were distant and an enormous excess of negative gradient when they were overhead, the occurrence of positive gradient being then extremely rare. While these storms illustrate the same general tendency as the English storms here studied, there is clearly a big difference in the distribution of potential gradient in the two cases.

The results which have been considered in this section may be presented in another way which brings out more clearly some of the salient facts. The figures given in Table IV may be used to compute approximately the average values of the pre-discharge potential gradient at various distances from the active centre of a thunderstorm. (For this purpose the average magnitudes of the potential gradient in the three rows of Table IV were assumed to be 500, 3000 and 7000 V/m. respectively.) It is then found, for example, that while discharges were occurring within 5 km., the pre-discharge gradient was positive for 224 min., with an average value of +2800 V/m. and negative for 444 min. with an average value of −3200 V/m. The average value of the gradient with respect to time, while discharges were within 5 km., was therefore −1200 V/m. A similar computation may be made for the next two ranges of distance. In order to obtain comparable figures for the most distant storms, however, attention was confined to cases when the distance could be fairly reliably fixed as being between 15 and 25 km. and, further, the value assumed for the average value of the potential gradient when it was less than 1000 V/m. was reduced to 300 V/m. to allow for the large number of occasions when the gradient was very small. It was found, in this range of distance, that the gradient was positive for 404 min. with an average value of +570 V/m. and negative for 190 min. with an average value of −880 V/m.; the time average value, including periods of both signs, was +110 V/m. The results of these computations are given in Table VI, and the mean value of the gradient is plotted against distance in fig. 2. It will be noted that, at all distances, negative gradients tend to be of greater magnitude than positive gradients; this fact, indeed, makes the average value of the gradient, at distances between 10 and 15 km., negative although periods of positive gradient are more frequent.

TABLE VI

Distance of nearest discharges km.	Average value of: Positive potential gradient V/m.	Average value of: Negative potential gradient V/m.	Average value with respect to time of the potential gradient V/m.
<3	+2950	−3750	−1200
<5	+2850	−3200	−1200
5–10	+1800	−2250	− 650
10–15	+1600	−2650	− 150
15–25	+ 570	− 880	+ 110

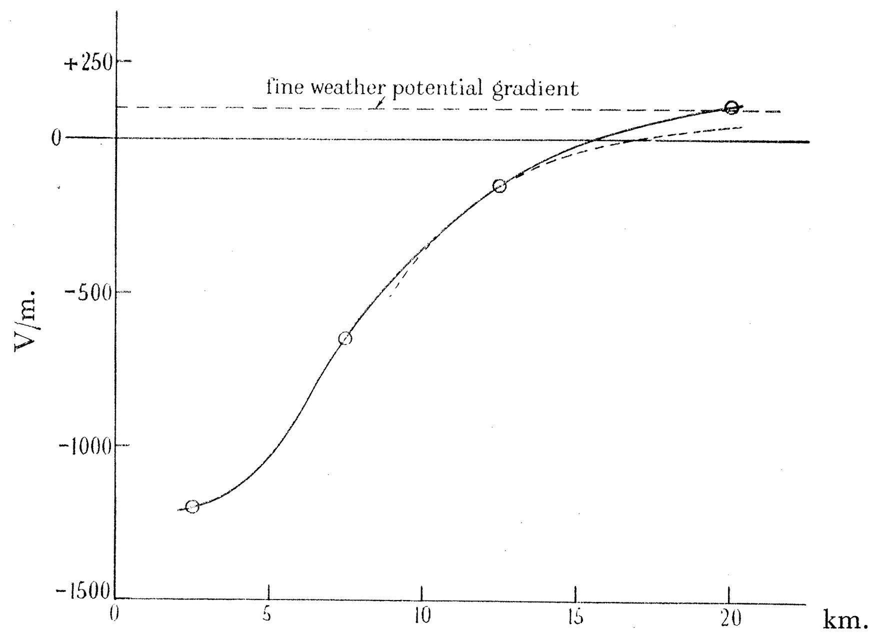


FIG. 2. The mean pre-discharge potential gradient at various distances from a thunderstorm.

The resulting curve (fig. 2) represents approximately the average distribution of potential gradient with distance from the active centre of a thunderstorm, the average being taken over all directions from the discharging region and over all phases in the development of the cloud so long as it is producing discharges. The average potential gradient is negative at all distances up to about 15 km. and the positive potential gradient at 20 km. is only of the same order as the fine-weather gradient. It will probably not be greatly in error if we assume for an average value of the fine-weather gradient during these observations (mostly on summer afternoons) a value of +100 V/m. This is indicated by the horizontal dotted line in fig. 2. The average effect of a storm is then the departure of the curve from this line, and it would appear that the average total effect on the gradient due to a storm at 20 km. is very small.

While the curve is not sufficiently accurately determined to warrant a detailed investigation, it is of some interest to consider whether a simple hypothetical distribution of charge in the cloud will represent the observed results. It is found that the departure of the curve from the fine-weather gradient at distances between 10 and 12·5 km. is well represented by the field, due to a negative point charge, the best fit being obtained when the height is taken to be about 3 km. The effect of such a charge is represented by the dotted curve in fig. 2. The divergence of the calculated and observed curves at smaller distances is of little significance since such a simple model becomes meaningless close to the storm, but it is interesting that the observed negative gradient is dying away beyond 15 km. more rapidly than that due to a single charge adjusted to fit the observations between 10 and 12·5 km. In other words, in order to fit all the observations beyond 10 km., it is necessary to supply the cloud with an upper positive pole. The effect of this upper positive charge is, of course, much more striking in the records of some individual storms; the very small average value of the field of a distant storm suggests, however, that usually the lower negative charge in the cloud considerably exceeds in magnitude the upper positive charge.

When the electric field of a thunderstorm is not disturbed by field-changes or by the recovery curves which follow them, its variations are usually comparatively slow. On a few occasions, however, it was observed to be disturbed by violent and rapid fluctuations. Striking examples of this not very common phenomenon are reproduced in figs. 45, 46, 48–50, and 54, Plates 8 and 9. These fluctuations were usually observed when the cloud was not producing lightning discharges and seemed on several occasions to be characteristic of an earlier stage in the development of the cloud. They were usually observed when the cloud was comparatively distant and could not therefore be explained by the passage overhead of small charged clouds. It would seem, in fact, that they were due to corresponding fluctuations in the electric moment of the cloud. This implies that the electric moment can fluctuate with a quasi-period of a few seconds and with an amplitude comparable with the whole value of the electric moment. The effect may conceivably be due to some form of turbulent motion in the cloud. It was noted that, on more than one occasion, during or shortly after the occurrence of such fluctuations, clouds in the neighbourhood developed pronounced mammatiform structure.

6. The interpretation of field-change observations

The essential principles on which the interpretation of all subsequent field-change data have been based were first stated by Wilson. The main results will be recalled briefly. All theories of the mechanism of production of electric charge in a thundercloud result primarily in a vertical separation of charges of opposite signs. A discharge removing electric charge of one sign to earth causes at an observing station on the earth's surface, at any distance, a field-change whose sign is opposite to the sign of the charge brought down. The same would presumably be true of the direct effect of a discharge removing a charge to the conducting upper atmosphere, if such discharges occur. The field-change due to a vertical discharge which does not reach the ground vanishes at a certain distance from the discharge path and the field-change has opposite signs inside and outside the reversal distance. It is irrelevant to the argument, as Simpson (1927) has pointed out, whether the discharge is between charges of opposite sign or simply changes the height of a single charge, provided it does not reach the ground. A discharge lowering a positive charge without reaching the ground causes a positive field-change within the reversal distance, and a negative field-change beyond it. The reversal distance, L, is approximately $\sqrt{2}$ times the height, H, of the centre-point of a vertical discharge in the air. (If a point charge is moving vertically, and F be the field it produces at the earth's surface at a horizontal distance L, $\partial F/\partial H$ vanishes when $L = H\sqrt{2}$; again, if the active region of separation of charge is approximately spherical, the primary distribution of charge in the cloud will approximate to a vertically polarized sphere. The field at the earth's surface due to such a sphere vanishes when $L = H\sqrt{2}$, when H is the height of the centre of the sphere.)

Visual or photographic observations of lightning suggest that discharges occur, not infrequently, with a considerable inclination to the vertical. This complicates the simple picture so far considered; the effects have been discussed by Schonland (1928). The reversal distance for an inclined discharge is considerably greater than that for a vertical discharge between the same heights, if the lower end of the discharge is closer to the observing station than the upper, and less than that for a vertical discharge if the horizontal distance of the upper discharge is the smaller.

One further possible complication must be remembered. A complicated discharge may, in effect, remove both charges to earth and be recorded as a simple field-change. In such a case, a discharge to earth may have a reversal distance.

If the simplest picture be adopted and we treat the two charges as if concentrated at their centres of mass, the field at any distance is readily calculated. If the values of the two charges are Q_1 and $-Q_2$, their heights H_1 and H_2, and their horizontal distances from the observing station L_1 and L_2, the potential gradient F, due to the bipolar cloud is

$$F = \frac{2Q_1H_1}{(H_1^2+L_1^2)^{\frac{3}{2}}} - \frac{2Q_2H_2}{(H_2^2+L_2^2)^{\frac{3}{2}}}.$$

In the case of a simple discharge in the cloud, if we write $Q_1 = Q_2$, we obtain the field F, which is destroyed by the discharge.

If H_1, H_2, and $(L_1 - L_2)$ are all small compared with L_1, the field-change produced by a flash conveying a single charge to earth is $\frac{2QH}{L^3}$ and by a flash not reaching the earth $\frac{2Q(H_1 - H_2)}{L^3}$. In either case FL^3 is equal to the electric moment of the discharge.

For purposes of illustration, some numerical examples are appended. If we assume $H_1 = 7$ km., $H_2 = 3$ km., the reversal distance L for a vertical discharge is 6·6 km. If now the two charges are displaced horizontally relative to one another by 5 km., in the line from the cloud to the observing station, without altering the height, the reversal distance measured from the nearer charge is beyond 15 km. when the lower charge is nearer; when the upper charge is nearer, the reversal point is under the cloud between the two charges. Finally, Table VII gives the value of FL^3 as a fraction of the true value of the electric moment, $2QH$ or $2Q(H_1 - H_2)$, when F is observed at various distances from the discharge. In the case of inclined discharges, L is the horizontal distance from the nearer of the two charges, and the charges have a horizontal displacement of 5 km. from one another in the direction of the observing station.

TABLE VII. VALUES OF $FL^3/2QH$

L in km.	10	15	20	25	30
Flash to earth from 3 km. height	0·88	0·94	0·97	0·98	0·99
Flash to earth from 7 km. height	0·55	0·74	0·84	0·89	0·92
Vertical flash from 7 to 3 km.	0·30	0·60	0·75	0·83	0·88
Inclined flash from 7 to 3 km.: Upper charge nearer	0·75	0·99	1·10	1·14	1·15
Lower charge nearer	*	*	0·08	0·20	0·30

* Within the reversal distance.

The possible occurrence of inclined flashes in the cloud introduces a difficulty into the measurements of electric moments. On one side of the cloud, in such cases, the observed values of FL^3 may exceed the moment of the discharge. The error introduced thereby is not likely to be a serious one, and even in the extreme case of a horizontal discharge, FL^3 is always less than the electric moment of a single charge at the same height. On the opposite side of the cloud, however, the difficulties are more serious, and even at 30 km. distance, the extreme limit of audibility of thunder, FL^3 may be much smaller than the electric moment.

Further consideration of these points is deferred until the observations have been discussed.

7. THE RELATION BETWEEN THE DISTANCE OF A DISCHARGE AND THE MAGNITUDE OF THE FIELD-CHANGE PRODUCED

When considering the observed magnitude of the field-change due to a discharge at a known distance, a certain difficulty arises, due to the complicated structure which many field-changes possess. When the field-change is simple, in the sense previously defined, the total change will usually be the effect of what would normally be called a single lightning flash, although, in some cases, nearly simultaneous discharges in widely separated channels may have caused field-changes of the same sign which

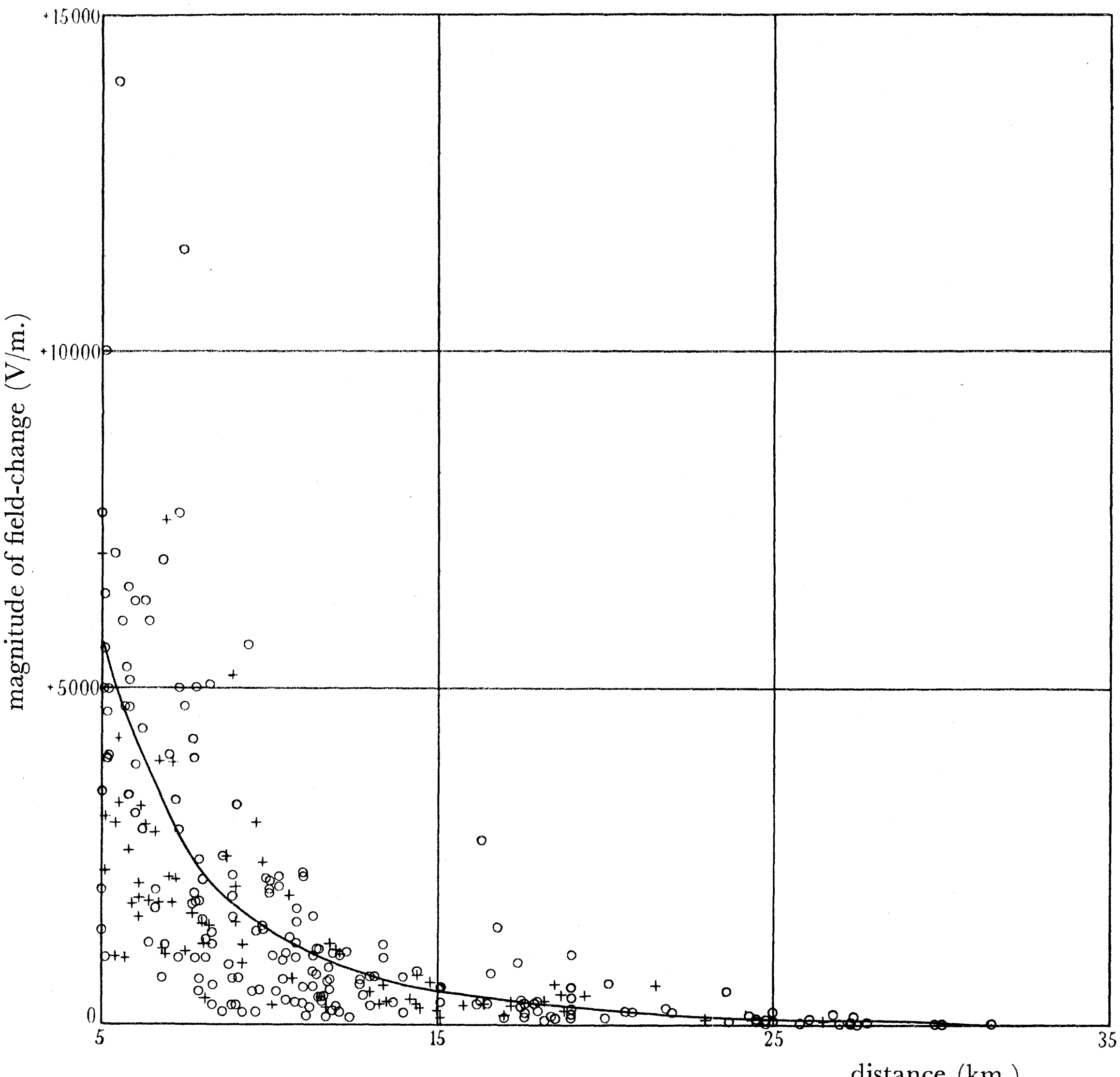


FIG. 3. Positive field-changes.

would be added together and considered a single simple change of field. When the field-change is complex, the difficulty is worse, but the following rather arbitrary procedure seems likely to yield results comparable with the simple field-changes. The complex field-change is reduced to a double field-change by adding together the components of the same sign. The bigger component of this double field-change will usually be due to the nearer discharge, if the discharges were widely separated, and is perhaps the quantity most directly comparable with the magnitude of a simple field-change due to a discharge at the same distance. It should, however, be noted that in many complex field-changes, the form of the record suggests that one component field-change is not completed before another of the opposite sign commences. The values deduced for the component field-changes may thus be considerably too small. The net effect of the whole complex field-change is, of course, the most reliably determined quantity and is also of considerable interest.

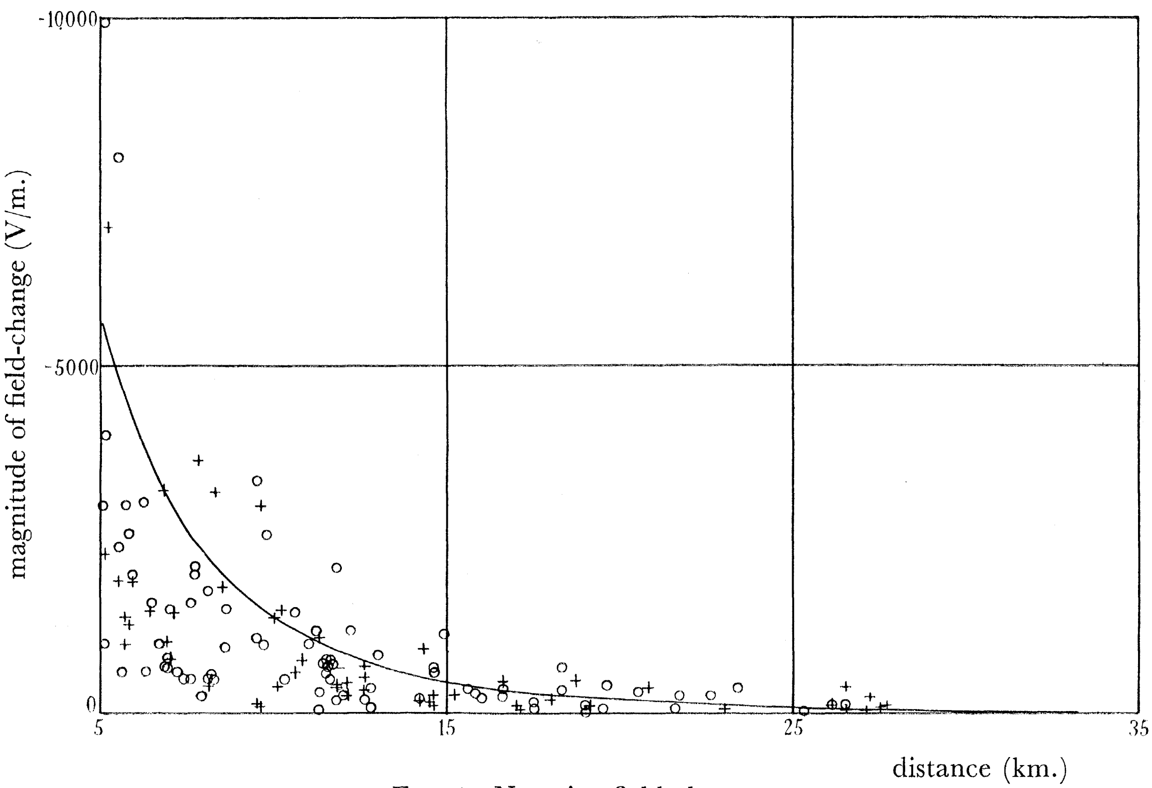


FIG. 4. Negative field-changes.

The relation between the magnitude, F, of a field-change and the nearest point on the corresponding discharge path is represented graphically in figs. 3–5. Points have been plotted corresponding to all observed field-changes when the distance of the discharge was unambiguously determined. Circles represent simple field-changes and crosses the bigger component of complex field-changes. The points in these diagrams show considerable scatter but on the average a steady decrease of F with increasing distance throughout the whole range of the observations. The curves drawn in figs. 3 and 4 represent the field due to a charge of 22 coulombs at a height of 5 km. In fig. 6 a similar plot has been made for the discharges from a single storm, that of 22 June 1933 (Plates 11–13). On this occasion all the discharges from which the thunder could be identified gave positive field-changes. The behaviour is similar to that of the previous diagram and it will be observed that, even for a single storm, there is considerable scatter of the points from the mean curve through them.

The rapid decrease of the mean value of F with increasing distance even at distances of only a few kilometres is strong support for Wilson's conclusion that the regions discharged by a lightning flash are not of great horizontal dimensions.

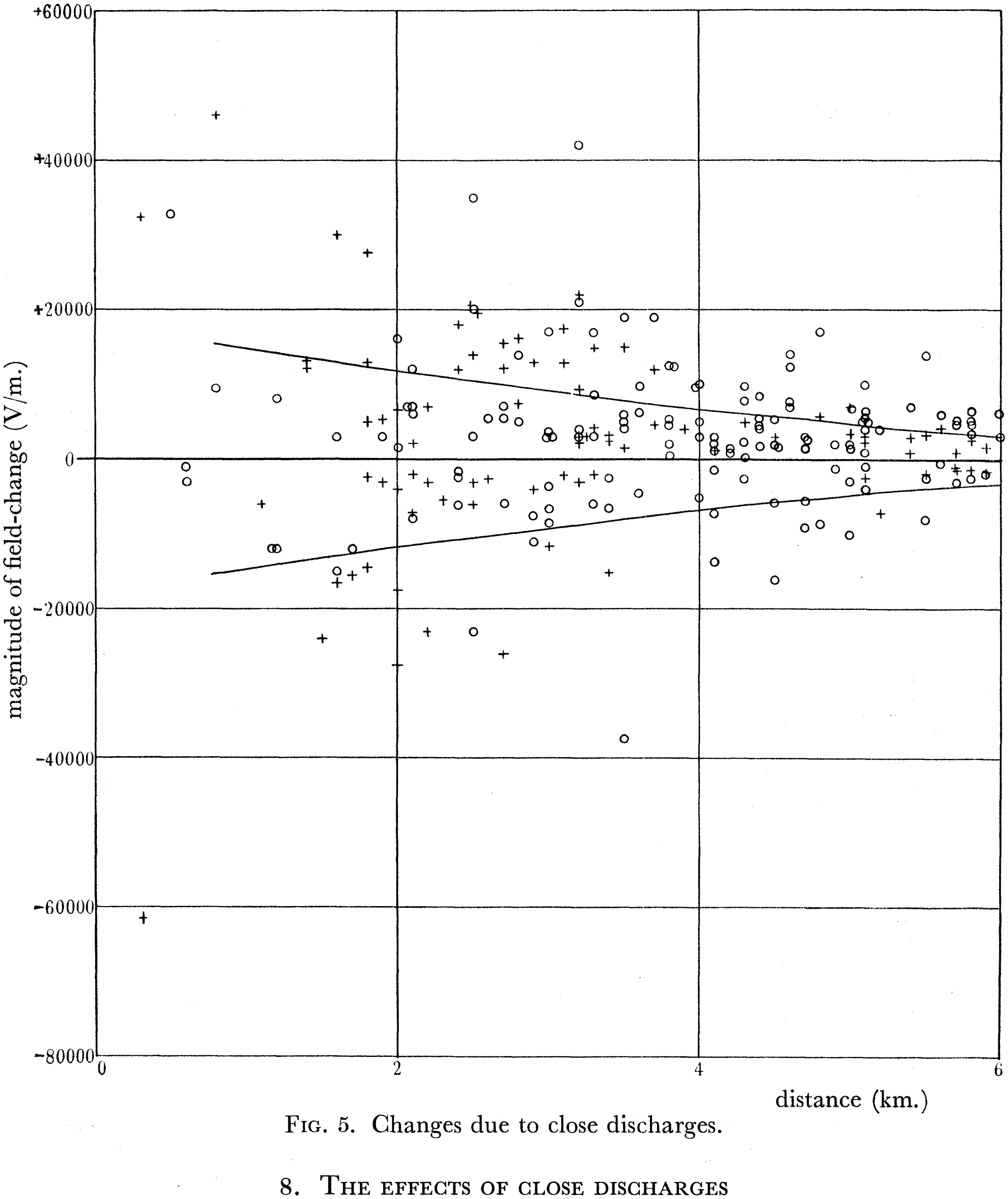


Fig. 5. Changes due to close discharges.

8. The effects of close discharges

The magnitudes of the field-changes due to close lightning discharges vary over an enormous range, as is obvious from an inspection of the data plotted in fig. 5. The mean observed values of field-changes in three ranges of distance are tabulated in Table VIII.

TABLE VIII

Mean observed values of magnitude of a field-change V/m.	Distance of discharge km. 0–2	2–4	4–6
Positive field-changes	+15,600 (17)	+9900 (69)	+4800 (67)
Negative field-changes	−14,600 (17)	−8200 (32)	−4600 (27)
Average magnitude irrespective of sign	15,100 (34)	9300 (101)	4700 (94)

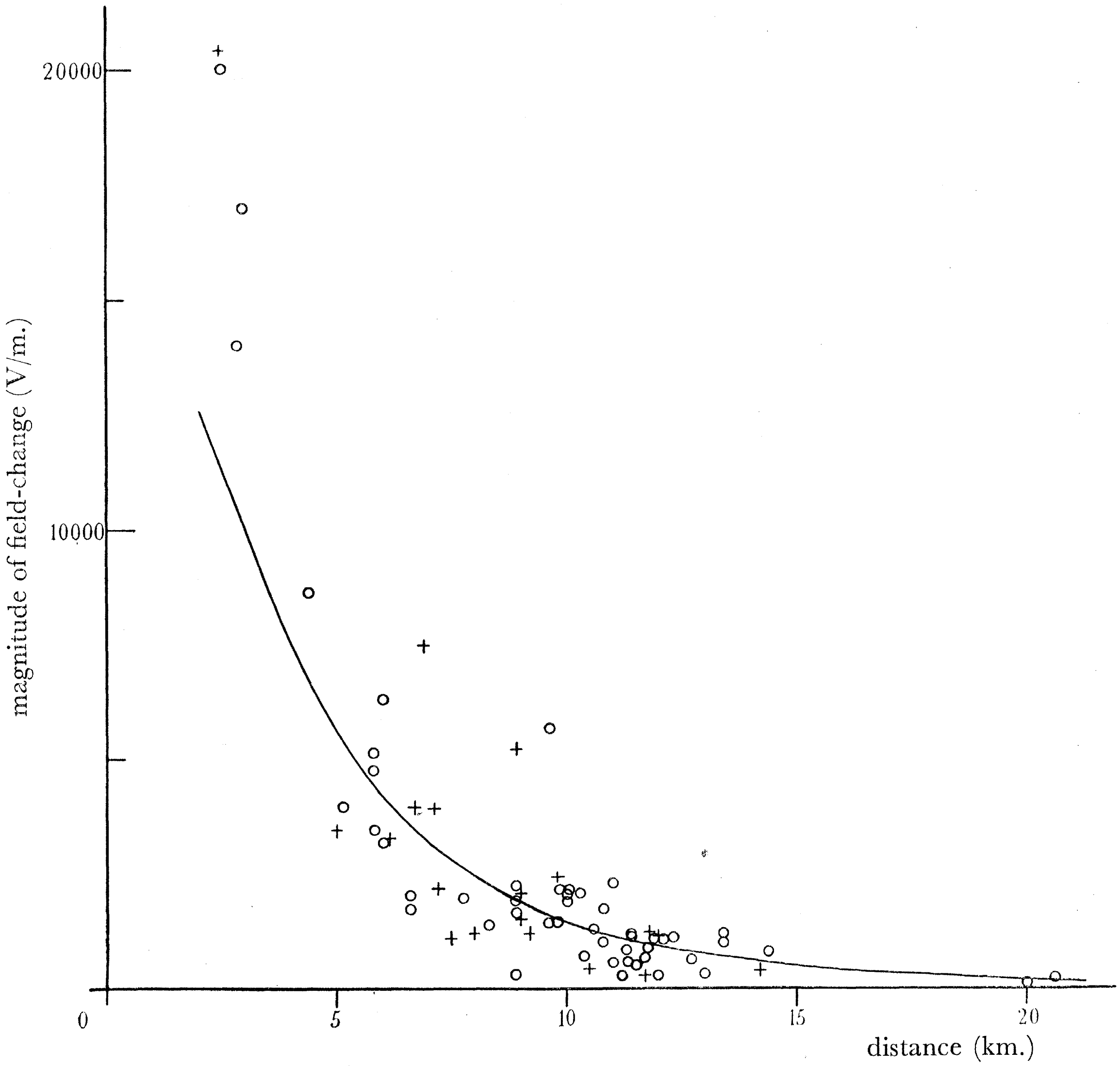


FIG. 6. Field-changes in a single storm, 22 June 1933. All field-changes were positive.

There were no very significant differences between the behaviour of simple and complex discharges (although the latter tended, on the whole, to be a little larger), and they have all been considered together in Table VIII. The figures in brackets in the table represent the number of observations from which each mean is derived. There is a fairly regular increase in the mean value of a field-change with decreasing distance of the discharge, but the scatter of the individual observations is very great and is greatest for observations at very short distances. Thus, for discharges within 2 km., the individual field-changes observed had values ranging from 1000 to 61,000 V/m. The range is almost the same when positive and negative field-changes are separately considered. It is, of course, possible that the smaller field-changes were really examples of unresolved complex field-changes whose components might have been considerably larger, but it is rather surprising that even the net effect of a very close complex discharge should sometimes be so small. The recorded effect of a close discharge may be small even when the discharge is to earth. Two flashes to earth, each within 1 km., were recorded as apparently simple negative field-changes of −3000 and −1000 V/m. respectively.

Whilst such a simple model should not be pushed too far, it is of interest to note that the variation with distance of the average value of a field-change for these close discharges is well represented by the field of a single point charge. The best fit is obtained if the height is about 4·5 km. The smooth curves drawn in fig. 5 representing the average observed values from the last row of Table VIII are almost indistinguishable from the computed values of the field due to a point charge of 17·6 coulombs at a height of 4·5 km.

The field-change due to a very close discharge usually exceeds in magnitude the value of the pre-discharge gradient and may be much greater. Thus, whatever the sign of the field-change relative to the pre-discharge gradient, the electric field just after the discharge is, not infrequently, considerably greater than the maximum values ever attained by the pre-discharge field. Such very intense fields only persist for a few seconds at most.

9. The electric moment of a lightning discharge

It has already been pointed out that, at sufficiently great distances from the discharge, its electric moment M is always given by the equation

$$M = 2QH = FL^3,$$

where H is the vertical length of the discharge path and the other symbols have their usual meanings. It has further been pointed out that it may be necessary to go to very considerable distance before this equation becomes approximately true. The quantity FL^3 is, however, a very convenient parameter for specifying the intensity of a discharge at moderate distance, and has been termed by Wilson (1916) the "uncorrected" moment of the discharge. Mean values of FL^3 are given in Table IX for discharges in various ranges of distances. All discharges at known distances greater than 5 km. are included.

TABLE IX. VALUES OF $FL^3 \times 10^{-6}$. V/m. $\times$ km.^{3}

Distance of discharge in km.	5–10	10–15	15–20	>20
Simple discharges:				
Positive field-changes	**1·07** 0·13 4·65 (82)	**1·30** 0·21 3·00 (58)	**2·43** 0·48 11·90 (27)	**1·75** 0·20 6·70 (28)
Negative field-changes	**0·65** 0·12 2·44 (34)	**1·23** 0·09 3·80 (26)	**1·48** 0·13 4·20 (12)	**2·32** 0·81 5·00 (9)
Complex discharges (bigger component only of the field-change):				
Positive field-changes	**0·91** 0·16 3·66 (42)	**1·30** 0·31 2·31 (18)	**1·74** 0·50 3·93 (12)	**2·87** 1·12 6·09 (3)
Negative field-changes	**0·66** 0·12 2·65 (20)	**1·01** 0·44 2·78 (20)	**1·35** 0·42 3·15 (7)	**2·99** 1·40 7·44 (9)

The main entry in black figures is in each case the mean value of the "uncorrected moment" for that particular type of field-change and range of distances, the two figures to the right of each mean value are the extreme individual values, and the figure in brackets is the number of field-changes included.

There do not appear to be any significant differences between the values for simple and complex discharges. Combining them the values shown in Table X are obtained.

TABLE X. $FL^3 \times 10^{-6}$

	5–10 km.	10–15 km.	15–20 km.	>20 km.
Positive discharges	1·02 (124)	1·30 (76)	2·22 (39)	1·86 (31)
Negative discharges	0·65 (54)	1·14 (46)	1·43 (19)	2·66 (18)

When a sufficiently great distance has been reached for the value of FL^3 to be a measure of the electric moment of the discharge, the mean value of FL^3 should cease to increase with increasing distance. It would appear from Table X that it is necessary to go to distances exceeding 15 km. (and perhaps to still greater distances for the negative discharges). It may be noted that the average value of FL^3 for the negative discharges is considerably less than that for the positive discharges in the range of distances 5–10 km. and slightly less from 10 to 15 km., while at distances beyond 15 km. the average values are not very different. The observations suggest that at great distances the values of FL^3 for negative discharges exceed those for positive ones. It would seem probable that the vertical height of negative discharges exceeds, on the average, that of positive discharges. A certain amount of caution is necessary in interpreting these results. The identification of the thunder from individual discharges beyond say 20 km. demands rather special conditions, namely, a calm day and infrequent discharges, and the discharges thus selected may not be typical of all storms. There is, moreover, the possibility that the more intense distant discharges will have a greater chance of being identified and included in the table.

The mean value of FL^3 for discharges beyond 15 km. is not far different from 2×10^6 V/m. $\times$ km.^{3} for both positive and negative discharges. This corresponds to an electric moment, $2QH$, of $6{\cdot}66 \times 10^{16}$ e.s.u. $\times$ cm. or 220 coulombs $\times$ km. The correct value for negative discharges may be somewhat higher if the increase in the last column of Table X is real.

The values of the electric moments deduced from the individual discharges vary over a rather considerable range from the mean values considered; the extreme values in each range of distances have already been indicated in Table IX. The detailed distribution of the individual values is represented graphically in figs. 7 and 8. Here the ordinates represent the number of flashes observed with values of FL^3 represented by the corresponding abscissae; the data for positive discharges are plotted above, those for negative discharges below, the axis of abscissae. Thus, in the case of discharges beyond 15 km., plotted in fig. 8, while the average value of FL^3 is about 2×10^6, the most frequent value is considerably less than this, being about $1{\cdot}2 \times 10^6$ for positive discharges and about $1{\cdot}0 \times 10^6$ for negative discharges. The mean value is raised by the occurrence of a comparatively small number of discharges of exceptionally large moment, in one case $11{\cdot}9 \times 10^6$. It seems very probable that the large value of the moment of these discharges is associated with exceptional vertical length, since such big values of FL^3 are only observed in the range of distances greater than 15 km.

We may sum up, then, by saying that the most frequent value of the electric moment of a positive discharge is about 130 coulomb-km. and of a negative discharge about 110 coulomb-km. The occasional occurrence of discharges of much greater electric moment (up to 1200 coulomb-km.) raises the mean values, however, for discharges of both signs to about 220 coulomb-km.

A determination of the electric moment of a discharge fixes the value of the electric charge carried by it within fairly narrow limits, since the vertical path must be of the order of a few kilometres. The result that the average value of QH is about 110 coulomb-km., and the most frequent value about 60 coulomb-km. may be compared with Wilson's estimate (1920), of 20 coulombs for the average value of Q. On the other hand, the extreme value of 600 coulomb-km. observed for one discharge demands that in this case Q was greater than 60 coulombs.

It is of considerable interest to consider together the values found from distant discharges for the electric moments and the effects of very close discharges. The field-change due to a very close discharge will be approximately $2Q/H^2$ if H is the height of the centre of the charge removed to earth, or of the lower charge, in the case of a flash

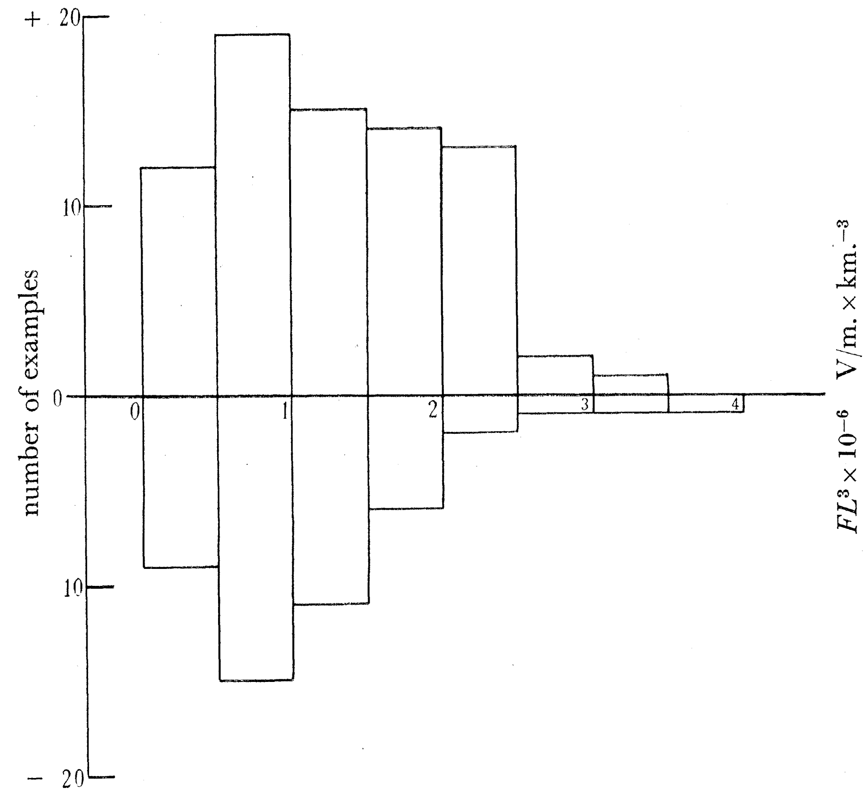


FIG. 7. Distribution of values of "uncorrected" moments for discharges at distances between 10 and 15 km.

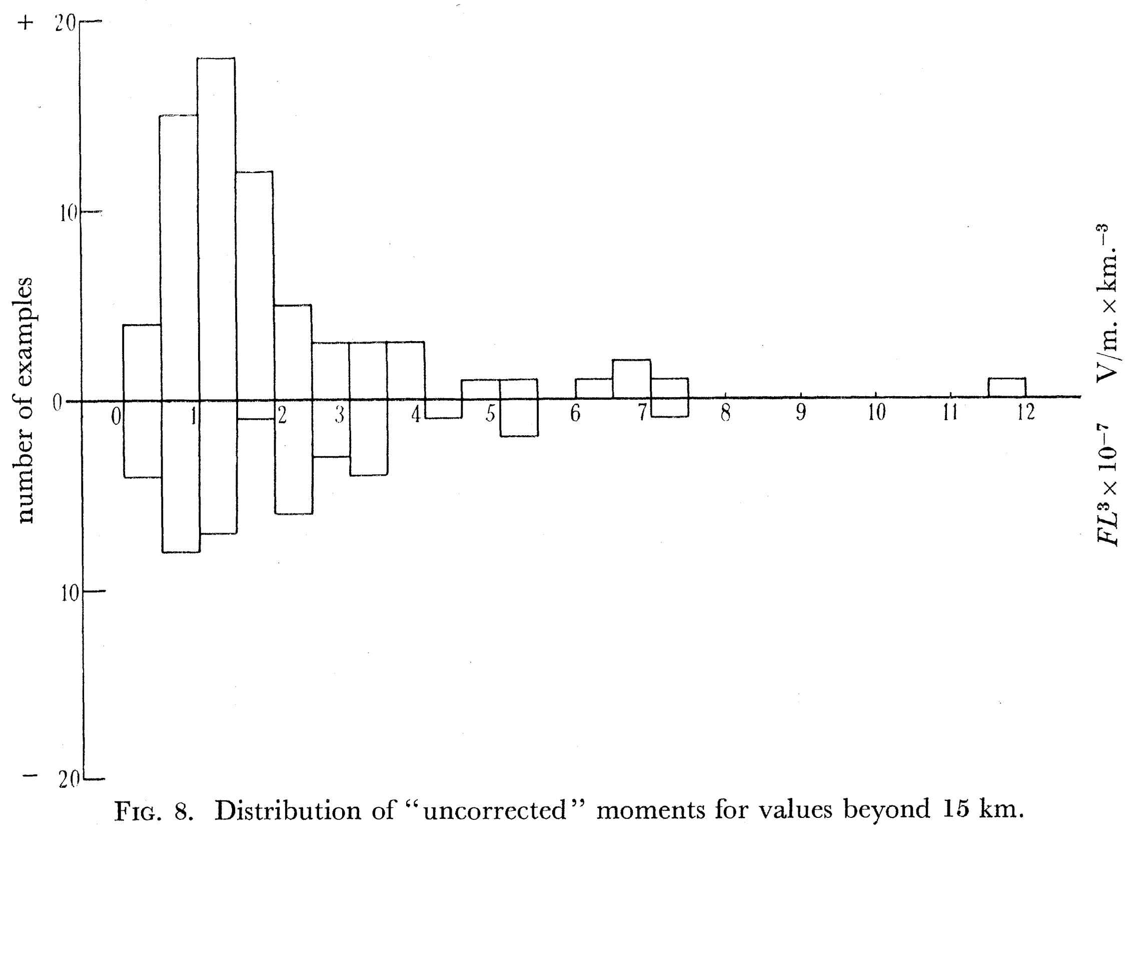


FIG. 8. Distribution of "uncorrected" moments for values beyond 15 km.

in the cloud. The approximation will only be a good one if the volume occupied by the charge is approximately spherical. If Q/H^2 and QH are both known, the values of Q and H may be separately determined. The effects of very close discharges vary over an enormous range, but the mean value of the field-change due to a very close discharge is about 15,000 V/m. Comparing this with the mean value of the electric moment we deduce $H = 5{\cdot}1$ km., $Q = 21{\cdot}6$ coulombs or, if we use the most frequent value rather than the mean value of QH, we find $H = 4{\cdot}2$ km., $Q = 14{\cdot}4$ coulombs. The best representation for the average behaviour of close discharges, considered alone, was previously found to be given by $Q = 17{\cdot}6$ coulombs, $H = 4{\cdot}5$ km.

Finally, if $2Q/H^2$ be equated to the value of the biggest field-change observed, 60,000 V/m., and compared with the mean electric moment, we deduce $Q = 34{\cdot}2$ coulombs, $H = 3{\cdot}2$ km., and similarly, employing a very small value of 3000 V/m. for the close discharge, $Q = 12{\cdot}7$ coulombs, $H = 8{\cdot}7$ km. It would seem, then, that the quantity discharged in the great majority of discharges is between 10 and 40 coulombs, the mean value being close to 20 coulombs. (Occasional discharges of high electric moment must, however, exceed these figures, as already pointed out.)

10. The prevailing sign of the field-changes due to lightning discharges

It has been well established by the work of previous investigators in various parts of the world that if observations are made fairly close to the discharge path the majority of discharges cause positive field-changes, while with discharges at greater distances negative field-changes are relatively more frequent. The material rendered available by the present investigation is unusually extensive and merits consideration in some detail. We consider, first, only the field-changes due to discharges at known distances. Table XI gives the numbers of positive and negative field-changes observed in four ranges of distance frequently considered by previous workers, namely, for distances less than 5, 5–10, 10–15, and greater than 15 km. respectively (the limit of the apparatus is about 40 km.). The sign associated with a complex discharge is the sign of the net effect or, what is the same thing, the sign of the bigger component. N_+ and N_- are the numbers of positive and negative field-changes, N_0 the number of complex field-changes whose net effect was zero, within the accuracy of the observations.

Table XI. 1926–36. Numbers of positive and negative field-changes observed

Distance km.	A Simple field-changes N_+	N_-	N_+/N_-	B Complex field-changes N_+	N_-	N_0	N_+/N_-	C All field-change N_+	N_-	N_0	N_+/N_-
< 5	94	40	2·35	52	23	2	2·21	146	63	2	2·30
5–10	82	33	2·48	35	17	6	1·90	117	50	6	2·26
10–15	75	42	1·79	31	27	0	1·15	106	69	0	1·54
> 15	1608	1372	1·17	91	174	60	0·59	1699	1546	60	1·10

In computing the ratio N_+/N_-, the discharges producing a complex field-change whose net effect is zero are divided equally between the positive and negative field-changes.

These results are in agreement with those of previous workers in showing a considerable preponderance of positive field-changes at small distances, while in the distance range of 15–40 km. field-changes of either sign are approximately equally frequent. Experience in observing actual storms and, in particular, the effects of very close discharges led, however, to the suspicion that the actual situation is more complicated than the above table would suggest. The closer discharges whose distances were known with sufficient accuracy were therefore regrouped with a finer subdivision of distances. Table XII then results.

TABLE XII. 1926–36. NUMBERS OF FIELD-CHANGES OBSERVED

Distance km.	A Simple field-changes N_+			B Complex field-changes N_+				C All field-changes at known distances N_+			
	N_+	N_-	N_+/N_-	N_+	N_-	N_0	N_+/N_-	N_+	N_-	N_0	N_+/N_-
<3	23	20	1·15	21	19	1	1·10	44	39	1	1·13
3–6	74	24	3·08	31	8	3	3·41	105	32	3	3·18
6–9	46	21	2·19	25	8	1	3·00	71	29	1	2·42
9–12	53	21	2·52	12	10	1	1·19	65	31	1	2·07
12–15	16	10	1·60	11	10	0	1·10	27	20	0	1·35

The number of field-changes available is rather small for this fine subdivision, but if the table be accepted at its face value the striking new fact which emerges is the small value of the ratio N_+/N_- for very close discharges. The effect is present among both the simple and the complex field-changes, and the difference in the value of the ratio N_+/N_- in the first two rows of the table is so great that it can hardly be a chance effect due to insufficient sampling. Before discussing the significance of these results we turn to the consideration of the large number of observed field-changes due to discharges whose distances could not be determined. These are tabulated according to the magnitude and sign of the field-changes. In the case of complex discharges separate figures are given for the bigger component only and for both components. The tables which follow include all observed field-changes whether the distance of the discharge was known or not.

If the numbers for simple and complex discharges be added together the following table may be constructed.

The general features of these tables are similar to those obtained when discharges are classified according to distance. The greater number of discharges which is here included, however, establishes the facts more definitely. The last row of figures in Tables XIII and XIV, representing the most distant discharges, shows a preponderance of negative field-changes.

Before discussing in detail the results given in Tables XI–XIV, it is of interest to compare them with the results of some earlier unpublished observations which were kindly supplied by Professor C. T. R. Wilson. These observations were made at Cambridge with a capillary electrometer during the years 1920–4 inclusive. The numbers of simple field-changes recorded in this period are given in Table XV.

TABLE XIII. 1926–36. NUMBERS OF FIELD-CHANGES OF DIFFERENT MAGNITUDES OBSERVED

Magnitude of field-change V/m.	A Simple discharges			B Complex discharges. Bigger component only				C Complex discharges. Both components	
	N_+	N_-	N_+/N_-	N_+	N_-	N_0	N_+/N_-	N_+	N_-
> 15,000	14	7	2·0	15	9	0	1·7	16	9
10,000–15,000	24	8	3·0	15	3	0	5·0	16	5
5000–10,000	76	23	3·3	27	7	1	3·7	35	27
1500–5000	228	105	2·2	79	31	10	2·3	110	75
500–1500	412	171	2·4	68	36	30	1·6	122	131
100–500	452	248	1·8	85	107	9	0·80	167	233
10–100	1192	944	1·3	64	139	50	0·54	298	307
< 10	279	319	0·88	4	2	8	—	44	21

TABLE XIV. 1926–36. NUMBERS OF FIELD-CHANGES OBSERVED

Magnitude of field-change V/m.	A Simple discharges together with bigger components of complex discharges				B All discharges		
	N_+	N_-	N_0	N_+/N_-	N_+	N_-	N_+/N_-
> 15,000	29	16	0	1·8	30	16	1·9
10,000–15,000	39	11	0	3·5	40	13	3·1
5000–10,000	103	30	1	3·4	111	50	2·2
1500–5000	307	136	10	2·2	338	180	1·9
500–1500	480	207	30	2·2	534	302	1·8
100–500	537	355	9	1·5	619	481	1·3
10–100	1256	1083	50	1·2	1490	1251	1·2
< 10	283	321	8	0·88	323	340	0·95

The same general tendency is manifest throughout the whole series of results available; namely, that positive field-changes are in a considerable preponderance when the storm is fairly close, while negative field-changes become more and more frequent as the storms observed are more distant and the field-changes smaller. This tendency is, however, very much more marked in the earlier (1920–4) than in the later (1926–36) series of results. In particular, the extreme rarity of big negative field-changes in the earlier series is remarkable. This difference cannot be explained by slight differences in the recording technique and must represent a real difference in the relative frequency of different types of discharges observed in different storms. Two individual years in the later series (1933 and 1936) gave an excess of big positive field-changes comparable with the figures of Table XV, but there was no occasion when this happened for several consecutive years. It is clear that a very long series of observations is necessary in order to determine the average behaviour of thunderstorms even in a single locality. Individual storms showed great diversity of behaviour at all distances within the range of the present apparatus.

TABLE XVA. 1920–4

Distance (km.)	0–5 Positive	0–5 Negative	5–10 Positive	5–10 Negative	>10 Positive	>10 Negative
Number of field-changes recorded	108	19	85	17	326	359
Mean magnitude V/m.	6000	1670	1740	1550	112	65

TABLE XVB. 1920–4

Magnitude of field-change V/m.	>10,000	5000–10,000	2000–5000	1000–2000	500–1000	100–500	10–100
Number of positive field-changes	22	41	54	72	33	117	249
Number of negative field-changes	0	3	14	11	15	99	295

Whipple and Scrase (1936), using a discharging point and galvanometer, recorded 562 field-changes with a ratio N_+/N_- of 3·5. Their technique would not distinguish between simple and complex field-changes, and the smallest field-change which could be detected was apparently about 2000 V/m. The proportion of positive and negative field-changes in their storms was intermediate in value between the two series of observations quoted above. Appleton, Watt and Herd (1926), observing rather more distant discharges than are here included, obtained a considerable preponderance of negative field-changes.

In considering the results which have been tabulated above, it must be remembered that they include flashes in the cloud and also flashes to earth. In the great majority of cases the flash was not seen. Most of the storms occurred in daylight, and in such conditions most of the flashes are only visible when the storm is fairly close. Any deductions from the results must therefore be based primarily on the behaviour of the field-changes themselves and their variation with the distance of the storm.

If we concentrate attention first on the simple field-changes, the most definitely established result is the gradual decrease of the value of the ratio N_+/N_- from a value exceeding 3 at a distance of 4 or 5 km. to a value less than unity at distances exceeding 30 km. say. This is most directly interpreted as indicating the frequent occurrence of a type of discharge which does not reach the ground and which, in effect, raises the height of a negative charge (or lowers a positive charge). We will call such discharges, discharges of type 1. It seems preferable to describe the effect in terms of the motion of a negative charge, since all the lightning discharges which have been studied in detail by Boys's camera photographs are apparently propagated from a negative charge in the cloud (Schonland *et al.* 1935). A discharge of type 1 causes a positive field-change within the reversal distance, a negative field-change beyond it.

Flashes visible in the cloud but not reaching the ground have not infrequently been observed to cause positive field-changes in close storms and negative field-changes in distant storms. Similar correlations have been observed by previous workers, especially Schonland and others. The reversal distances of individual discharges of this type appear to vary over a very considerable range, from 6 to more than 20 km. If, for instance, it be assumed that cases of reversal distances of about 7 km. correspond to vertical discharges, the centre point of the discharge must be at a height of the order of 5 km. above the ground. The much greater reversal distances could then be readily explained as due to inclined discharges at a similar height. As has already been pointed out, an inclined discharge has a very great reversal distance in the direction of displacement of the lower end of the path and a rather smaller reversal distance than a vertical discharge in the opposite direction. This aspect of the observations may thus be satisfactorily accounted for without assuming any great diversity in the heights of individual discharges of this type, although the possibility of such a diversity is by no means excluded.

A similar but more marked variation of sign with distance or magnitude occurs also among the complex field-changes, many of which are accompanied by a discharge to earth. The result of such a discharge will be in effect to remove charges of both signs to earth. The higher proportion of negative field-changes at great distances indicate that frequently the positive charge removed was at the greater height. The actual value of the reversal distance will depend on the relative magnitudes of the two charges.

We turn next to the consideration of the effects of very close discharges. While the number of field-changes observed is rather low, yet they represent the closest flashes from a number of storms, and it would seem to be established that the proportion of negative field-changes is considerably greater for flashes within 3 km. of the observer than for flashes at slightly greater distances. The fact that a similar effect occurs among both simple and complex field-changes strengthens belief in its reality. Again, the very large field-changes, those greater than 15,000 V/m., also show a considerably higher proportion of negative field-changes than the field-changes in the range 5000–15,000 V/m., although the effect is not so well marked as when variation with distance is considered. (By no means all of the field-changes greater than 15,000 V/m. were within 3 km.) There is one obvious effect tending to diminish the proportion of positive field-changes when we select very close discharges. It has been shown that the frequent type of discharge in the cloud which causes a positive field-change at small distances occurs usually at a considerable height from the ground. When we consider discharges within 3 km. measured distance we are in effect only considering discharges which penetrate within a hemisphere of 3 km. radius and are clearly excluding some discharges which occur in the cloud above the hemisphere while including all flashes which come to earth within a radius of 3 km. In other words, we may be excluding a considerable proportion of the flashes which occur above a circle of 3 km. radius and produce a positive field-change. It does not appear, however, that this accounts for the whole effect. If we take the most favourable case possible and assume that in considering field-changes within 3 km. we have excluded all flashes which do not reach the ground, which is certainly not true, it would follow that flashes to earth carrying positive and negative charges were approximately equally frequent. When the effects of discharges of type 1 are included, positive field-changes are rather more than three times as frequent as negative field-changes. It would follow that discharges of type 1 in the cloud constitute at least 55 % of all discharges. At great distances from the discharge, discharges of type 1 produce negative field-changes which should be more than three times as frequent as positive field-changes. The observed ratio at great distances is only 1·5 (Appleton *et al.* 1926).

The observations can be most readily explained by assuming that there occurs a further type of flash which does not reach the ground, which lowers a negative charge in the atmosphere. This type of discharge will be termed type 2. The small reversal distance, of perhaps 3 km. or less, indicates that such discharges are low down, their centre points being commonly less than 2 km. from the ground and they cannot be of great vertical length.

There is, further, direct evidence supporting the existence of flashes of type 2. Several of the large negative field-changes due to very close flashes were observed to be due to flashes which were very low down but did not reach the ground. Thus, for example, in the storm of 20 May 1928 (figs. 18 and 19, Plate 4), several such flashes were observed. One in particular, for example, caused the cloud to be brightly illuminated at an altitude of about 40°, there being no trace of a discharge to earth visible. The lightning-thunder interval indicated a distance of only 1·2 km., and the discharge caused a negative field-change of −12,000 V/m.

The complex field-changes which so frequently accompany very close discharges again show a similar behaviour with distance. It would seem that a complicated discharge process often involves the main negative charge of the cloud together with a positive charge beneath it and very low down.

The data which have just been discussed represent the average behaviour of the lightning discharges during all phases of a thunderstorm. The individual storms are so diverse that any attempt to generalize concerning the variations during the history of a storm is somewhat hazardous; nevertheless, on several occasions the course of events during the development of a large active thunderstorm was approximately as follows. The first few discharges were irregular and at fairly wide intervals of time. There followed a period of very frequent discharges; during this period most of the discharges were apparently of type 1, with occasional discharges to earth, and most of the field-changes simple. Later, discharges became less frequent and many of the field-changes were very complex. The proportion of flashes to earth was now higher.

Finally, discharges were infrequent and close discharges often produced negative field-changes, either simple or complex.

The proportion of positive and negative field-changes from close discharges, observed in a storm where such a sequence of events occurred, would depend very largely on the distance of the storm during the last stage.

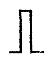
11. The structure of the field-change

Complex Discharges

The data concerning the relative frequency of positive and negative net changes of field when the field-change is complex have already been tabulated in Tables XII and XIII. The form of the variation with distance or with magnitude of field-change is very similar whether the field-changes are simple or complex, but the variation is more pronounced for complex field-changes. Positive and negative changes of field are about equally frequent for very close discharges whether the field-changes are simple or complex, but the preponderance of positive field-changes at moderate distances and of negative field-changes at great distances are both greater for complex than for simple field-changes.

In attempting to interpret the behaviour of the complex field-changes it is necessary to remember that they do not form a homogeneous group. A complex field-change is not infrequently produced by two or more consecutive lightning discharges, including discharges to earth and a discharge entirely in the cloud. The sign of the field-change due to a simple discharge to earth is the same at all distances, while a cloud discharge exhibits the phenomenon of a reversal distance. It is thus quite possible that the same complicated system of discharges would be recorded by a nearby observer as a complex field-change and by a distant observer as a simple field-change or vice versa. In this fact is probably to be found the explanation of a rather curious feature in the observations, namely, that the proportion of field-changes showing complexity is considerably higher for the very close discharges and very large field-changes than for the others. In order to eliminate instrumental effects in this comparison, field-changes were only included if the displacement on the original record was at least a millimetre and were classified as complex if they included components of both signs, the smaller being at least 10% of the larger. Defined in this way, about one-quarter of all field-changes recorded are complex, and the proportion is practically independent of the magnitude of the field-change over the range from 100 to 10,000 V/m. For field-changes between 10,000 and 15,000 V/m. the proportion rises, however, to 0·38, and for field-changes exceeding 15,000 V/m. to 0·47.

We proceed next to examine the relative frequency of the various possible types of complex field-changes, and the variation with magnitude and with the distance of the discharge. Attention is first concentrated on the comparatively simple types which include only two component changes. They may conveniently be divided into the following six types:

	First component	Diagrammatic representation	Typical recorded examples
Net change positive:			
Type A	Positive		Fig. 3*c*, Plate 2; fig. 23*b*, Plate 5
Type B	Negative		Fig. 8*b*, Plate 3; fig. 33, Plate 6 (at 18 h. 30·7 m.)
Net change negative:			
Type C	Positive		Fig. 79, Plate 12 (at 15 h. 52·4 m.); fig. 118, Plate 17 (at 13 h. 35·1 m.)
Type D	Negative		Fig. 17, Plate 4; fig. 114, Plate 16 (at 13 h. 51·2 m.)
Net change very small:			
Type E	Positive		Fig. 6*b*, Plate 2; fig. 108, Plate 16 (at 11 h. 17·7 m.)
Type F	Negative		Fig. 5 *c*, Plate 2; fig. 104, Plate 15 (at 14 h. 50·5 m.)

Field-changes are classified under types E and F if the net effect is less than 10 % of the larger component.

An examination of all recorded double field-changes yielded the following numbers of examples of the different types (Table XVI).

Table XVI. Distribution of double field-changes

	Magnitude (V/m.) of bigger component						
	> 15,000	10,000–15,000	5000–10,000	1500–5000	500–1500	100–500	10–100
Type A	1	5	12	27	19	29	18
Type B	8	5	3	20	20	30	31
Type C	1	1	0	3	6	37	47
Type D	2	1	4	10	18	45	64
Type E	0	0	1	5	20	8	22
Type F	0	0	0	2	11	5	26

Turning to the more complex field-changes (including at least three components) a similar classification may be made. In this case the types (as closely analogous as possible to those employed for the double changes) are as follows:

	First component	Typical examples
Net change positive:		
Type A	Positive	Fig. 23*a*, Plate 5; fig. 119, Plate 17 (first field-change)
Type B	Negative	Fig. 24*c*, Plate 5; fig. 104, Plate 15 (at 14 h. 48·1 m.)
Net change negative:		
Type C	Positive	Fig. 10*a*, Plate 3; fig. 20*b*, Plate 5
Type D	Negative	Fig. 8*a*, Plate 3; fig. 111, Plate 16 (last field-change)
Net change small:		
Type E	Positive	Fig. 107, Plate 16 (at 11 h. 14·7 m.)
Type F	Negative	Fig. 21*b*, Plate 5; fig. 101, Plate 15 (last field-change)

The distribution of all the observed field-changes of such complexity is given in Table XVII.

TABLE XVII. DISTRIBUTION OF COMPLEX FIELD-CHANGES HAVING AT LEAST THREE COMPONENTS

	Magnitude (V/m.) of the biggest individual component						
	>15,000	10,000–15,000	5000–10,000	1500–5000	500–1500	100–500	10–100
Type A	1	1	8	18	24	19	8
Type B	3	3	2	10	9	2	2
Type C	1	0	0	3	4	11	1
Type D	5	2	1	15	8	15	25
Type E	0	0	0	2	0	2	3
Type F	0	0	0	1	1	4	3

In order to make the analysis as definite as possible we also consider the distribution among the different types when the classification is made according to the distance of the discharge.

TABLE XVIII

	Double field-change. Number of examples						Complex field-change with three or more components. Number of examples					
Type ...	A	B	C	D	E	F	A	B	C	D	E	F
Distance km.												
<3	2	9	2	6	1	0	4	5	0	10	0	0
3–6	8	12	1	2	1	1	7	3	1	5	1	0
6–9	8	5	2	2	0	1	9	3	1	4	0	0
9–12	4	1	2	5	1	0	6	1	1	2	0	0

For the more distant discharges the behaviour with distance can be deduced with sufficient accuracy from Tables XVI and XVII.

In attempting to sum up the contents of the Tables XVI–XVIII, we note first that for very close discharges and for very large field-changes, the commonest types of field-change are, for double field-changes, types B and D, in that order; for the more complicated field-change type D is the commonest one and type B the next. Types B and D are alike in that the first detected effect is a negative change of field. At rather greater distances (or with rather smaller field-changes), the proportion of cases of type A increases and beyond about 5 km. in Table XVIII, and in the central columns of Tables XVI, XVII, it is the most frequent type. At still greater distances the proportion of types C and D increases and type D ultimately becomes the most frequent type of complex field-change at the greatest distances to which these observations extend. There are some other differences of detail between the behaviour of the double and the more complex field-changes; for example, for distant discharges type C is comparatively common among the double field-changes but is rare among the more complex ones.

One of the most striking facts which emerge is that when a complex field-change accompanies a flash within 3 km. the first perceptible effect is in 80% of cases a negative change of field. If simple field-changes are included, the proportion of all observed field-changes due to discharges within 3 km. in which the first detected change is negative is just over 60%. At slightly greater distances, on the other hand, the proportion of cases with a negative first process is much smaller. The detailed study of the lightning discharge by Schonland *et al.* (1935) showed that the first detectable effect was, in South African storms, nearly always a comparatively slowly moving leader streamer travelling downwards from a negative charge in the base of the cloud. An identification of the initial negative change for very close discharges with a leader of this type, which should cause a negative change of field when the storm is overhead but a positive change at all points outside its comparatively small reversal distance, is immediately suggested. If the identification is correct, it is rather surprising that the present recording technique can separate the effect of such a process which takes on the average (Schonland *et al.* 1935) 0·01 sec. to reach the ground. The electrometer itself should certainly give some response to the field-change due to such a leader, and it is just possible that the effect of the leader could be made out on the records, in the slower cases, if the following field-change were of the opposite sign. Moreover, if the leader streamer stops short of the ground, the whole succession of events may be somewhat slower than in the case of the discharge to earth studied by the South African observers. The smaller proportion of cases with a negative first change, when we proceed to slightly larger distances, is explained at any rate in part by the reversal of the effect of a leader of this type. At considerable distances from the discharge, however, we again find that the most frequent type of complex field-change begins with a negative change. It is necessary to assume, therefore, the existence of another type of initiating process or leader, higher in the cloud (and therefore with a much greater reversal distance) and consisting of a leader streamer upwards from a negative charge or downwards from a positive charge; it must be assumed, further, to fit in with the data for very close discharges, that when a process is initiated in this way the whole complex process usually remains high up in the cloud.

The considerable preponderance of net negative changes of field, which is observed when the storm is distant, indicates without ambiguity that the whole effect of a series of discharges, recorded at a distant station as a complex field-change, is, in the majority of cases, the destruction of a positive electric moment in the cloud. It is scarcely possible to attempt an identification of the processes responsible for the individual components in most cases, but it would seem very probable that the main negative change due to a distant discharge is commonly caused by a discharge in the cloud of the type 1, probably the commonest type of lightning discharge.

It has already been pointed out that a complex field-change is not infrequently observed when only a single flash (either to earth or in the cloud) is visible. It is not possible to deduce with certainty that charges of both signs have travelled down the same channel since it is always possible that further discharges were hidden by the cloud.

Complicated field-changes are most frequently observed in large violent storms, in the later stages of the storm. On the other hand, a storm which produces only a few discharges at wide intervals of time may give mainly complex field-changes.

12. The duration of the field-change

It is well established that a lightning discharge (carrying a negative charge to earth) frequently consists of a series of strokes down the same channel. The time interval between successive strokes may, according to Schonland *et al.* (1935), have any value from 0·001 to 0·53 sec., but is usually between 0·01 and 0·10 sec. The effects of these multiple strokes can be recognized in many of the records discussed in this paper as the "steps" on some of the simple field-changes. The stepped appearance is here found on field-changes of either sign, and there is no obvious difference in the time intervals in field-changes of opposite signs. The duration of the individual strokes, consisting mainly of the time required for the leader process to develop, is, according to the same authors, about 0·01 sec. for the first stroke of the discharge and considerably less for the subsequent strokes. Again, the field-change associated with an individual lightning stroke was found by Appleton and Chapman (1937), in the majority of their published examples, to have a total duration of the order of 0·01 sec. It might, therefore, have been expected that the change of field accompanying an individual lightning stroke would appear on the capillary electrometer records as an apparently instantaneous jump on the record. This is by no means always the case. While many simple field-changes show no appreciable duration on the records, it is quite common for a simple change of field of either sign which shows no sign of a stepped structure to last more than 0·1 sec., and a few exceed 0·5 sec. in duration. Many examples of field-changes with appreciable duration may be picked out from the records reproduced; some particularly striking examples occur in the distant storm of 11 July 1927 (Plates 2 and 3), and in the close storm of 24 May 1929 (Plates 5 and 6). In the records of the latter storm it is impossible, in many cases, to distinguish by simple inspection of the records the effect of a field-change from the comparatively slow process of shielding or uncovering the inverted test-plate. The appreciable duration of a field-change is most obvious when the actual vertical displacement on the record is small (e.g. fig. 112, Plate 16); it is, however, not then possible to be sure that each individual field-change is not stepped. It seems extremely improbable that these fairly common slow changes really consist of the effects of a large number of rapid changes due to individual strokes. Schonland *et al.* (1935) state that a flash consisting of more than six component strokes is rare, and such a small number of steps should be separated on a field-change lasting, say, 0·20 sec. It would seem, then, to be established that the major part of the change of electric moment during a lightning stroke is frequently a comparatively slow process, lasting up to 0·2 sec. and sometimes still longer. It is of considerable interest to note that Malan and Collens (1937) state that the luminosity of a single stroke (to earth) commonly lasts only a millisecond after the completion of the return stroke but occasionally lasts as long as half a second. Similar results have been obtained by McEachron and McMorris (1936). The field-change corresponding to such a process would be expected to consist of a rapid portion followed by a "slow tail". Such an effect is sometimes present in these records, but in the majority of slow changes recorded (which may, of course, be associated with flashes in the cloud) the whole variation of the field appears to be slow. It is interesting also that Chapman (1937) has, with a very open time-scale, obtained records of a process, which he terms a "volley of discharges", in which the electric field is continuously disturbed for more than a second.

In a complex field-change, the component field-changes have durations of the same order as typical simple field-changes. The interval between the completion of one component and the beginning of the next is variable and frequently imperceptible, indeed the record not infrequently suggests that they overlap. A complicated field-change may thus last for a considerable time, certainly more than a second (cp. Plate 5).

13. The frequency of occurrence of lightning discharges

The number of field-changes due to lightning discharges which could be identified as being within 5 km. of the observing station was about 200 in ten years of observation (1927–36). This number is to be increased somewhat since a number of field-changes were at unknown distances. The correction should not be very large for such close discharges, since the thunder can usually be identified. Again, the average value of the field-change due to a discharge whose nearest point is 5 km. away is about 5000 V/m. The number of discharges exceeding this magnitude observed in these years was also just over two hundred. The apparatus was not recording continuously during this period, but attempts were made to secure records whenever possible, and it is estimated that multiplying by a factor of between two and three would be an ample allowance for the close discharges which were missed. Finally, the nearest point of a lightning discharge may be some distance from the ground. If it be assumed that on the average it was 3 km. above the ground, we arrive at the estimate that very roughly 500 flashes occurred in 10 years above a circular area of radius 4 km., i.e. over an area of about 50 sq. km. This corresponds to an average frequency of 1 flash per $km.^2$ per annum.

In a recent paper, Whipple and Scrase (1936) have estimated that at Kew the annual frequency is about 3 flashes per $km.^2$ per annum. It would seem, however, that this estimate is too high. It is apparently based on the assumption that a field-change of about 2200 V/m. is caused on the average by a discharge 5 km. away, and is obtained by equating the number of field-changes exceeding this value which were recorded to the number of flashes which occurred over an area of 5 km. radius.

In the present work, field-changes of this magnitude were not infrequently observed up to distances exceeding 10 km. and it seems very probable that the correct figure for Kew is nearer to 1 flash per km.^{2} per annum.

Since only a fraction of these discharges are flashes to earth, and they include discharges of each sign, it is possible to conclude definitely that the electric charge brought to the earth by lightning in this neighbourhood is much smaller than the integrated air earth current of fine weather, and probably much smaller than the transfer of electricity by point-discharge currents (Wormell 1930).

14. The recovery of the electric field after a lightning discharge

One of the most striking features of the records of potential gradient during a thunderstorm with a time scale of the order employed in this investigation is the "recovery curve" of the field which usually follows a lightning discharge. The importance of the information yielded by these curves has been stressed by Wilson (1920, 1929). It is perhaps desirable, first, to emphasize that these curves do really represent variations of the observed electric field and are not to any appreciable extent instrumental. This is clearly shown if the exposed conductor happens to be screened during the rapid variation of the field (e.g. fig. 15, Plate 4) when the actual value of the potential gradient is determined at two instants a few seconds apart.

In many cases the recovery curves approximate to exponential curves; we may conveniently describe a recovery curve as being of the simple type when the rate of recovery is a maximum immediately after the discharge and, thereafter, continually decreases; the rate of variation of the field may have become very small before the next discharge occurs. This type is the commonest and examples occur in the majority of the Plates. It is in a sense, however, equally significant that more complicated types of recovery also occur. The most frequent departure from the simple type consists in a small initial rate of recovery which later increases and finally dies away to small values. Clear examples of this type of recovery occur, for example, in fig. 44, Plate 8, and fig. 94, Plate 14. In this type of recovery the initial rate may be zero (see for example, fig. 40, Plate 7). Examples of this phenomenon were given also by Wilson (1920, fig. 10, Plate 4). Occasionally, the initial variation of field after the completion of a field-change may be in the same direction as the net effect of the field-change. This phenomenon is rare after a simple field-change (fig. 115, Plate 17, fourth field-change) and not common, though less rare, after a complex field-change (fig. 3*c*, Plate 2; fig. 22*c*, Plate 5; fig. 52, Plate 9, at 14 h. 30·7 m.). Yet again, on some occasions, the field shows no sign of recovery but remains almost constant after the field-change is completed (many examples occur on Plate 6).

We consider, following the simple picture suggested by Wilson (1929), the case of a discharge between opposite charges in the cloud. Immediately after the discharge the electric field throughout a considerable volume of the cloud will presumably be very small. It is necessary, in order to explain the rapid regeneration of electric moment which is observed to occur, to assume, further, that this volume although electrically neutral is filled with oppositely charged carriers of different sizes. (There is now general agreement that, in the main body of the thundercloud, the smaller particles carry positive charges, the larger ones negative charges.) In the region where the electric field is small the carriers of different sizes separate under gravity. The rate of separation is, initially, practically the rate of fall in air of the larger particles but soon decreases owing to the development of an electric field opposing the separation and due to the appearance of positive charge at the top and negative charge at the base of the region considered. The field observed at a distant observing station due to this region of the cloud is proportional to the electric moment, M, of these charges. The internal field tending to stop the separation of the charge carriers will also be roughly proportional to M. Thus the velocity of separation v, of the carriers, may be written in the form

$$v = v_0 - kM = k(M_0 - M),$$

where v_0 is the velocity of separation of the large and small carriers in the absence of an electric field, and k and M_0 are constants.

We have further
$$\frac{dM}{dt} = Qv \qquad (1)$$
$$= kQ(M_0 - M), \qquad (2)$$

where Q is the total negative charge on the larger carriers in the whole volume considered.

If Q be constant and we write $kQ = \lambda$, the solution with the condition that $M = 0$ when $t = 0$, is
$$M = M_0(1 - e^{-\lambda t}). \qquad (3)$$

The rate of growth of M with t also falls off as M increases due to dissipation of the charges. This will not in general be the same for both charges, but if, as a crude approximation, we consider the dissipation as proportional to M, the form of the final equation for M will be unchanged. We thus obtain a satisfactory explanation of the simple type of recovery curve. It may be noted that a determination of the value of dM/dt immediately after a discharge yields a minimum value for Q, since v cannot exceed the rate of fall of the biggest particles in the cloud.

It is of some interest to consider what would be observed if we abandoned the hypothesis that there are plenty of charged carriers present after the flash and assumed instead that they were all destroyed and that new ones must be produced. We can represent this (ignoring the difficulty of finding a process which can produce charged carriers with sufficient rapidity) by assuming $Q \propto t$ and writing $kQ = \mu t$, where μ is a constant, in equations (1) and (2). Ignoring dissipation, we now obtain an approximate equation of the type

$$\frac{dM}{dt} = \mu t(M_0 - M) \tag{4}$$

or

$$M = M_0(1 - e^{-\frac{1}{2}\mu t^2}), \tag{5}$$

to represent the beginning of the recovery curve. The essential result is that, in this case, the initial value of dM/dt is zero. A recovery curve of such a type is observed so rarely after a distant discharge that it is clear that such a picture must be far from the truth.

The effects of continuous dissipation of the charges merits somewhat closer consideration. The processes involved at the top and base of the cloud are very different, and thus the two charges may become very unequal unless or until the process is interrupted by a discharge to earth. The effects on the field at the ground will be most striking near the distance at which the sign of the field-change due to a flash between charges in the cloud reverses. At this point the effect of a flash in the cloud vanishes and the primary regeneration of the charges has no effect on the field. We have, in fact, if q_1 and $-q_2$ be the charges at the top and base of the region of the cloud under consideration,

$$\frac{dF}{dt} \propto \frac{d}{dt}(q_1 - q_2).$$

Moreover, $\frac{d}{dt}(q_1 - q_2)$ will be represented approximately by an expression of the form $bq_2 - aq_1$, where a and b are constants. Immediately after a complete discharge of the cloud, the rate of regeneration of the field at this critical distance will be zero, it will later become appreciable and finally die away. There will, moreover, be a whole range of distances where the initial recovery rate of the field, after such a process, will be small.

We turn next to a consideration of the observational results. The examples measured only include cases when the displacement on the record corresponding to the field-change was at least 1 mm.; for the smaller field-changes an estimate of the initial rate of recovery would be too inaccurate. For convenience, a recovery of the simple type is described as being of type A, one, in which the initial rate is slow, but the rate of variation of field increases later, is described as being of Type B. The results are tabulated in Table XIX which refers to simple field-changes only.

In the great majority of cases selected as suitable for measurement, the rate of variation of the field just before the discharge was small compared with its value at the beginning of the recovery curve. When the field was varying at an appreciable rate before the discharge, the initial rate of recovery was computed from the difference between the rates of variation immediately after and immediately before the field-change. The results thus give, in the case of distant discharges, a minimum value for the true maximum rate of regeneration of electric moment by the cloud.

The individual values of the initial recovery rates from which the mean values given in Table XIX were deduced may have any value from zero to about 0·5 sec.$^{-1}$ or even more. About 90% of the examples recorded, for discharges beyond 10 km., have initial rates less than 0·20 sec.$^{-1}$. There is some doubt as to the reality of the occasional examples with very rapid recovery, since the rate of variation of the field is then of the same order as during a slow field-change. It is thus sometimes impossible to decide with certainty whether the effect being recorded is a rapid recovery or a slow discharge. The number of occasions when such an uncertainty arises is, however, quite small.

Table XIX

Distance km.	Type	Initial rate of recovery $\left(\frac{1}{F}\frac{dF}{dt}\right)$, sec.$^{-1}$, after simple field-changes: Positive field-change: No. of examples	Positive field-change: Mean initial rate	Negative field-change: No. of examples	Negative field-change: Mean initial rate
>15	A	149	$0{\cdot}14_6$	103	$0{\cdot}15_3$
	B	28	$0{\cdot}04_8$	13	$0{\cdot}09_4$
	All	177	$0{\cdot}13_1$	116	$0{\cdot}14_7$
10–15	A	91	$0{\cdot}14_3$	27	$0{\cdot}12_6$
	B	19	$0{\cdot}04_3$	4	$0{\cdot}06_4$
	All	110	$0{\cdot}12_6$	31	$0{\cdot}11_8$
5–10	All	58	$0{\cdot}09_0$	13	$0{\cdot}06_3$

When the discharges are beyond 15 km. there is very little difference between the mean initial rates of recovery after positive and after negative field-changes, the recovery after the negative changes being slightly more rapid. The interpretation of these figures is complicated by the fact that both positive and negative field-changes presumably include both flashes to earth and also discharges in the cloud. It would be expected, in view of the earlier discussion, that the recovery rate after a discharge to earth would be slower than after a flash in the cloud when the regeneration of the field is proportional to the speed of the primary process of separation of charges. When we turn to the figures for slightly nearer discharges, at distances between 10 and 15 km., there is little change in the recovery rates. It is interesting to note, however, that there is a small decrease in the mean initial rate of recovery after negative field-changes. This is just what would be anticipated, since the proportion of negative field-changes which are due to discharges to earth is considerably higher between 10 and 15 km. than beyond 15 km., since the reversal distance for a cloud discharge of type 1 is not infrequently between 10 and 15 km. Recoveries of type B occur in both ranges of distances after field-changes of either sign; they are relatively more frequent, however, and the initial recovery rates are smaller after positive than after negative field-changes. There is some evidence for a low recovery rate after flashes to earth in the records of certain individual storms. Thus, for example, in figs. 1 and 2, Plate 2, in the record of a moderately distant storm the occasional flashes to earth caused positive changes of field followed by very slight recovery, while the more frequent negative field-changes, due to flashes hidden in the cloud, were followed by active regeneration of the field. In general, however, it is not possible by examination of the recovery curve following an individual field-change to tell whether it was caused by a flash to earth or not.

The figures for still closer discharges, at distances between 5 and 10 km., show a decided diminution in the mean initial recovery rate for field-changes of either sign; the recoveries after negative field-changes, due to discharges in this range of distances, are on the average very slow. With such slow recoveries the separation of the recovery curves into types A and B is rather indefinite and has not been attempted.

In the case of very close discharges the recovery curve is complicated by local effects. Immediately after a close discharge the electric field at the ground may be more intense than the cloud can maintain. This intense field is commonly ascribed to a space charge in the lower layers of the atmosphere and would be expected to die away rapidly. In the intense field after the flash, the space charge, if it consist of free ions, is driven downwards towards the ground; assuming that the field-change reversed the direction of the field there may thus be a sudden large rush of ionization current to the earth's surface and to any exposed conductors. (A suggestion of such an effect, detected as an apparent shift in the zero after several close flashes, has been noted in the discussion of the records of the storm of 20 May 1928.) Also, there is an upward rush of ions of opposite sign discharged from projecting points near the earth's surface. It is, in fact, observed that when a close discharge creates a very intense field, the initial rate of recovery may be very large, in some cases greater than 1·0 sec.$^{-1}$. In fig. 9 the initial rate of recovery has been plotted against the value of the potential gradient immediately after the field-change for close discharges in cases where that gradient was large. The diagram shows a definite tendency for very rapid recovery when the potential gradient is very large but the scatter of the individual points is considerable. It is only when the gradient is very large indeed (greater than perhaps 25,000 V/m.) that the initial rate of recovery is always found to be very large. For gradients between 10,000 and 20,000 V/m. the average rate of recovery is still high, but the individual figures are so variable that the rate cannot be uniquely determined by the value of the gradient just after the discharge. The conditions in and below the cloud may be very variable, and it is conceivable that variations in the efficiency of the natural sources of point-discharge current at the earth's surface may occur. (It would appear, for example, that the maximum predischarge gradients which occur below summer thunderstorms are considerably smaller than those beneath spring showers.) For close discharges (within 5 km.), when the gradient after the field-change does not exceed 10,000 V/m., the recovery rates are comparatively slow. For twenty-three simple positive field-changes the mean initial rate was 0·11 sec.$^{-1}$. (This includes an example with a very fast recovery rate of 1·0 sec.$^{-1}$; if it be omitted, the mean of the remainder is 0·07 sec.$^{-1}$.) Similarly, nineteen negative simple field-changes had a mean initial recovery rate of 0·06 sec.$^{-1}$.

It would seem then to be definitely established that except in the cases when the field-change creates a very intense electric field, the recovery is on the average much slower after discharges within 10 km. than for the more distant discharges. The most direct interpretation of this conclusion would be to associate it with the fact that many of the discharges, in this range of distances, will be near the reversal distance for flashes in or below the cloud. The observation of a simple field-change does not necessarily mean a simple discharge between charges in the cloud; two different types of discharges may cause field-changes of the same sign, or in some cases, the detail may be unresolved and only the net effect recorded as a simple field-change. The primary process of regeneration of charges may then produce a small effect on the field until the two charges become unequal, due to their different rates of dissipation.

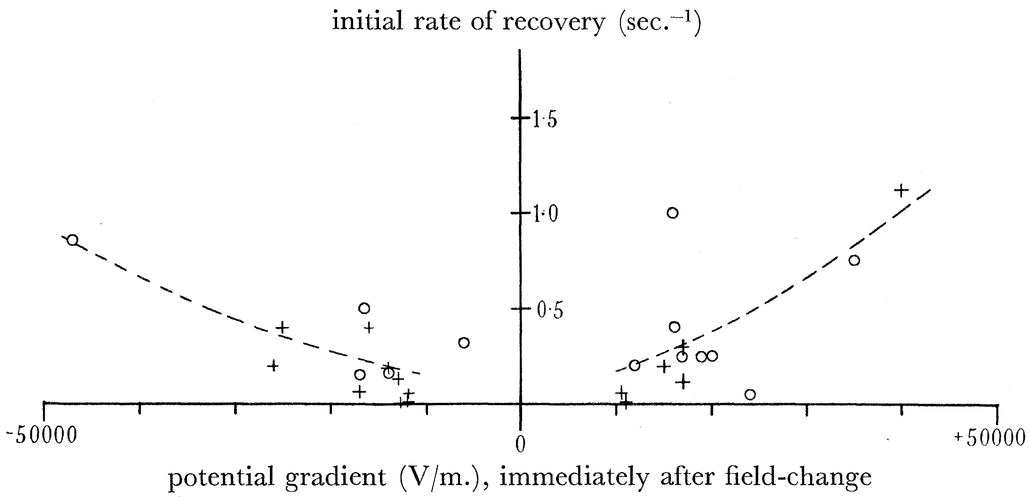


FIG. 9

In the case of the distant field-changes the interpretation is much less ambiguous, since the field-change is proportional to the electric moment destroyed by the discharge and the variation of the field after the field-change to the rate of regeneration of the moment. It seems possible to conclude definitely that the initial rate of regeneration of electric moment by the primary process in the cloud is on the average at least 0·15 of the moment destroyed by the flash.

After a complex field-change the recovery curve may behave in various ways. Each of the component discharges destroys an electric moment in the cloud and all these electric moments will begin to be regenerated at different rates. The resulting rate of variation of the field, when compared with the net effect of the complex field-change, may be small or large. In the great majority of cases the variation of field after the complex discharge is a recovery of the field, but cases where that variation is in the same direction as the net change of field are much more frequent than after simple discharges. Twenty-four cases were found in the records when this phenomenon occurred after a complex distant discharge. In nineteen of these cases the net effect of the field-change was positive. There were also three cases in which the net effect of a complex field-change was sensibly zero and it was followed by a marked variation of field in the positive direction. We have thus further evidence that when the discharges are distant the recovery of the field after a negative field-change tends to be more rapid than after a positive change.

15. General remarks

It is of interest to use the results of this series of observations to revise the estimates given by Wilson (1929) for some of the fundamental quantities in a thundercloud. These estimates are, of course, independent of the precise mechanism by which the charged carriers are originally produced.

If a region of separation of charges is limited by plane upper and lower boundaries the electric moment M of the charges removed in a lightning discharge is related to the field in the region just before the flash by the equation

$$M = \frac{F}{4\pi} \times \tau, \tag{1}$$

where τ is the volume of the region and F is the critical field necessary to initiate a discharge.

(M, as here defined, is only half of what has previously been called the electric moment of the discharge, which includes an equal contribution due to the image in the ground.)

The observed initial rate of recovery of the electric moment is frequently about $0{\cdot}15M$ per sec. This is equal to Qv, where Q is the total charge of either sign in the region, and v the velocity of fall relative to the air of the larger carriers in the absence of an electric field.

We have thus
$$Qv = 0{\cdot}15M. \tag{2}$$

For the field to reach the value F, the total weight W of the larger carriers must slightly exceed the upward force on them due to the field, i.e.

$$W > QF.$$

Thus, if w be the weight of water and ice per unit volume,

$$w = \frac{W}{\tau} > \frac{QF}{\tau}$$

$$> \frac{QF^2}{4\pi M}$$

$$> \frac{0{\cdot}15F^2}{4\pi v} \text{ dynes/cm.}^3. \tag{3}$$

If we assume that the critical field F is 10,000 V/cm. or 33 e.s.u. (the sparking field in the presence of fair-sized water drops) and $v = 600$ cm./sec. we find $w > 22$ g./m.^{3}.

Simpson and Scrase (1937) have recently suggested that the main region of separation of charges is frozen and that the largest particles will fall with velocities considerably less than 6 m./sec. If this is true the value of w must be correspondingly increased. It will be noted, also, that the critical value of F could not be greatly increased without obtaining impossibly high values for w: there will, presumably, always be water drops present in the lower part of the region so that F will not rise appreciably above the value assumed.

The most frequently observed value for M, for a discharge producing a negative field-change at a distance, is $1{\cdot}7 \times 10^{16}$ e.s.u. It follows from equations (1) and (2) that τ is about 6 km.^{3}, and hence, if v is 6 m./sec., Q is 1400 coulombs and W must exceed $1{\cdot}4 \times 10^{11}$ g. If v were smaller, Q and W would be increased, both varying as $1/v$.

A similar calculation may be carried through for a spherical region of separation of charges; in this case the maximum internal field is only one half the critical field of 33 e.s.u. which would occur immediately above and beneath the region of separation. The numerical values obtained for the various quantities in this case are very similar to those already given above.

The change in the relative frequency of positive and negative field-changes with distance (Wilson 1920; Appleton *et al.* 1926) led these authors and also Schonland, from similar observations in South Africa, to conclude that the essential feature of a thunderstorm was most frequently a bipolar distribution of charge of positive polarity (i.e. with the positive charge uppermost). The predominance of negative predischarge gradient beneath a storm together with the more frequent occurrence of positive gradients when the storms were more distant led Schonland (1928) and Wormell (1930) to the same conclusion. The behaviour of the predischarge gradient is, however, frequently very complicated; the individual storms considered earlier are sufficient indication of this. It is, of course, not possible to infer uniquely the distribution of charge in the cloud from observations at the ground. Moreover, observations are usually made at a single point and it is impossible to separate the variations due to movement of the cloud from those due to temporal variations of the charges in the cloud. An interesting new attack on the problem has recently been made by Simpson and Scrase (1937), who obtained records of the variation of potential gradient with height through a thundercloud by means of an apparatus attached to a sounding balloon. They confirmed in striking fashion that the upper part of a thunderstorm is always positively charged and the main portion of the base negatively charged. They, however, also obtained a few records which were interpreted as indicating a positively charged region in the base of the cloud. The evidence consists essentially in the fact that in the few cases when a balloon was released beneath a storm in a region of positive potential gradient, the gradient never remained positive all the way up to the positive charge at the top of the cloud. While the existence of a positive charge near the base of the cloud is the most direct and perhaps the most natural interpretation of such a record, such a conclusion is by no means inevitable. In the first place, the balloon takes about 30 min. to rise through the cloud and thus the temporal variations of the charges have not been eliminated. Secondly, the path of the balloon in the cloud is unknown and it may suffer considerable horizontal displacement relative to the cloud. It would seem, for example, that a balloon released in the region of positive gradient near the front of an advancing simple cloud of positive polarity would be carried horizontally by the air currents converging on the region of active separation of charge and might well reach a point where negative gradient existed and, indeed, extended right to the ground. In such a case the record would give all the effects interpreted as a positive charge in the base of the cloud. The present series of observations has disclosed a surprisingly high proportion of negative field-changes due to close discharges, and established the frequent occurrence of a type of discharge with a very small reversal distance and producing a negative field-change at short distances. Such behaviour would be explained by a discharge between a positive region in the base of the cloud and the negative charge above it; but other interpretations are possible. A discharge from the negative base of the cloud into the positive space charge beneath it, but stopping short of the ground, would also give effects of the type observed. Discharges of this type have been photographed by Schonland *et al.* (1935). The very short reversal distance, in some cases apparently less than 3 km., rather favours the second interpretation. The regular occurrence of positive charge in the base of the cloud cannot, therefore, be considered to be yet established with certainty.

There is, on the other hand, no ambiguity about the distribution of charge in the main portion of the cloud, and the question arises as to the mechanism by which these charges are produced. The induction process suggested by Wilson (1929) and demonstrated experimentally by Gott (1933, 1935) is the only theory producing electrification of the correct sign which has been developed in any detail. Simpson and Scrase (1937) raise a series of objections to this theory based on the fact that the estimated temperatures in the main body of the cloud are well below freezing point. They conclude, therefore, that all the larger particles will be ice crystals and that there will be no particles which can fall more rapidly than the rate at which positive ions are dragged down by the field. It is, of course, necessary to assume, as Wilson (1929) clearly stated, that in strong fields the positive ions are of low mobility due to their attachment to nuclei or cloud particles. This assumption is unavoidable whether the larger particles are ice crystals or water drops. The velocity of the ions, even in a field of 10,000 V/cm., is then only a few centimetres per second and the observed form of the recovery curves after a discharge or, indeed, the development of strong fields at all is sufficient evidence that negatively charged particles do fall more rapidly than this. Moreover, the spherical shape and conductive property of the water-drop are not essential to the Wilson mechanism. Recent investigators (Errera 1924; Wintsch 1932; Murphy 1934) are in agreement that, at low frequencies, the dielectric constant of ice is very high over a considerable range of temperature below the freezing-point; indeed, according to Murphy, the dielectric constant in a steady field remains of the order of 100 from freezing-point down to nearly -100° C. In a strong electric field the crystals will thus tend to set themselves with their longest axes in the direction of the field and this may conceivably enable them to fall more rapidly. Further, however, the electric field in the air surrounding an uncharged ice crystal will be practically indistinguishable from that around a conductor of the same shape, and the crystal, if the initial potential gradient is positive, may thus absorb negatively charged large ions and supercooled small cloud particles at its lower surface as they move upwards relative to the larger particles which will gradually acquire a negative charge.

While no attempt has been made to redescribe the Wilson mechanism in detail in the presence of ice crystals, sufficient has perhaps been said to indicate that the criticisms raised by Simpson and Scrase are inadequate reasons for rejecting it.

In conclusion, it gives me great pleasure to express my deep gratitude to Professor C. T. R. Wilson. My indebtedness to his published work is obvious and I have had, also, the benefit of his continual advice and encouragement. My thanks are due also to Professor H. F. Newall, on whose land the observations were made, for his interest, and to Professor F. J. M. Stratton, Director of the Solar Physics Observatory, for his encouragement in the long series of observations. I am further indebted to Mr L. J. Stanley for the construction of apparatus and to Messrs W. H. Manning and T. G. Arthur, who made for me numerous enlargements from the original records.

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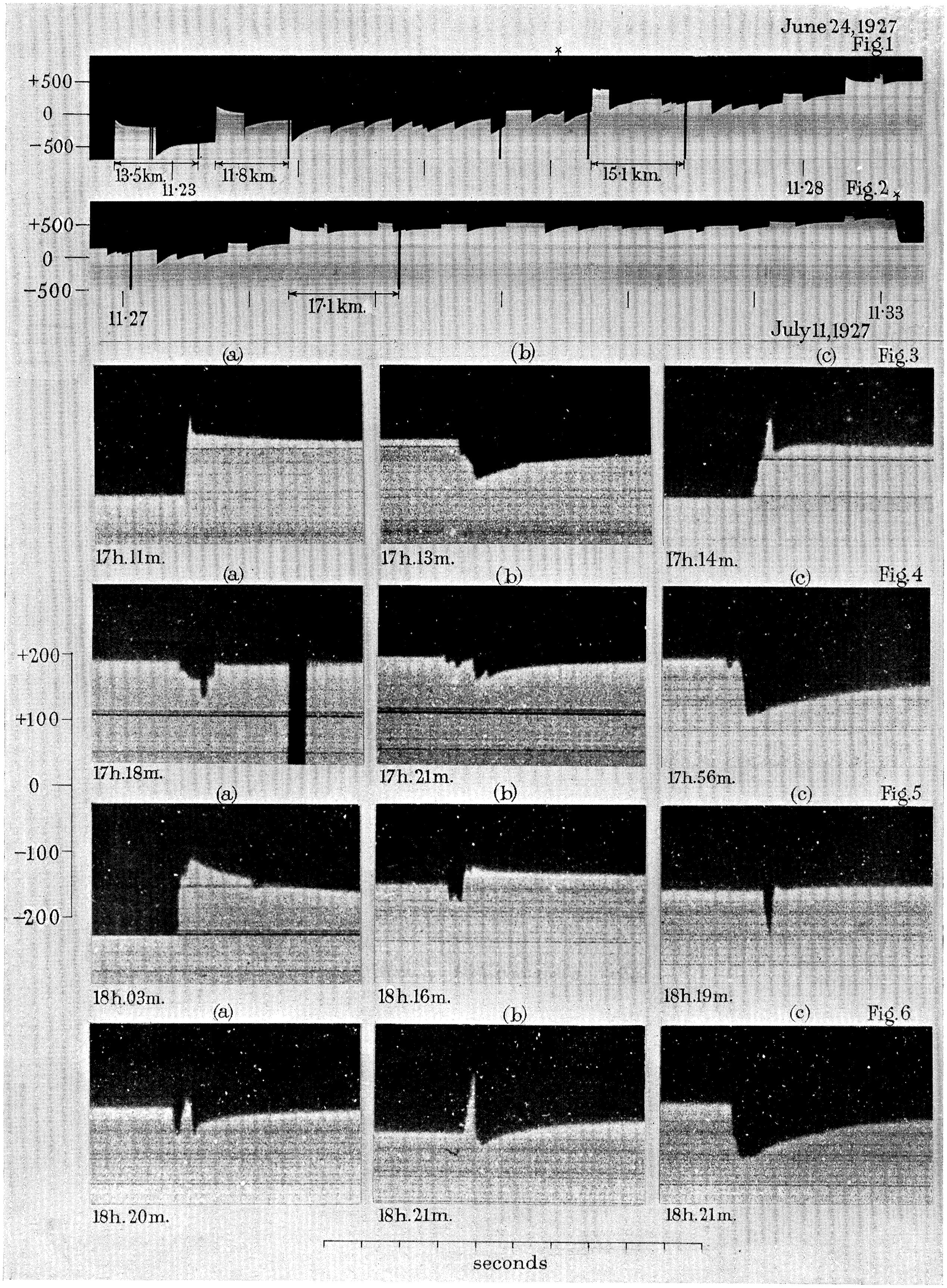
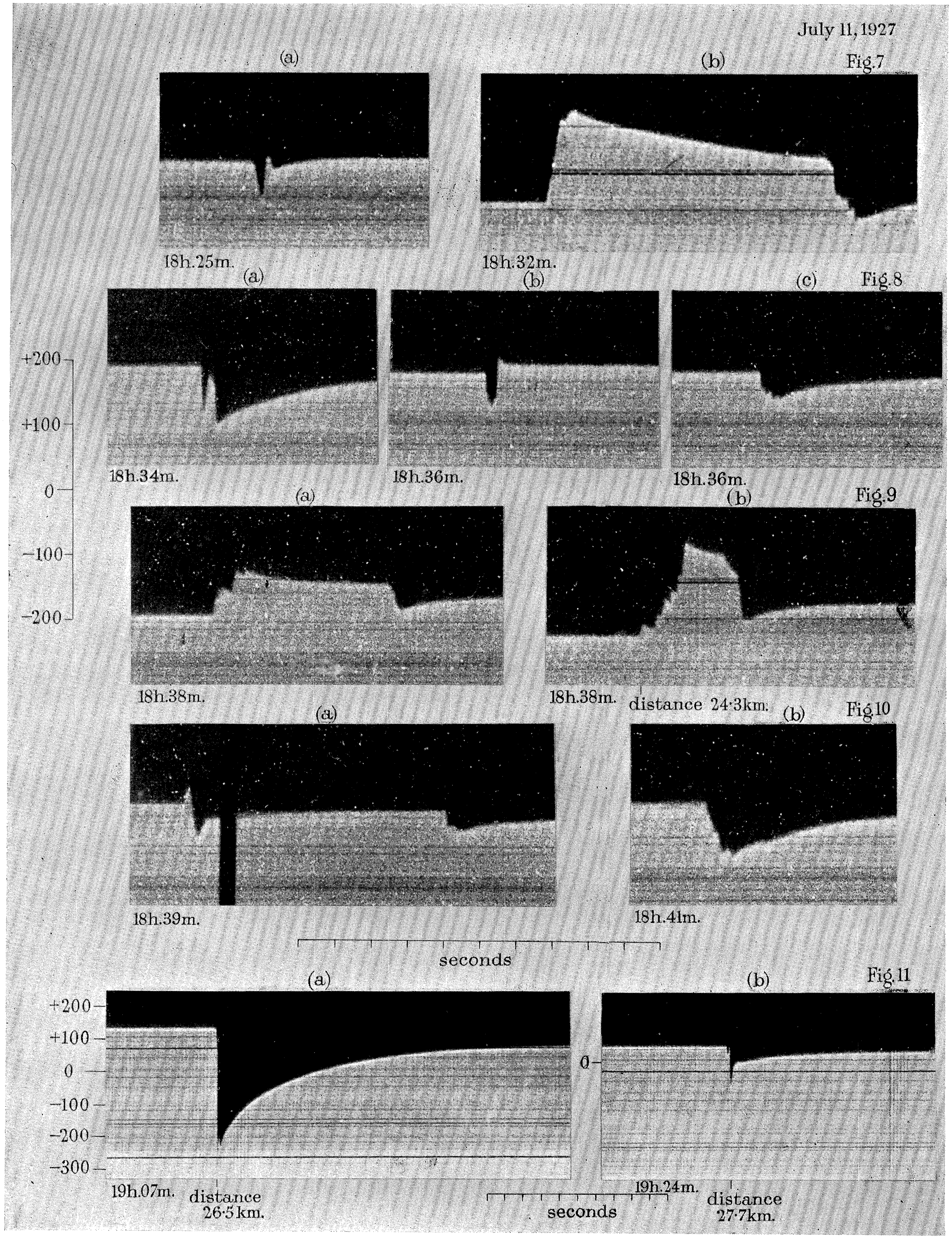
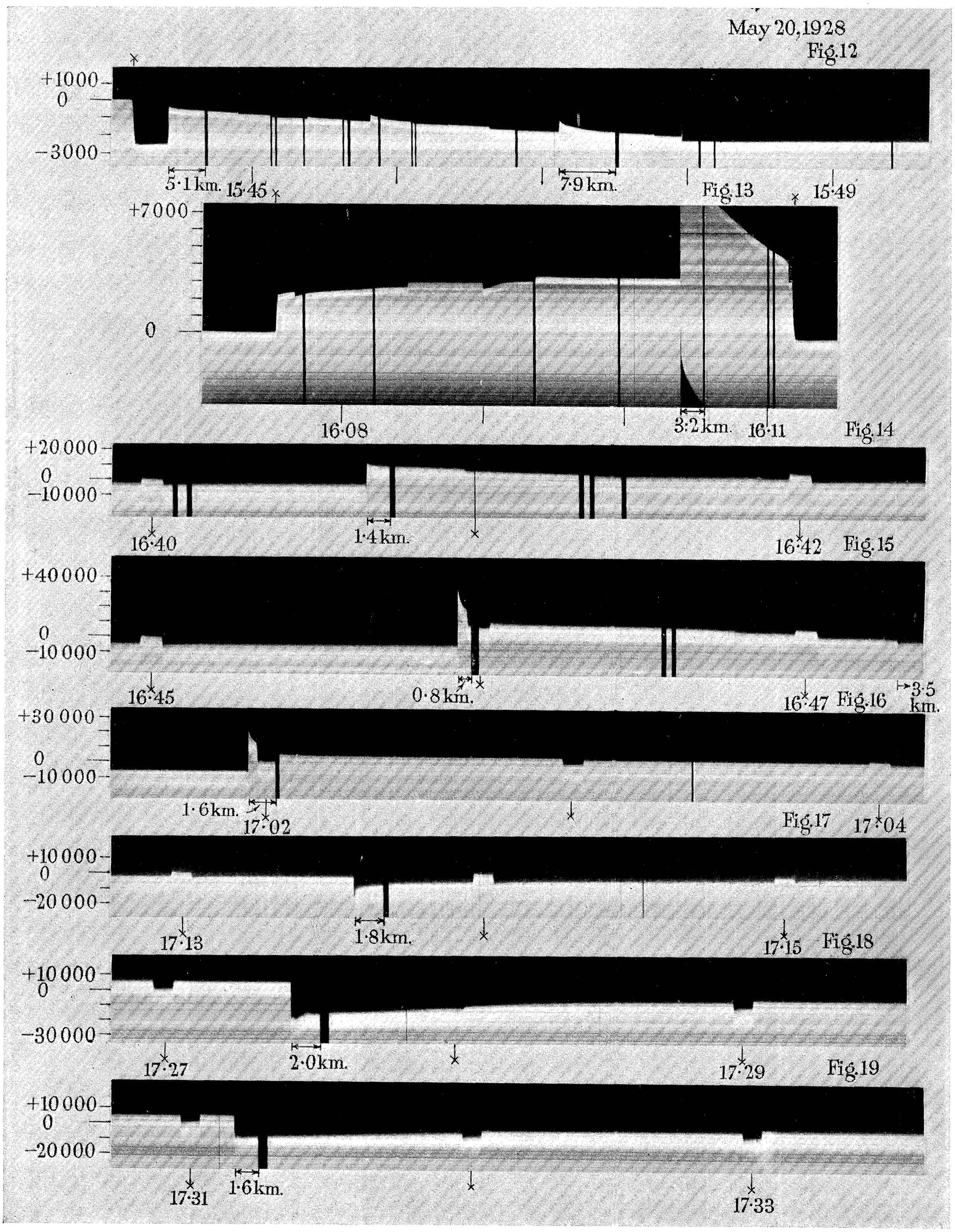
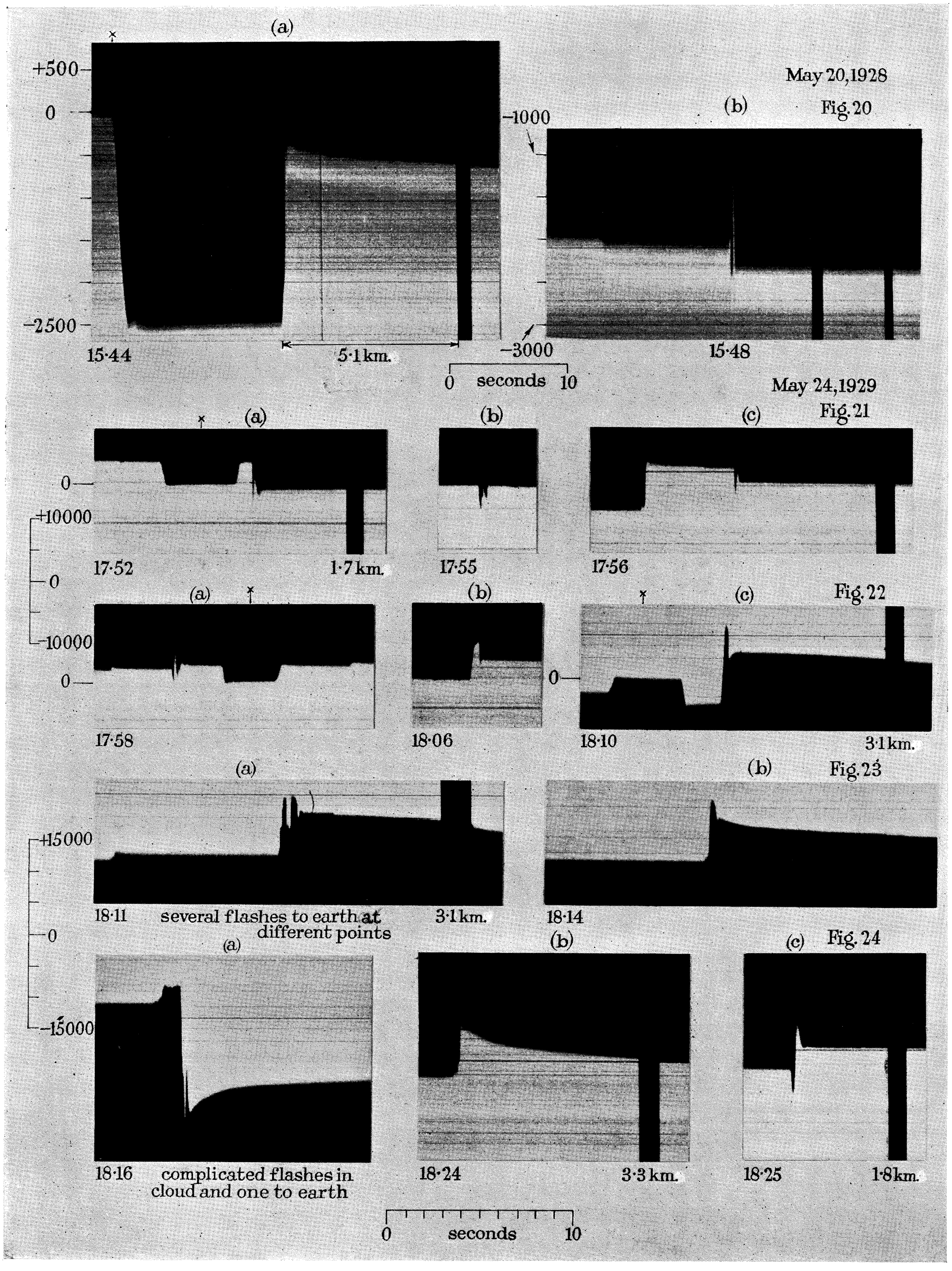
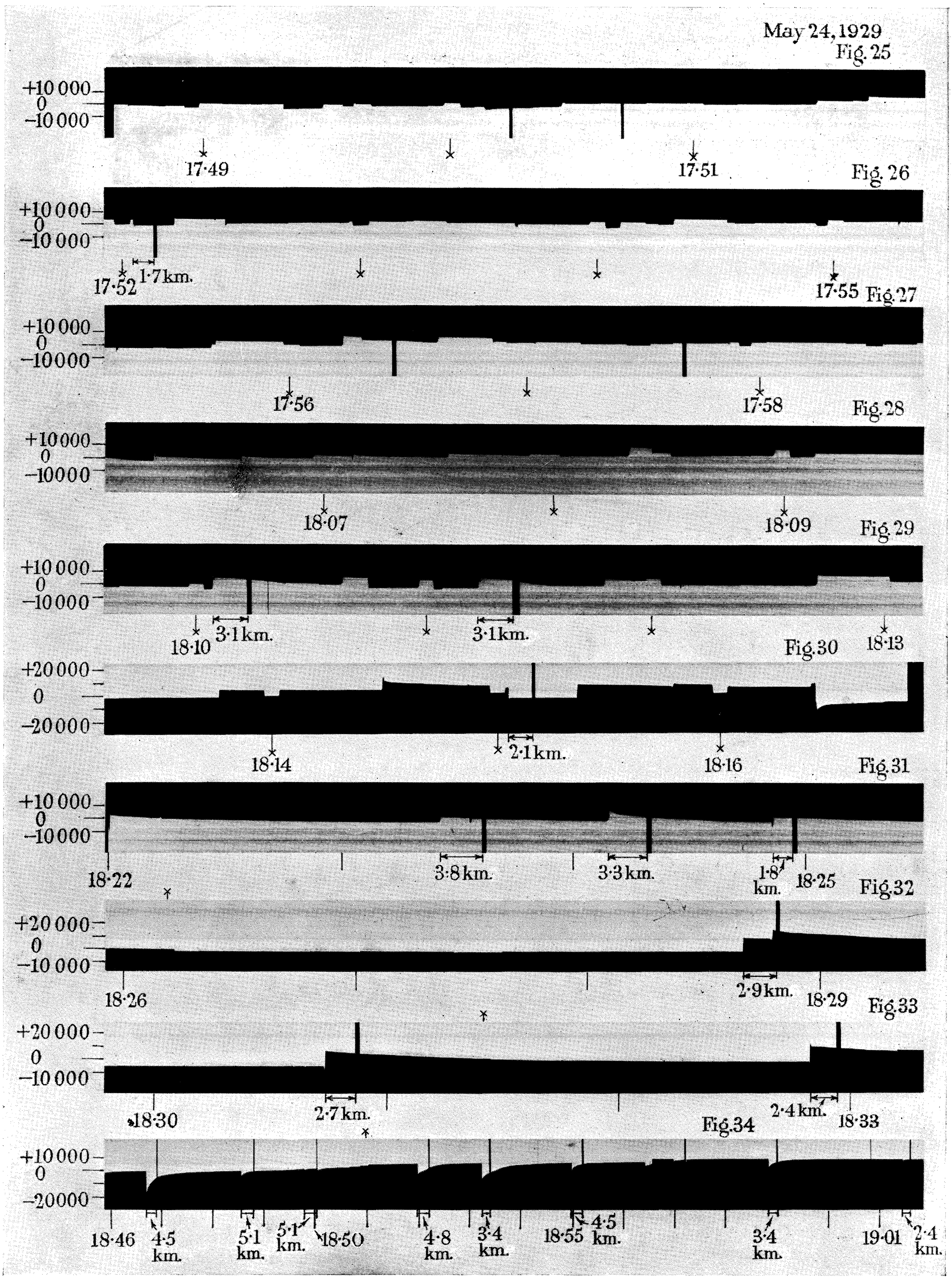
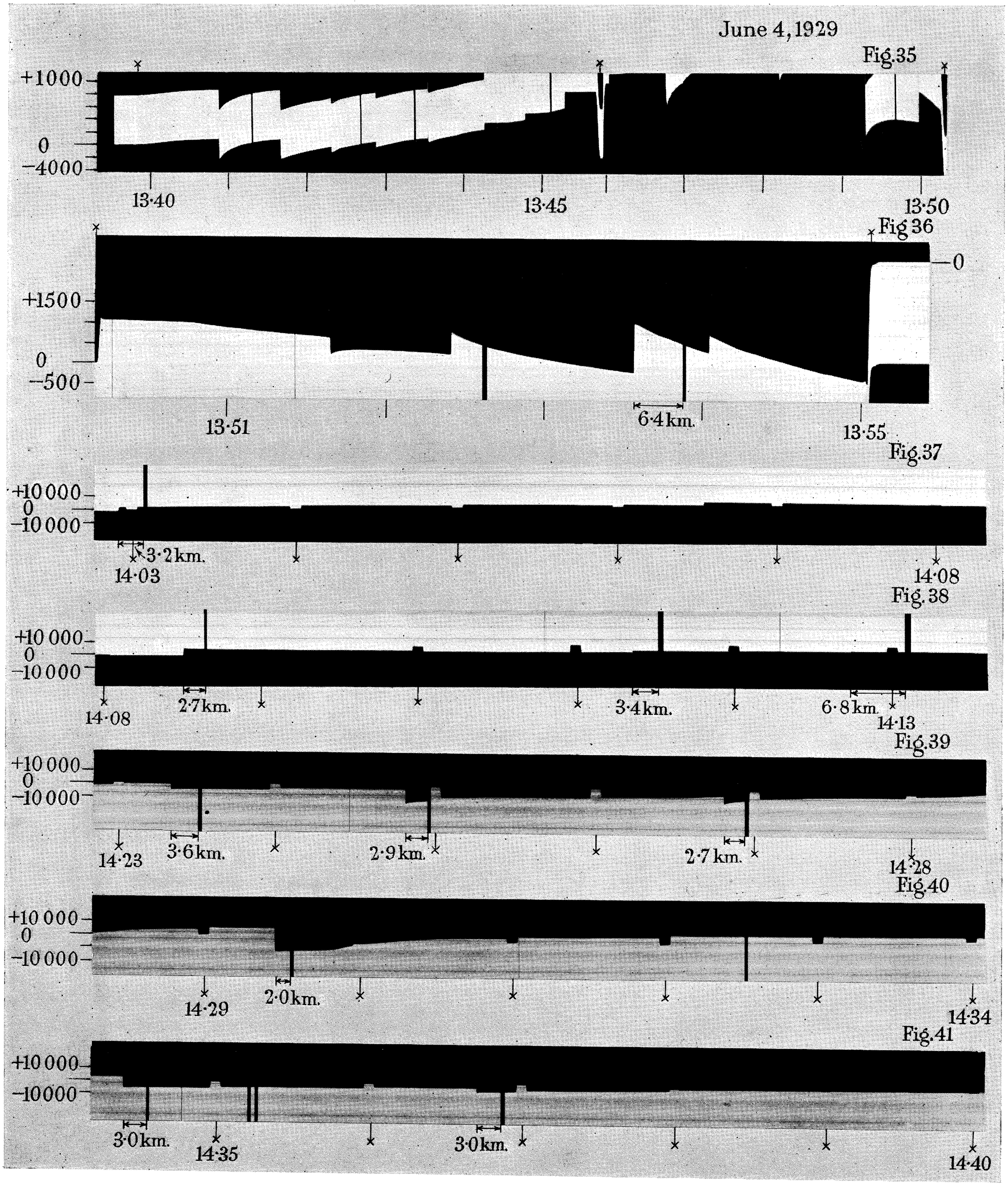

June 24, 1927
Fig. 1
+500
0
−500
13·5 km.
11·23
11·8 km.
15·1 km.
11·28
Fig. 2
+500
0
−500
11·27
17·1 km.
11·33
July 11, 1927
(a)
(b)
(c)
Fig. 3
17h. 11m.
17h. 13m.
17h. 14m.
(a)
(b)
(c)
Fig. 4
+200
+100
0
−100
−200
17h. 18m.
17h. 21m.
17h. 56m.
(a)
(b)
(c)
Fig. 5
18h. 03m.
18h. 16m.
18h. 19m.
(a)
(b)
(c)
Fig. 6
18h. 20m.
18h. 21m.
18h. 21m.
seconds


July 11, 1927
Fig. 7
(a)
18h.25m.
(b)
18h.32m.
Fig. 8
(a)
18h.34m.
(b)
18h.36m.
(c)
18h.36m.
+200
+100
0
−100
−200
Fig. 9
(a)
18h.38m.
(b)
18h.38m.
distance 24·3 km.
Fig. 10
(a)
18h.39m.
(b)
18h.41m.
seconds
Fig. 11
(a)
+200
+100
0
−100
−200
−300
19h.07m.
distance
26·5 km.
(b)
0
19h.24m.
distance
27·7 km.
seconds


May 20, 1928
Fig. 12
+1000
0
−3000
5·1 km.
15·45
7·9 km.
Fig. 13
15·49
+7000
0
16·08
3·2 km.
16·11
Fig. 14
+20 000
0
−10 000
16·40
1·4 km.
16·42
Fig. 15
+40 000
0
−10 000
16·45
0·8 km.
16·47
Fig. 16
3·5 km.
+30 000
0
−10 000
1·6 km.
17·02
Fig. 17
17·04
+10 000
0
−20 000
17·13
1·8 km.
17·15
Fig. 18
+10 000
0
−30 000
17·27
2·0 km.
17·29
Fig. 19
+10 000
0
−20 000
17·31
1·6 km.
17·33


(a)
+500
0
−2500
15·44
5·1 km.
May 20, 1928
(b)
Fig. 20
−1000
−3000
15·48
0 seconds 10
May 24, 1929
Fig. 21
(a)
(b)
(c)
0
+10000
0
−10000
17·52
1·7 km.
17·55
17·56
Fig. 22
(a)
(b)
(c)
0
17·58
18·06
0
18·10
3·1 km.
(a)
(b)
Fig. 23
+15000
0
−15000
18·11
several flashes to earth at different points
3·1 km.
18·14
(a)
(b)
(c)
Fig. 24
18·16
complicated flashes in cloud and one to earth
18·24
3·3 km.
18·25
1·8 km.
0 seconds 10


May 24, 1929
Fig. 25
+10 000
0
−10 000
17·49
17·51
Fig. 26
+10 000
0
−10 000
17·52
1·7 km.
17·55
Fig. 27
+10 000
0
−10 000
17·56
17·58
Fig. 28
+10 000
0
−10 000
18·07
18·09
Fig. 29
+10 000
0
−10 000
18·10
3·1 km.
3·1 km.
18·13
Fig. 30
+20 000
0
−20 000
18·14
2·1 km.
18·16
Fig. 31
+10 000
0
−10 000
18·22
3·8 km.
3·3 km.
1·8 km.
18·25
Fig. 32
+20 000
0
−10 000
18·26
2·9 km.
18·29
Fig. 33
+20 000
0
−10 000
18·30
2·7 km.
2·4 km.
18·33
Fig. 34
+10 000
0
−20 000
18·46
4·5 km.
5·1 km.
5·1 km.
18·50
4·8 km.
3·4 km.
18·55
4·5 km.
3·4 km.
19·01
2·4 km.


June 4, 1929
Fig.35
+1000
0
−4000
13·40
13·45
13·50
Fig 36
0
+1500
0
−500
13·51
6·4 km.
13·55
Fig.37
+10 000
0
−10 000
3·2 km.
14·03
14·08
Fig. 38
+10 000
0
−10 000
14·08
2·7 km.
3·4 km.
6·8 km.
14·13
Fig.39
+10 000
0
−10 000
14·23
3·6 km.
2·9 km.
2·7 km.
14·28
Fig.40
+10 000
0
−10 000
14·29
2·0 km.
14·34
Fig.41
+10 000
−10000
3·0 km.
14·35
3·0 km.
14·40

June 6, 1931

Fig. 42

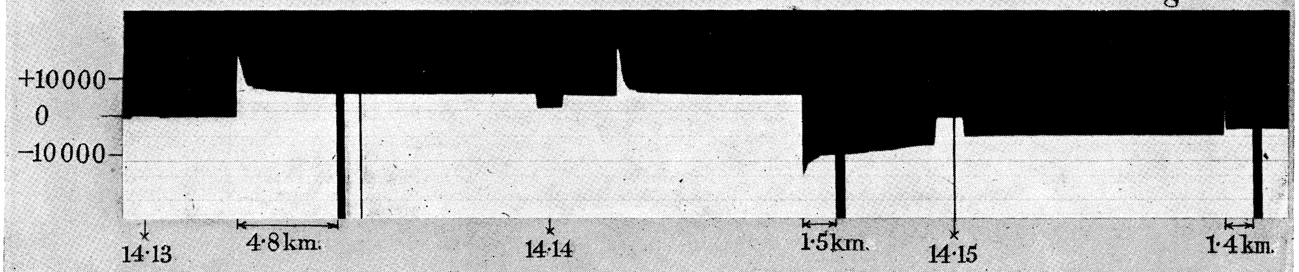


Fig. 43

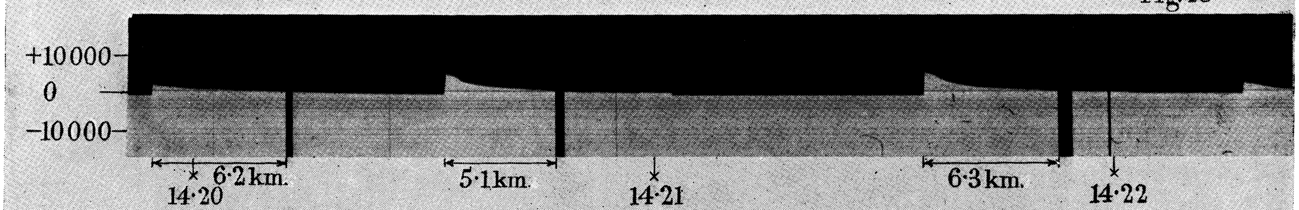
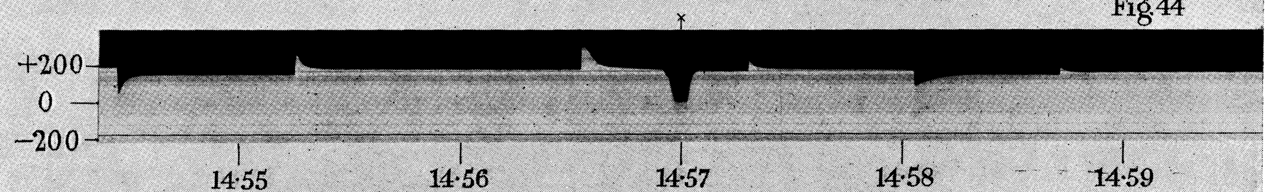


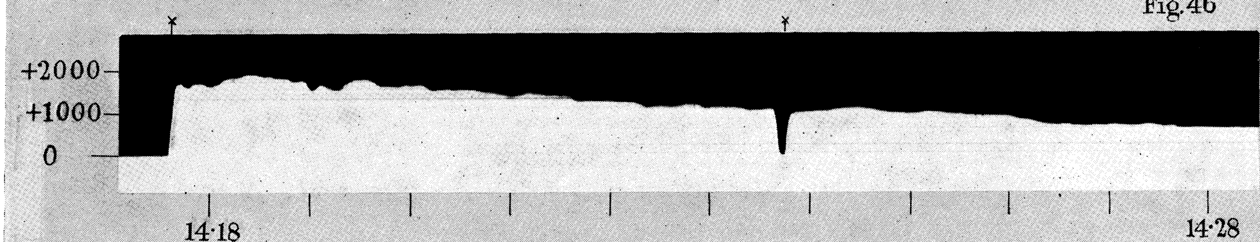
Fig. 44



July 26, 1932

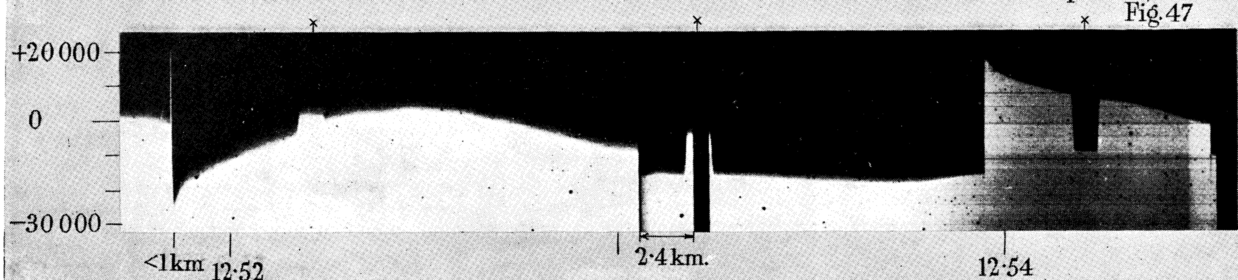
Fig. 45

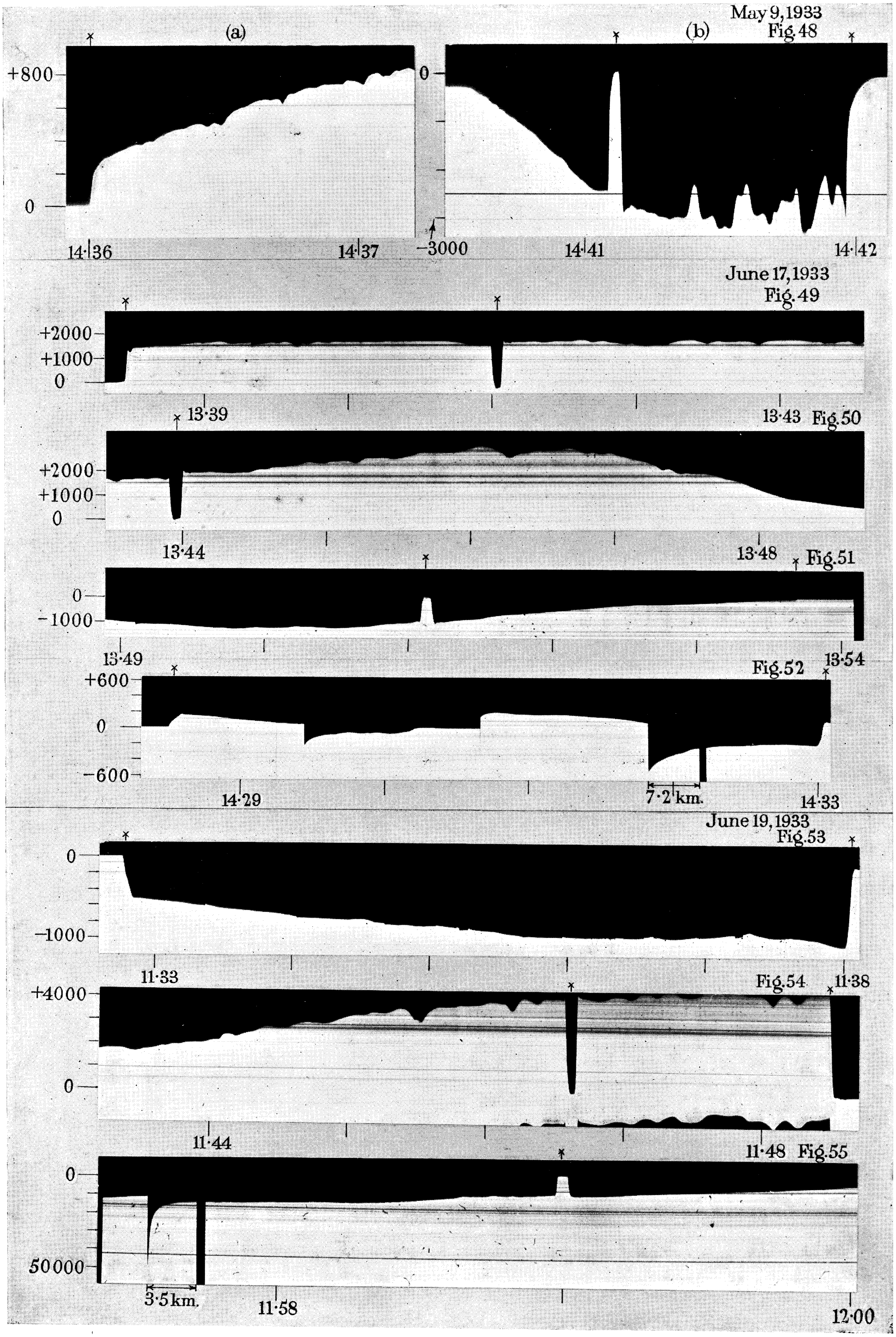
Fig. 46

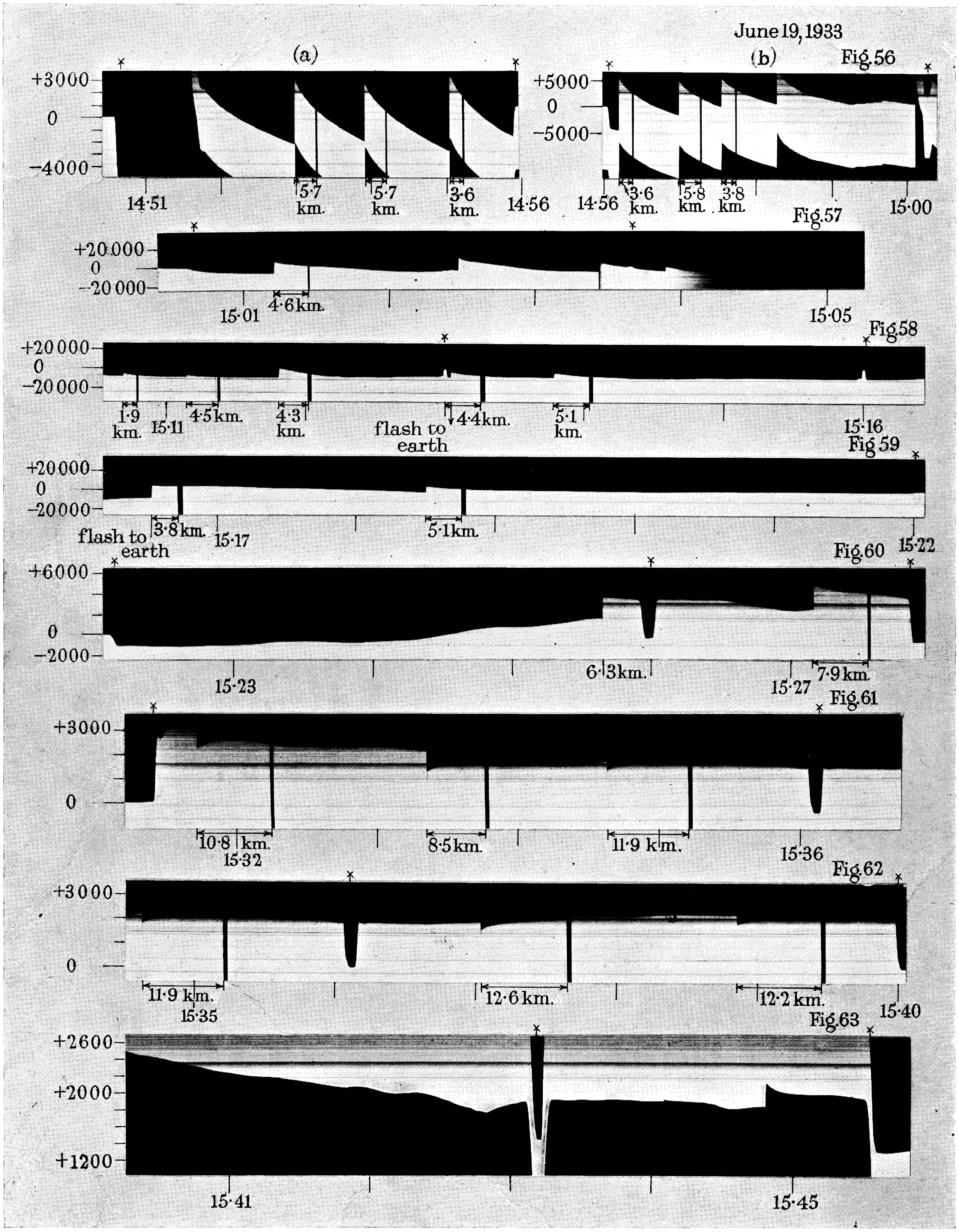


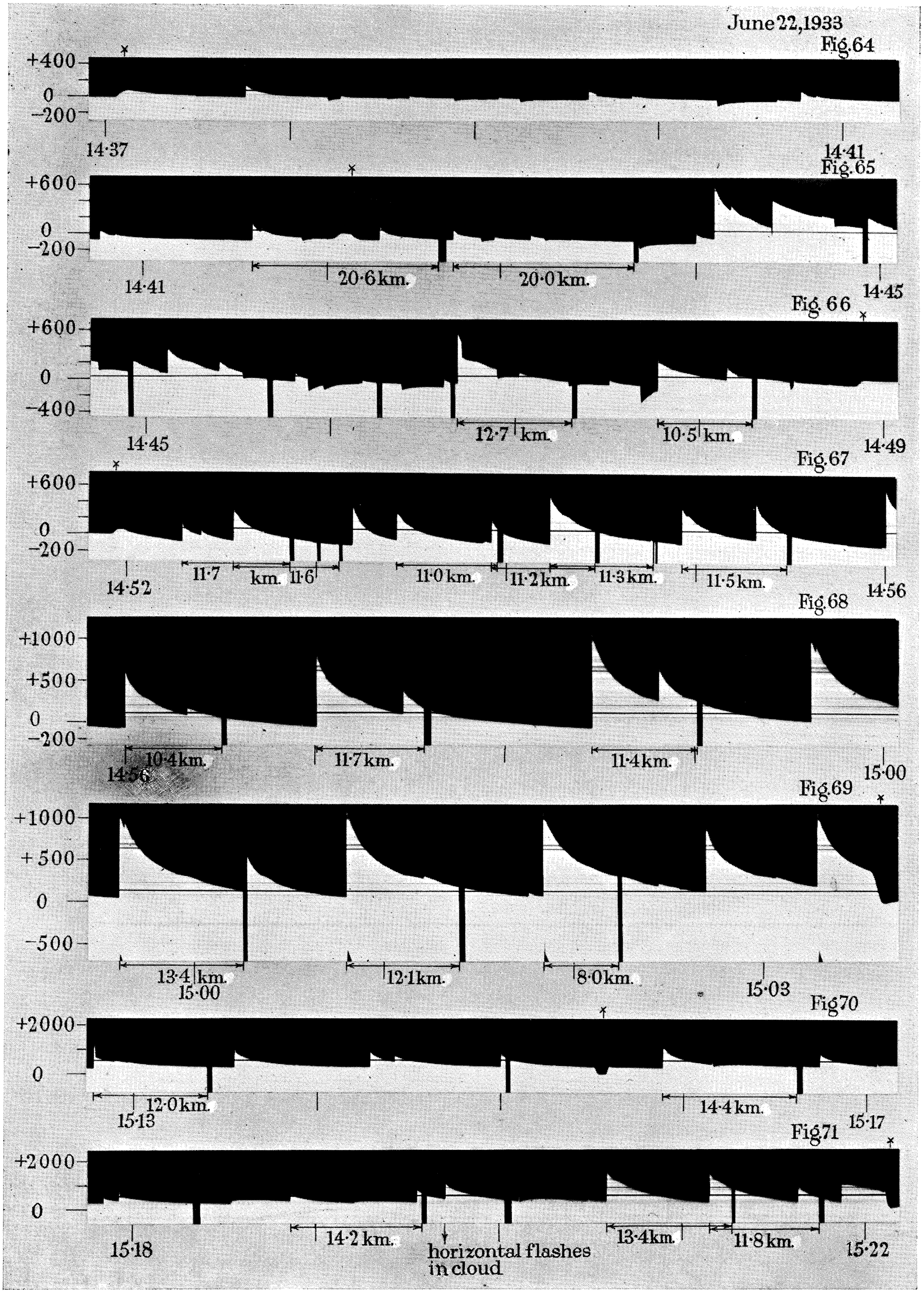
April 29, 1933

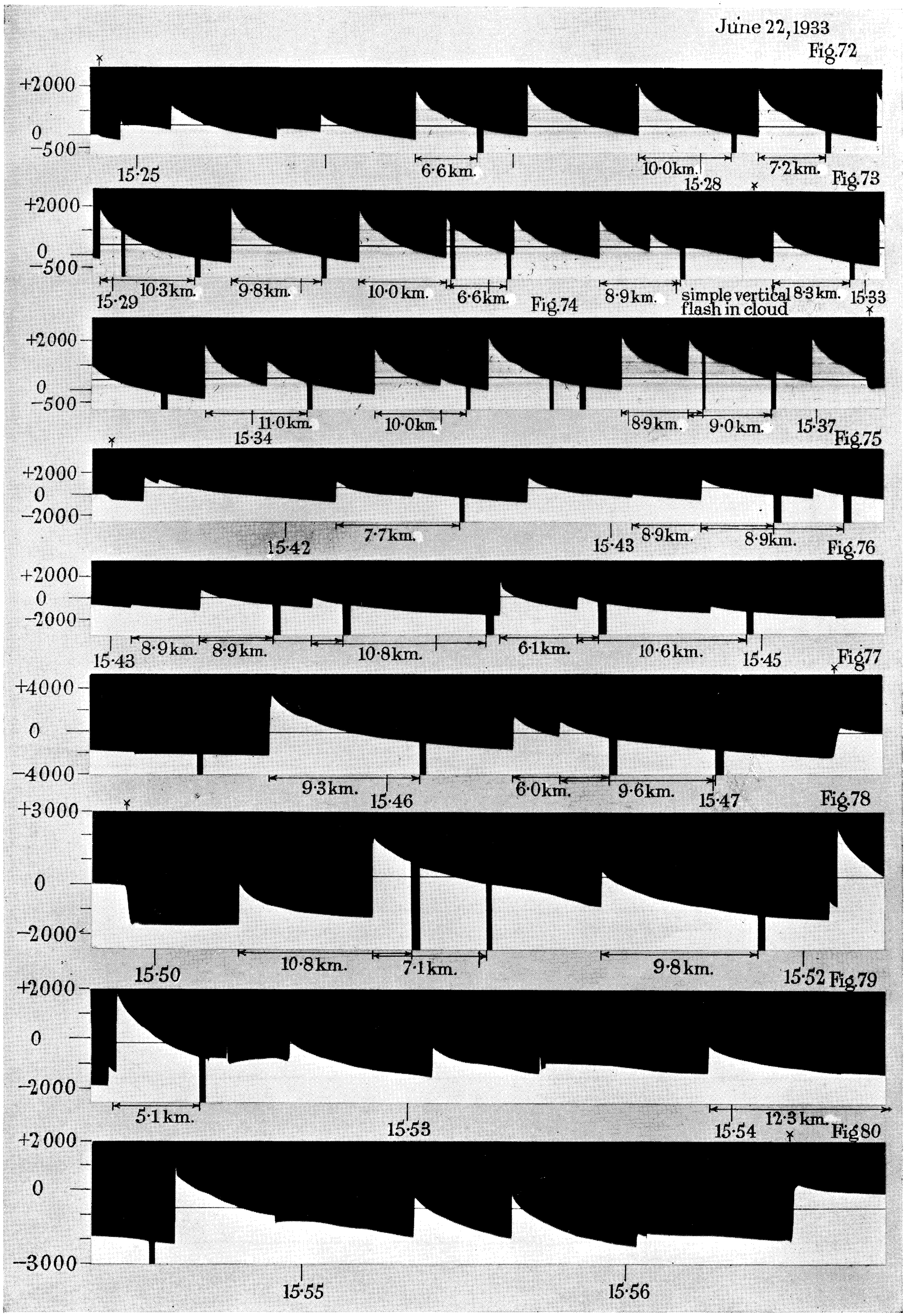
Fig. 47

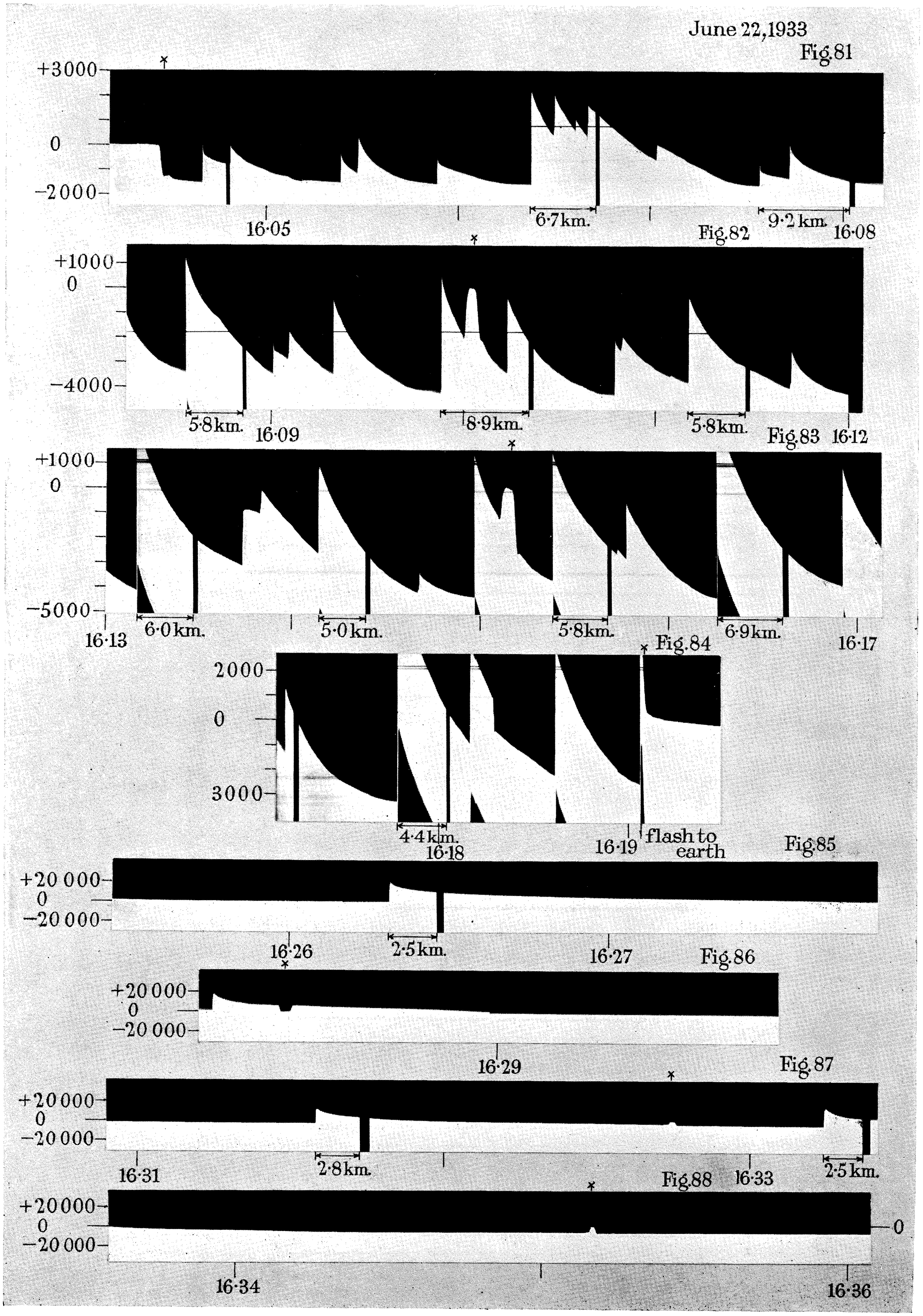


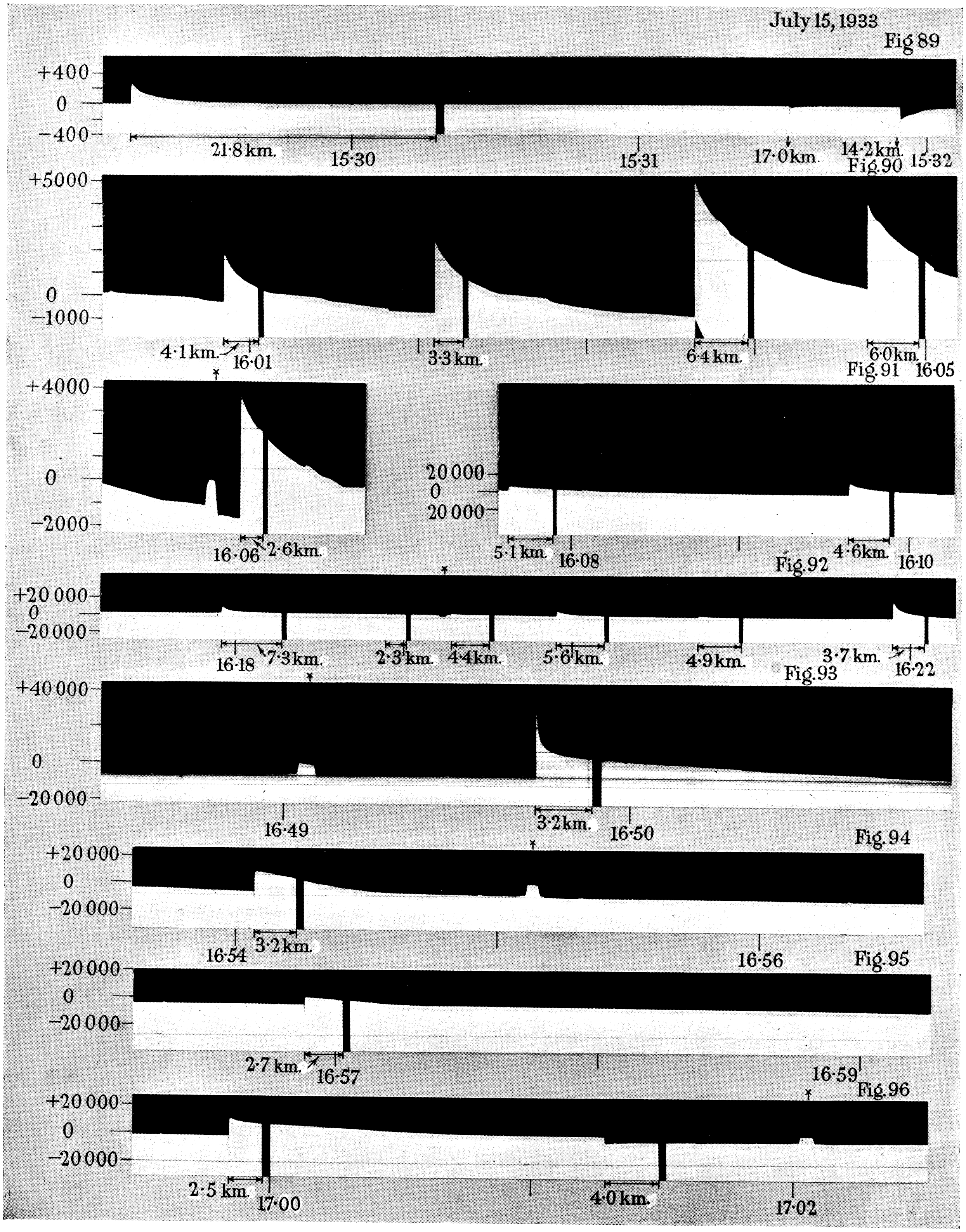

May 9, 1933
Fig. 48
(a)
(b)
+800
0
0
−3000
14·36
14·37
14·41
14·42
June 17, 1933
Fig. 49
+2000
+1000
0
13·39
13·43
Fig. 50
+2000
+1000
0
13·44
13·48
Fig. 51
0
−1000
13·49
13·54
Fig. 52
+600
0
−600
14·29
7·2 km.
14·33
June 19, 1933
Fig. 53
0
−1000
11·33
11·38
Fig. 54
+4000
0
11·44
11·48
Fig. 55
0
50000
3·5 km.
11·58
12·00

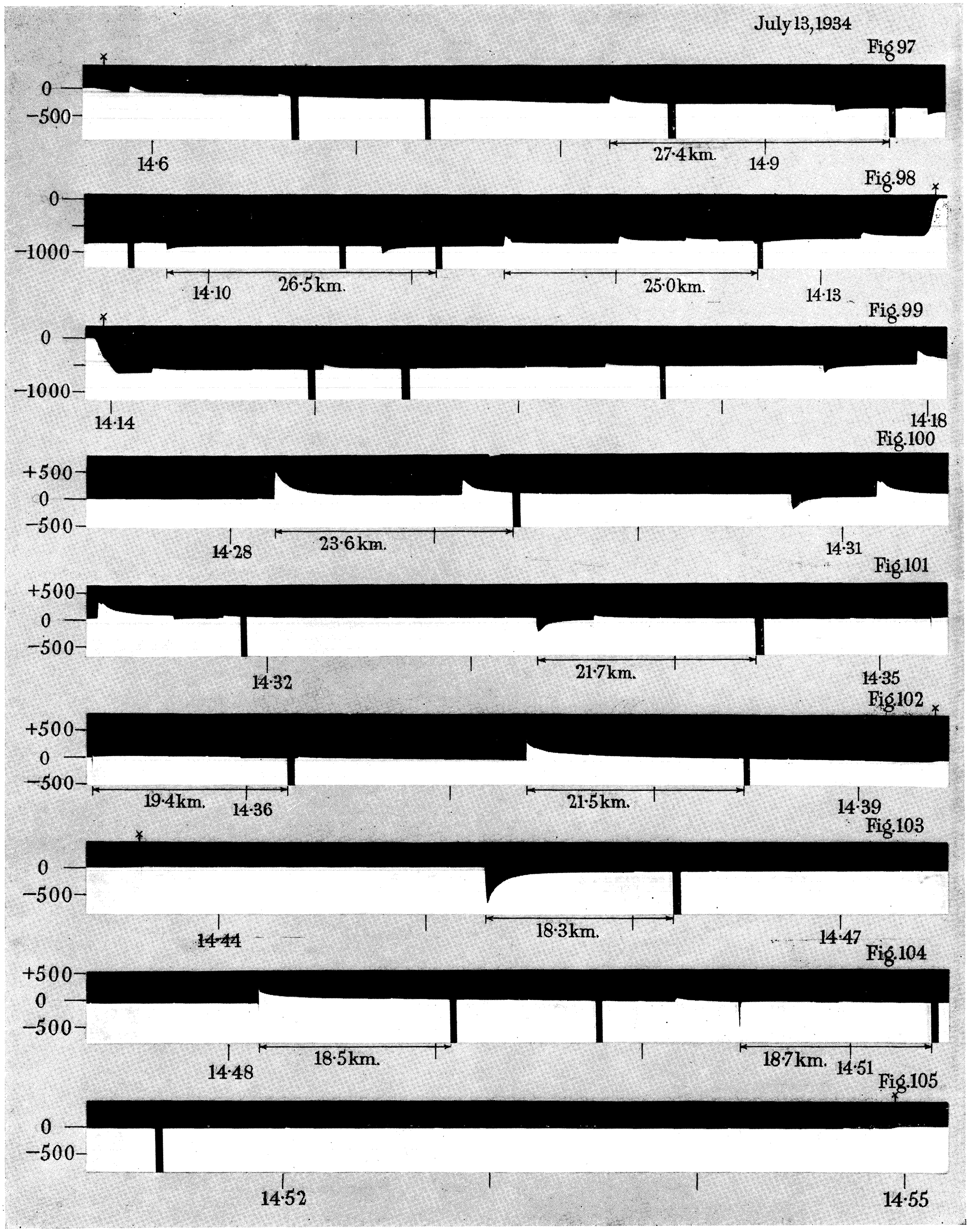

June 19, 1933
Fig. 56
(a)
(b)
+3000
0
−4000
5·7 km.
5·7 km.
3·6 km.
14·51
14·56
+5000
0
−5000
14·56
3·6 km.
5·8 km.
3·8 km.
15·00
Fig. 57
+20 000
0
−20 000
15·01
4·6 km.
15·05
Fig. 58
+20 000
0
−20 000
1·9 km.
15·11
4·5 km.
4·3 km.
flash to earth
4·4 km.
5·1 km.
15·16
Fig. 59
+20 000
0
−20 000
flash to earth
3·8 km.
15·17
5·1 km.
15·22
Fig. 60
+6000
0
−2000
15·23
6·3 km.
15·27
7·9 km.
Fig. 61
+3000
0
10·8 km.
15·32
8·5 km.
11·9 km.
15·36
Fig. 62
+3000
0
11·9 km.
15·35
12·6 km.
12·2 km.
15·40
Fig. 63
+2600
+2000
+1200
15·41
15·45


June 22, 1933
Fig. 64
+400
0
−200
14·37
14·41
Fig. 65
+600
0
−200
14·41
20·6 km.
20·0 km.
14·45
Fig. 66
+600
0
−400
14·45
12·7 km.
10·5 km.
14·49
Fig. 67
+600
0
−200
14·52
11·7
km.
11·6
11·0 km.
11·2 km.
11·3 km.
11·5 km.
14·56
Fig. 68
+1000
+500
0
−200
14·56
10·4 km.
11·7 km.
11·4 km.
15·00
Fig. 69
+1000
+500
0
−500
13·4 km.
15·00
12·1 km.
8·0 km.
15·03
Fig 70
+2000
0
15·13
12·0 km.
14·4 km.
15·17
Fig 71
+2000
0
15·18
14·2 km.
horizontal flashes in cloud
13·4 km.
11·8 km.
15·22

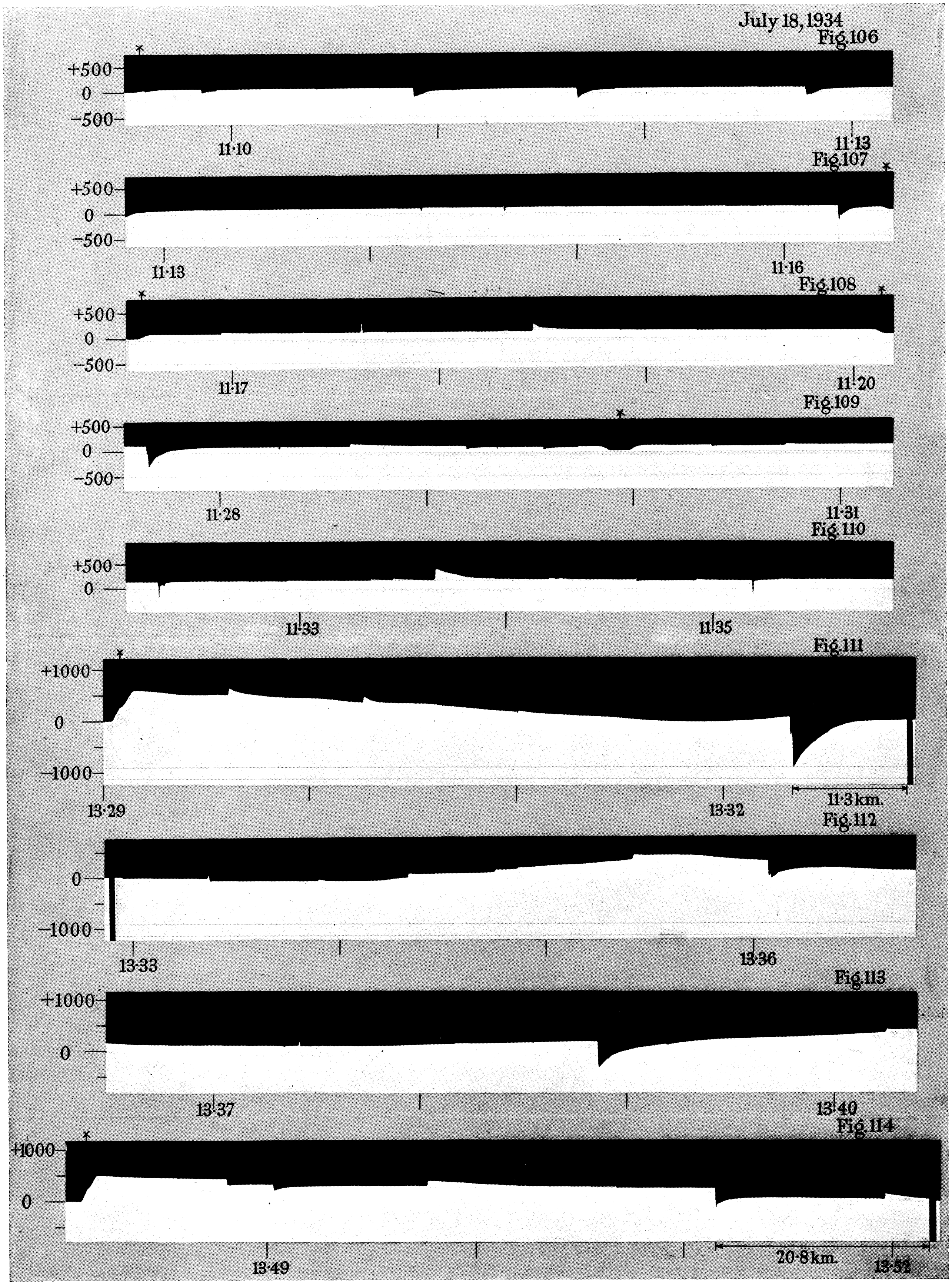

June 22, 1933
Fig. 72
+2000
0
−500
15·25
6·6 km.
10·0 km.
7·2 km.
15·28
Fig. 73
+2000
0
−500
15·29
10·3 km.
9·8 km.
10·0 km.
6·6 km.
8·9 km.
simple vertical flash in cloud
8·3 km.
15·33
Fig. 74
+2000
0
−500
11·0 km.
15·34
10·0 km.
8·9 km.
9·0 km.
15·37
Fig. 75
+2000
0
−2000
15·42
7·7 km.
15·43
8·9 km.
8·9 km.
Fig. 76
+2000
0
−2000
15·43
8·9 km.
8·9 km.
10·8 km.
6·1 km.
10·6 km.
15·45
Fig. 77
+4000
0
−4000
9·3 km.
15·46
6·0 km.
9·6 km.
15·47
Fig. 78
+3000
0
−2000
15·50
10·8 km.
7·1 km.
9·8 km.
15·52
Fig. 79
+2000
0
−2000
5·1 km.
15·53
15·54
12·3 km.
Fig. 80
+2000
0
−3000
15·55
15·56

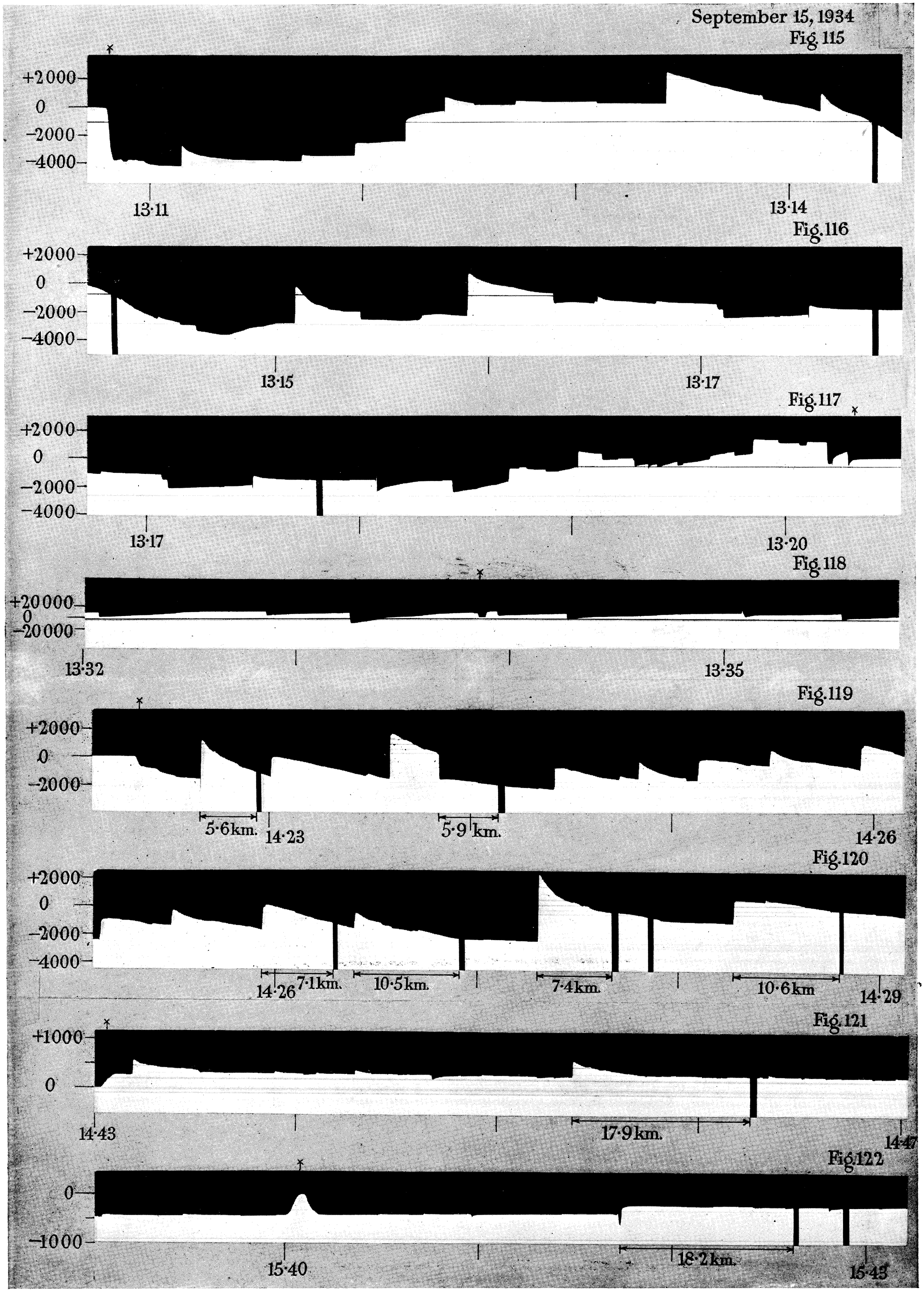

June 22, 1933
Fig. 81
+3000
0
−2000
16·05
6·7 km.
9·2 km.
16·08
Fig. 82
+1000
0
−4000
5·8 km.
16·09
8·9 km.
5·8 km.
Fig. 83
16·12
+1000
0
−5000
16·13
6·0 km.
5·0 km.
5·8 km.
6·9 km.
16·17
Fig. 84
2000
0
3000
4·4 km.
16·18
16·19
flash to earth
Fig. 85
+20 000
0
−20 000
16·26
2·5 km.
16·27
Fig. 86
+20 000
0
−20 000
16·29
Fig. 87
+20 000
0
−20 000
16·31
2·8 km.
16·33
2·5 km.
Fig. 88
+20 000
0
−20 000
0
16·34
16·36


July 15, 1933
Fig 89
+400
0
−400
21·8 km.
15·30
15·31
17·0 km.
14·2 km.
15·32
Fig. 90
+5000
0
−1000
4·1 km.
16·01
3·3 km.
6·4 km.
6·0 km.
16·05
Fig. 91
+4000
0
−2000
16·06
2·6 km.
20 000
0
20 000
5·1 km.
16·08
4·6 km.
16·10
Fig. 92
+20 000
0
−20 000
16·18
7·3 km.
2·3 km.
4·4 km.
5·6 km.
4·9 km.
3·7 km.
16·22
Fig. 93
+40 000
0
−20 000
16·49
3·2 km.
16·50
Fig. 94
+20 000
0
−20 000
16·54
3·2 km.
16·56
Fig. 95
+20 000
0
−20 000
2·7 km.
16·57
16·59
Fig. 96
+20 000
0
−20 000
2·5 km.
17·00
4·0 km.
17·02



July 13, 1934
Fig. 97
0
−500
14·6
27·4 km.
14·9
Fig. 98
0
−1000
14·10
26·5 km.
25·0 km.
14·13
Fig. 99
0
−1000
14·14
14·18
Fig. 100
+500
0
−500
14·28
23·6 km.
14·31
Fig. 101
+500
0
−500
14·32
21·7 km.
14·35
Fig. 102
+500
0
−500
19·4 km.
14·36
21·5 km.
14·39
Fig. 103
0
−500
14·44
18·3 km.
14·47
Fig. 104
+500
0
−500
14·48
18·5 km.
18·7 km.
14·51
Fig. 105
0
−500
14·52
14·55


July 18, 1934
Fig. 106
+500
0
−500
11·10
11·13
Fig. 107
+500
0
−500
11·13
11·16
Fig. 108
+500
0
−500
11·17
11·20
Fig. 109
+500
0
−500
11·28
11·31
Fig. 110
+500
0
11·33
11·35
Fig. 111
+1000
0
−1000
13·29
13·32
11·3 km.
Fig. 112
0
−1000
13·33
13·36
Fig. 113
+1000
0
13·37
13·40
Fig. 114
+1000
0
13·49
20·8 km.
13·52


September 15, 1934
Fig. 115
+2000
0
−2000
−4000
13·11
13·14
Fig. 116
+2000
0
−2000
−4000
13·15
13·17
Fig. 117
+2000
0
−2000
−4000
13·17
13·20
Fig. 118
+20000
0
−20000
13·32
13·35
Fig. 119
+2000
0
−2000
5·6 km.
14·23
5·9 km.
14·26
Fig. 120
+2000
0
−2000
−4000
14·26
7·1 km.
10·5 km.
7·4 km.
10·6 km
14·29
Fig. 121
+1000
0
14·43
17·9 km.
14·47
Fig. 122
0
−1000
15·40
18·2 km.
15·43

June 24, 1927
Fig. 1

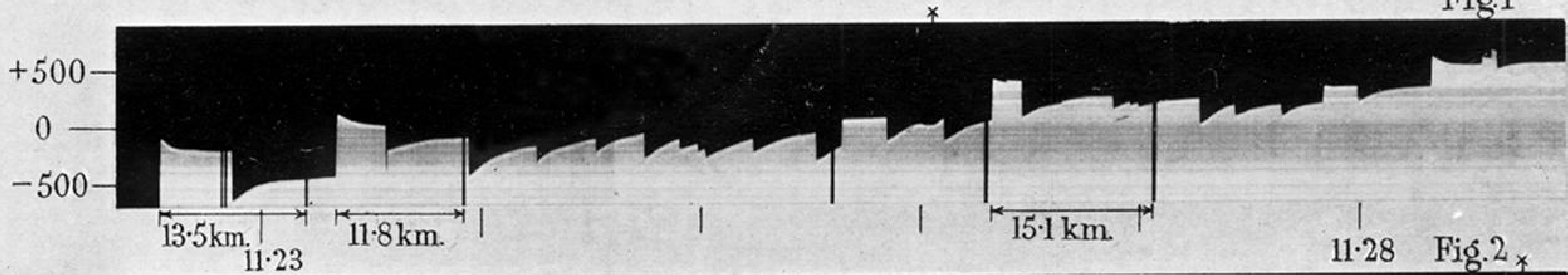
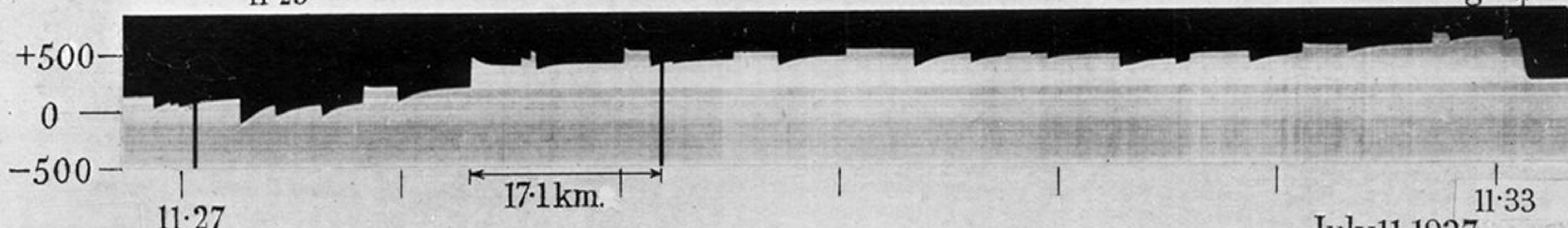
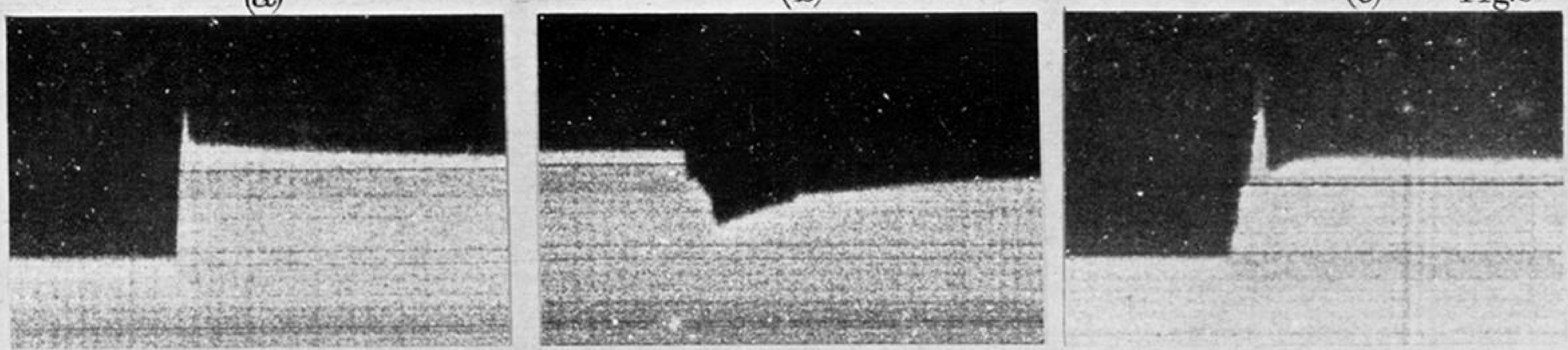


Fig. 2



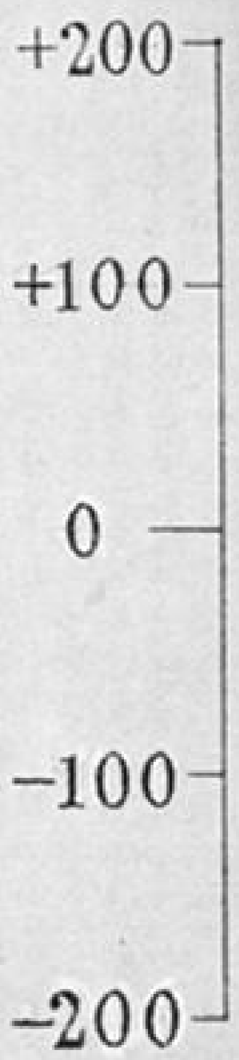
July 11, 1927

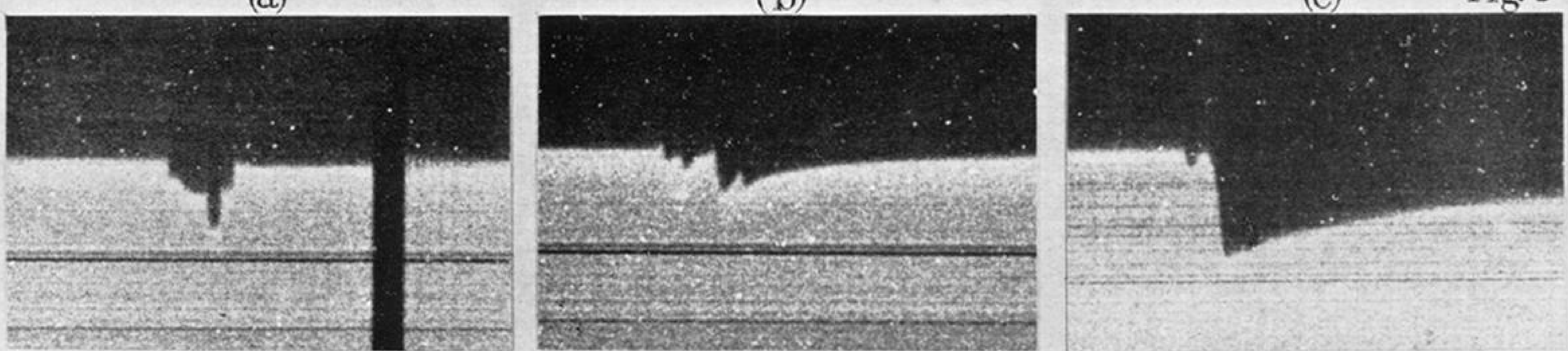
Fig. 3
(a) (b) (c)



17h. 11m. | 17h. 13m. | 17h. 14m.

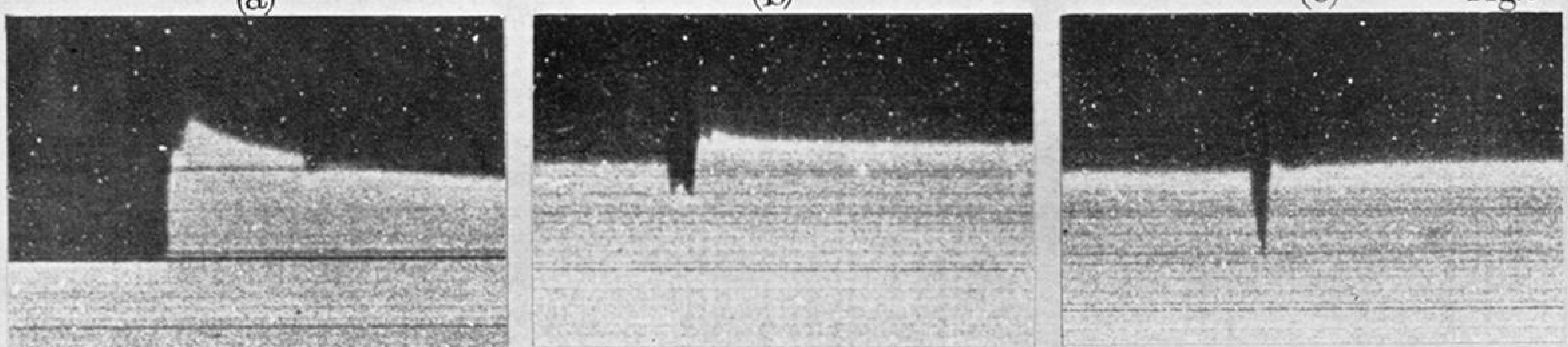
Fig. 4
(a) (b) (c)





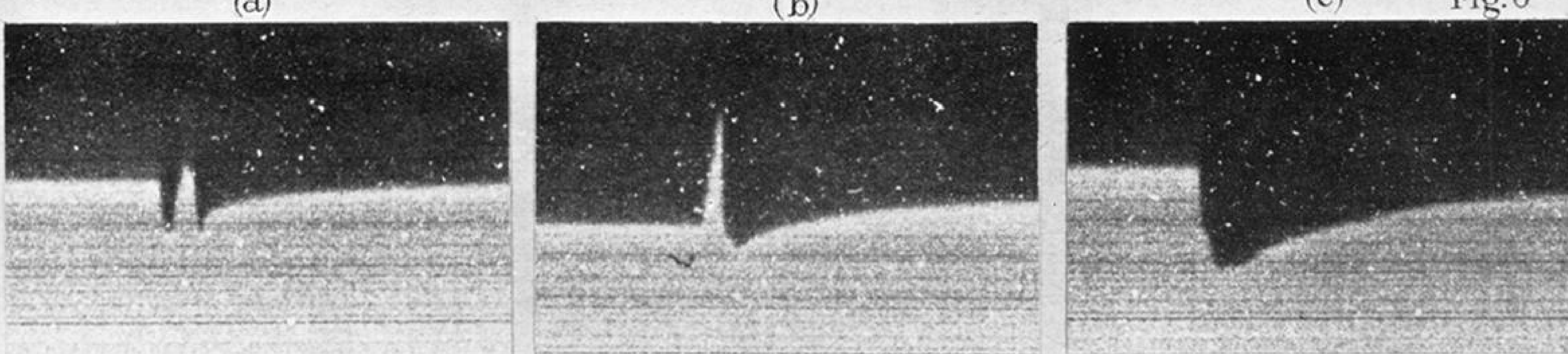
17h. 18m. | 17h. 21m. | 17h. 56m.

Fig. 5
(a) (b) (c)



18h. 03m. | 18h. 16m. | 18h. 19m.

Fig. 6
(a) (b) (c)



18h. 20m. | 18h. 21m. | 18h. 21m.

July 11, 1927

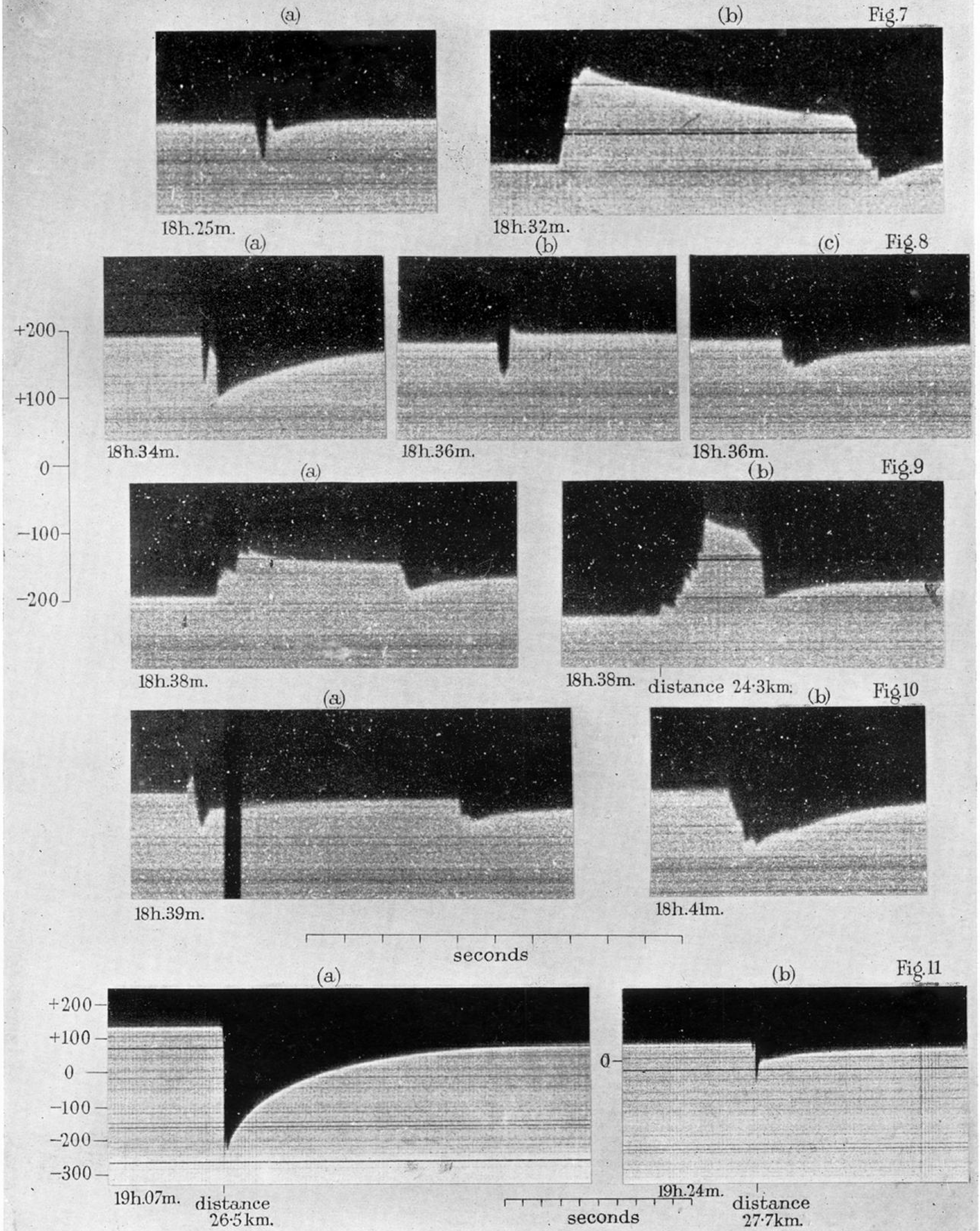


Fig.7
(a)
(b)
18h.25m.
18h.32m.
Fig.8
(a)
(b)
(c)
+200
+100
0
−100
−200
18h.34m.
18h.36m.
18h.36m.
Fig.9
(a)
(b)
18h.38m.
18h.38m.
distance 24·3km.
Fig.10
(a)
(b)
18h.39m.
18h.41m.
seconds
Fig.11
(a)
(b)
+200
+100
0
−100
−200
−300
19h.07m.
distance
26·5 km.
0
19h.24m.
distance
27·7km.
seconds

May 20, 1928

Fig. 12

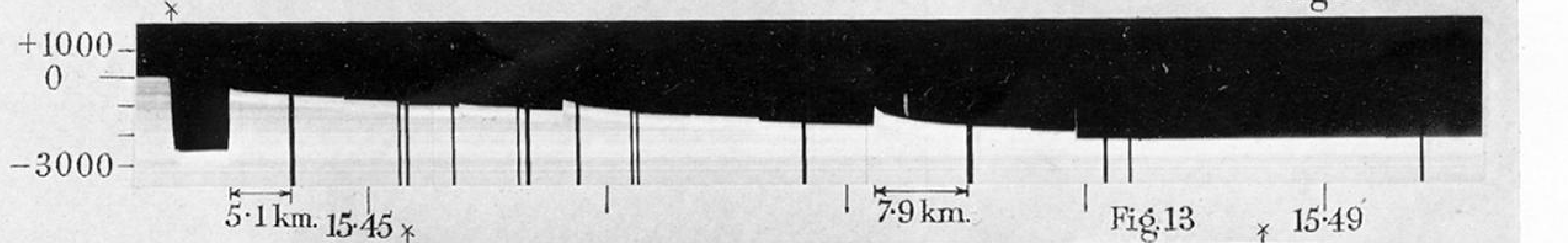


Fig. 13

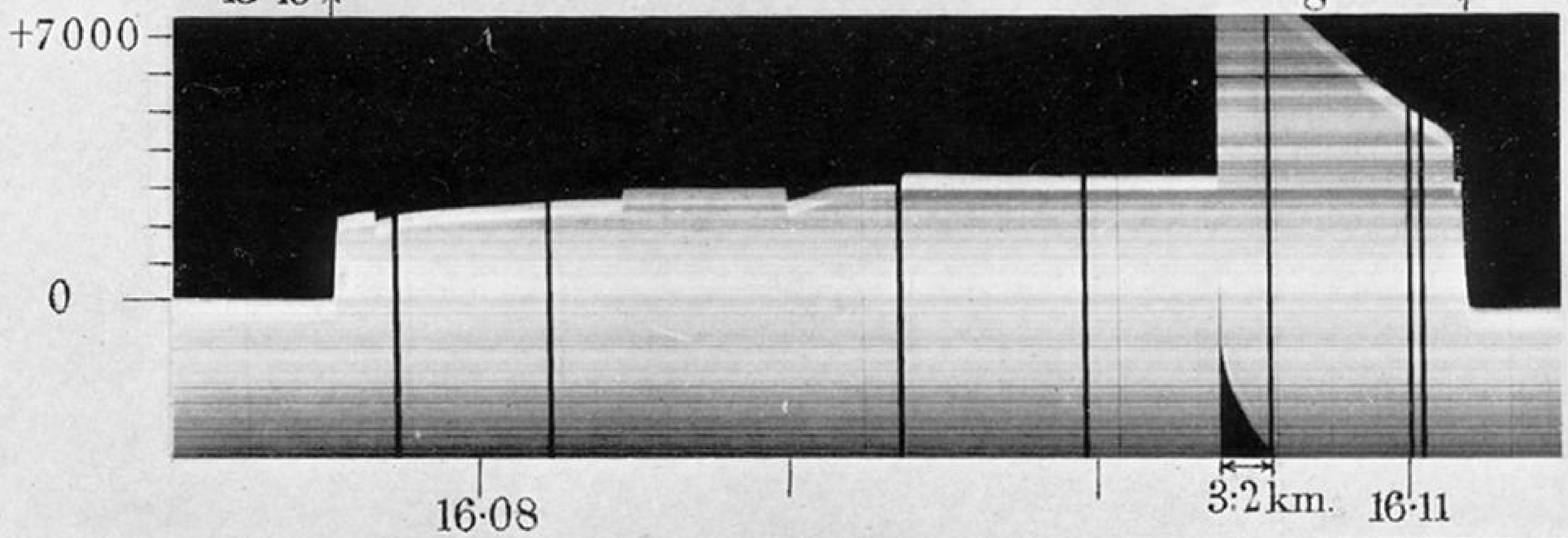


Fig. 14

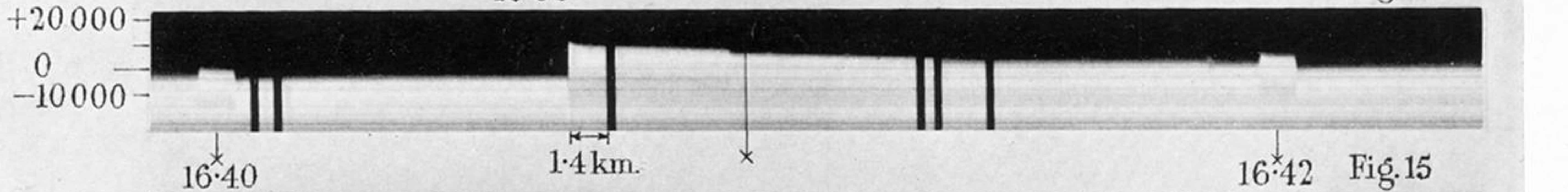


Fig. 15

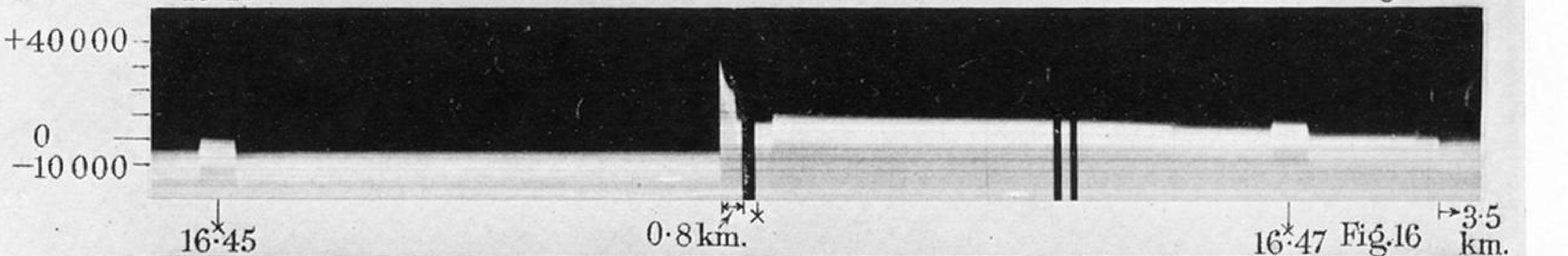


Fig. 16

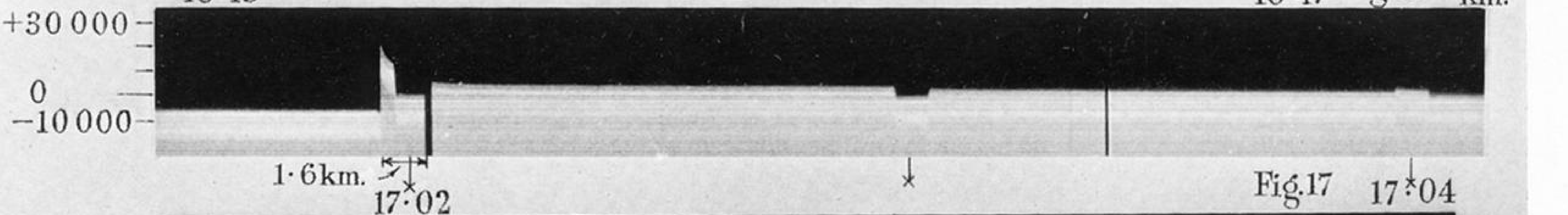


Fig. 17

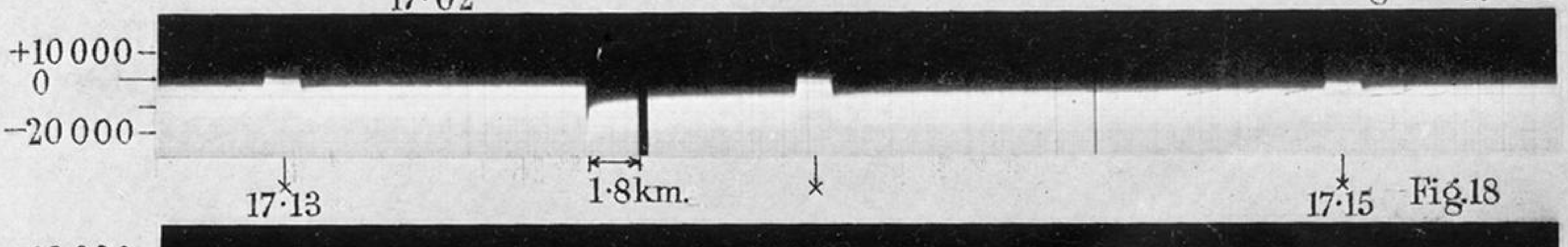


Fig. 18

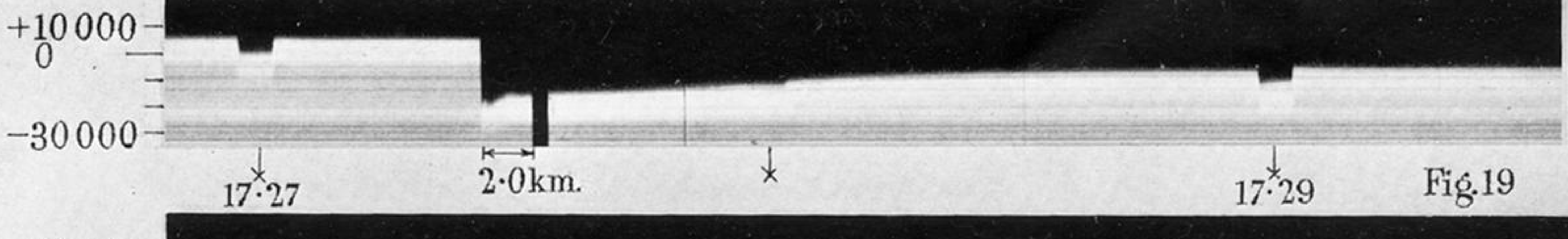
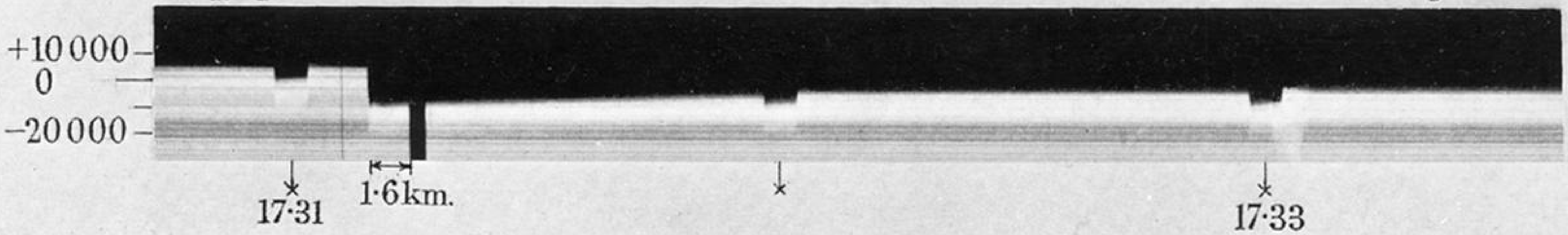
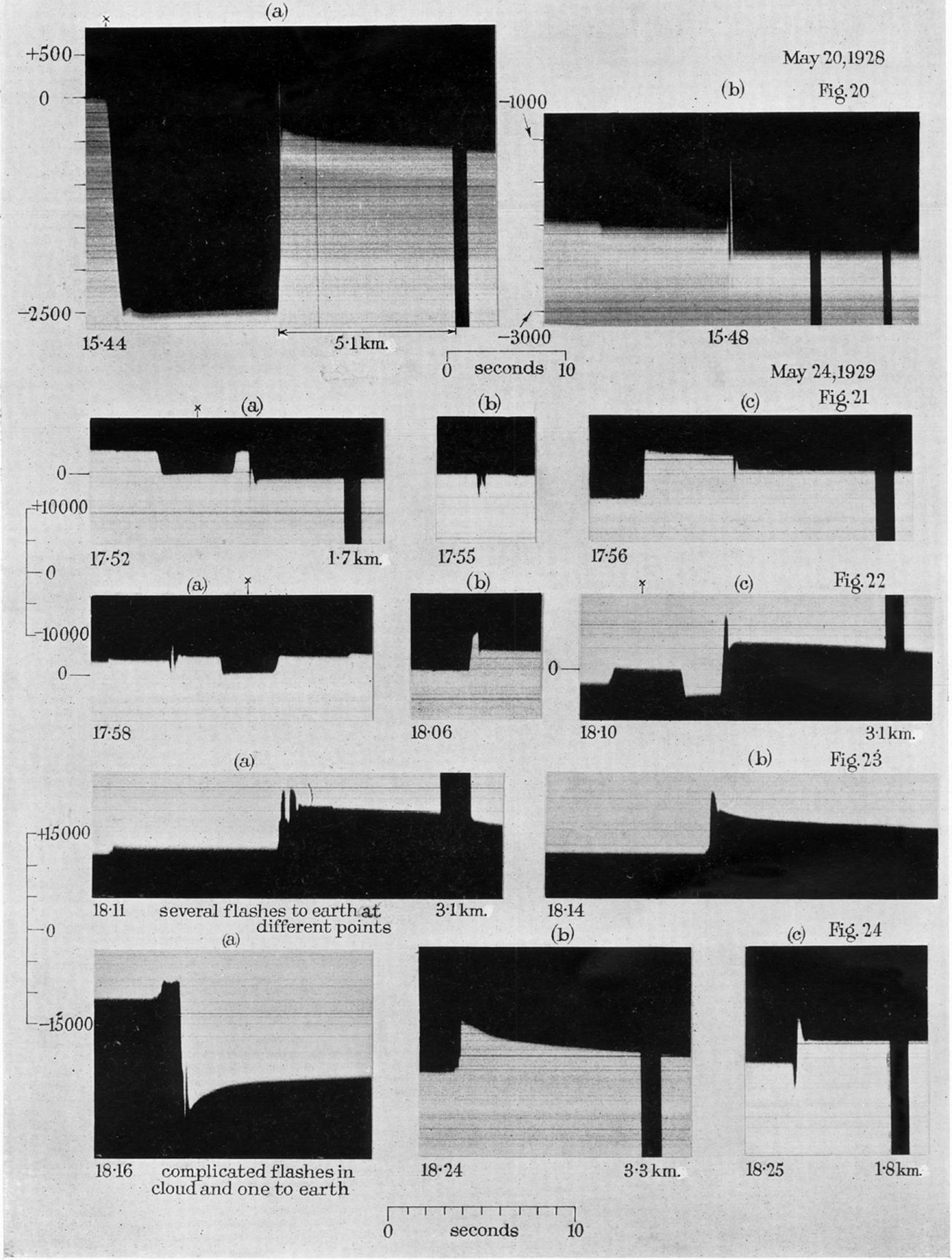


Fig. 19





May 20, 1928 Fig. 20

May 24, 1929 Fig. 21

Fig. 22

Fig. 23

Fig. 24

May 24, 1929

Fig. 25

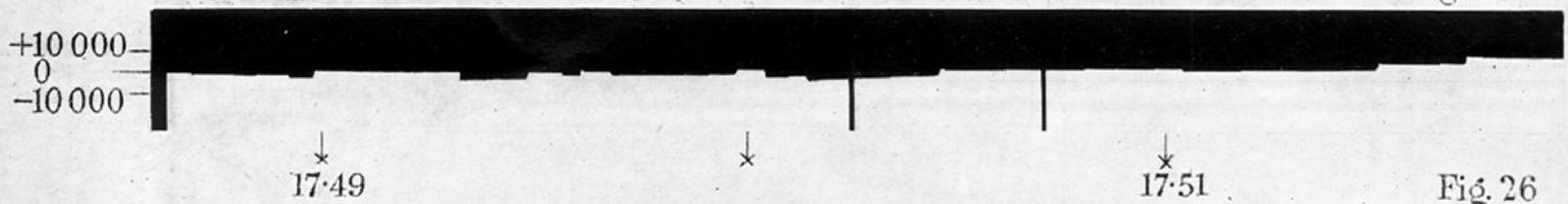


Fig. 26

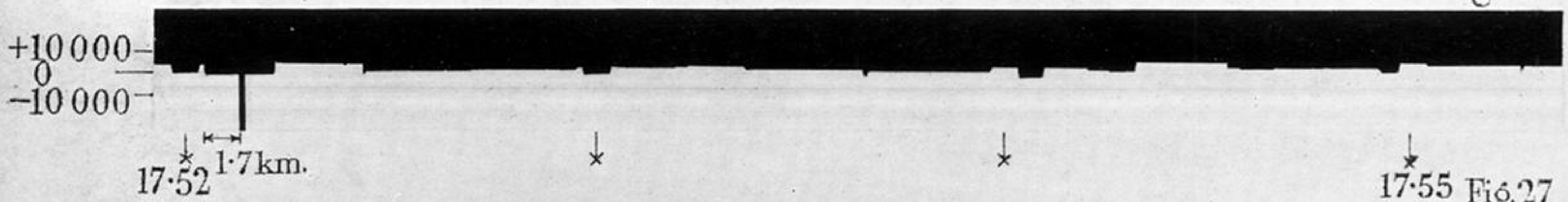


Fig. 27

Fig. 28

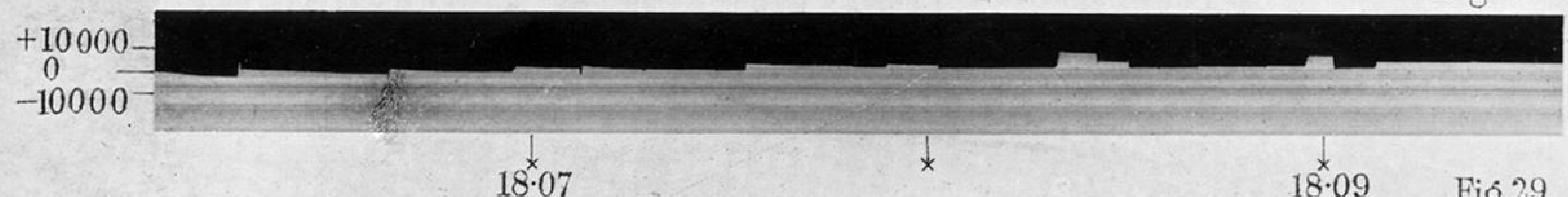


Fig. 29

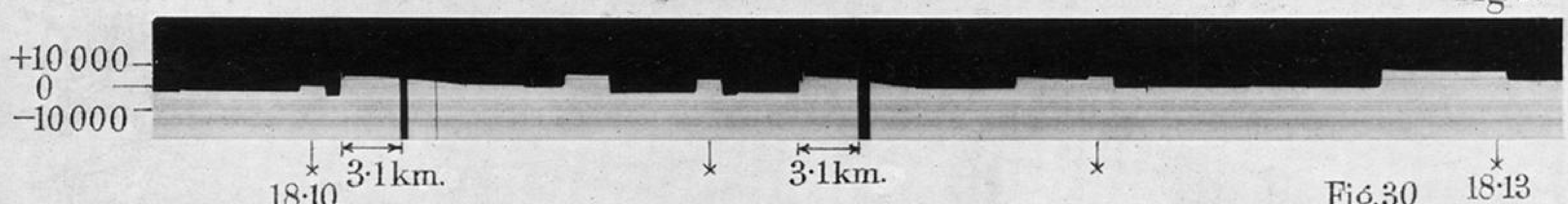


Fig. 30

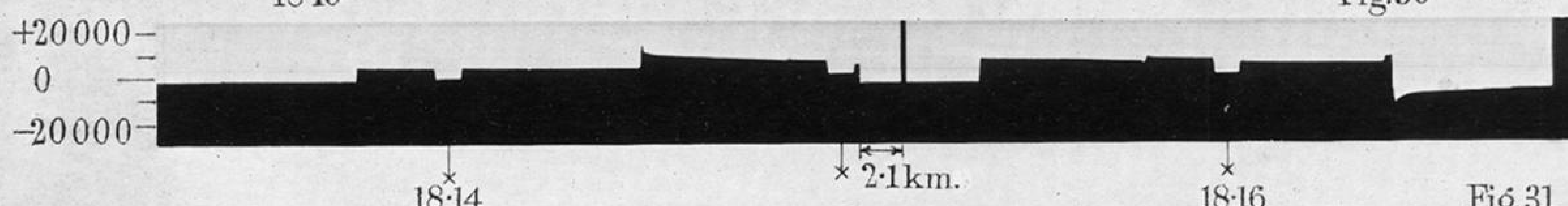


Fig. 31

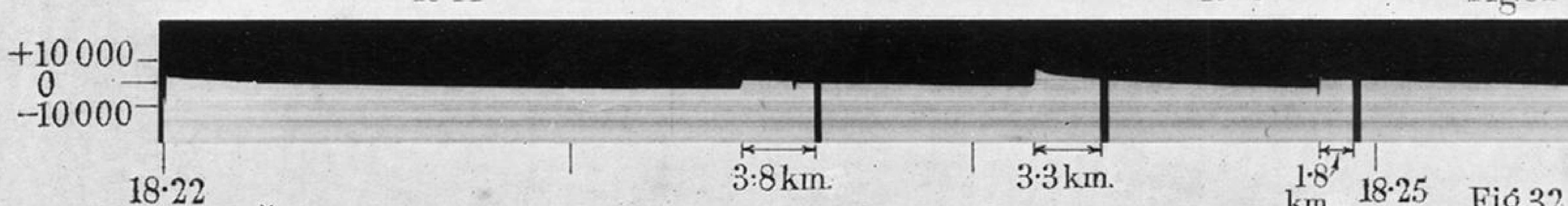


Fig. 32

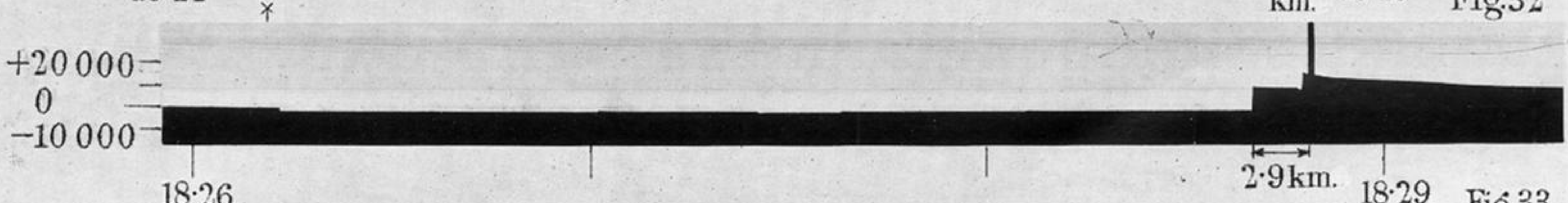


Fig. 33

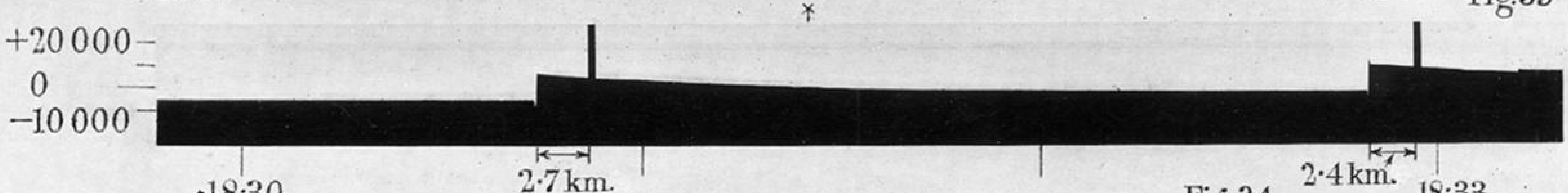
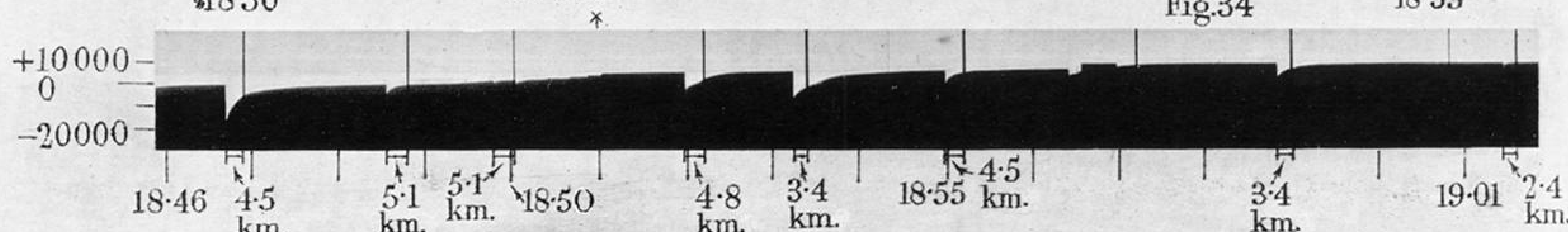


Fig. 34



June 4, 1929

Fig. 35

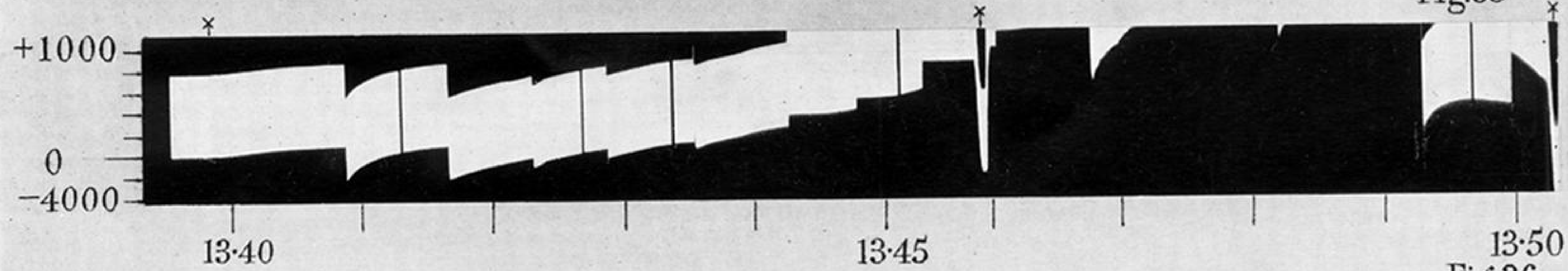


Fig 36

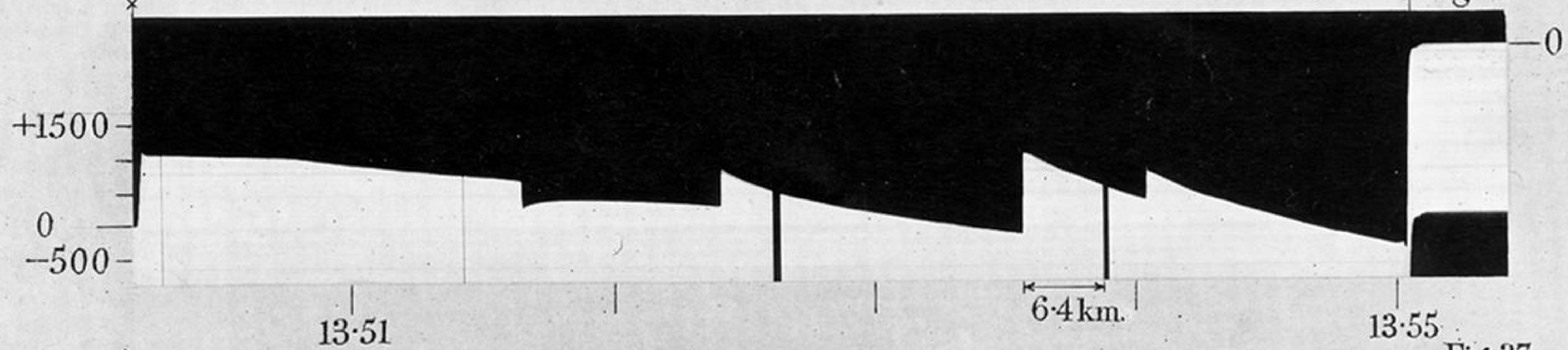


Fig. 37

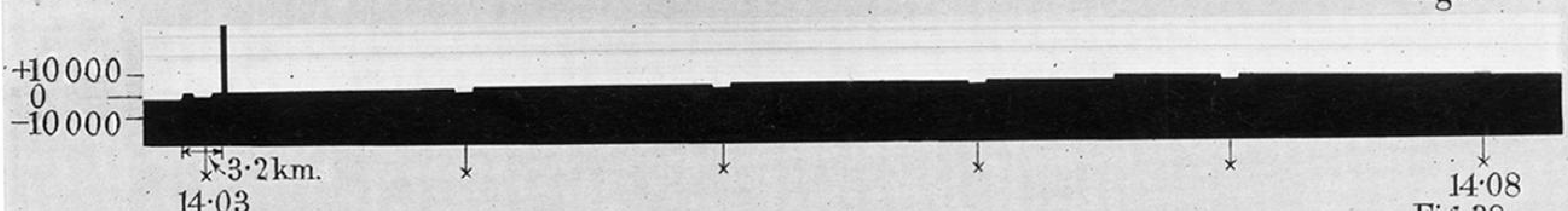


Fig. 38

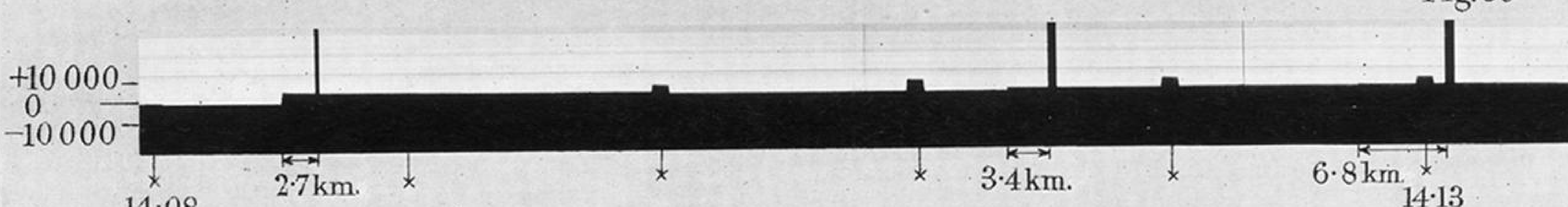


Fig. 39

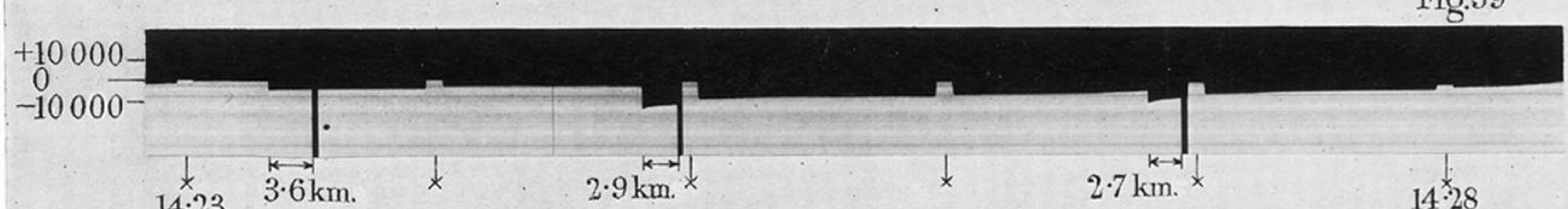


Fig. 40

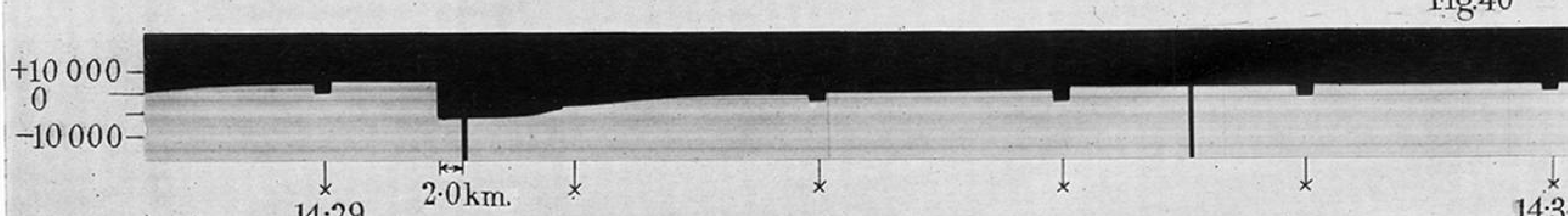
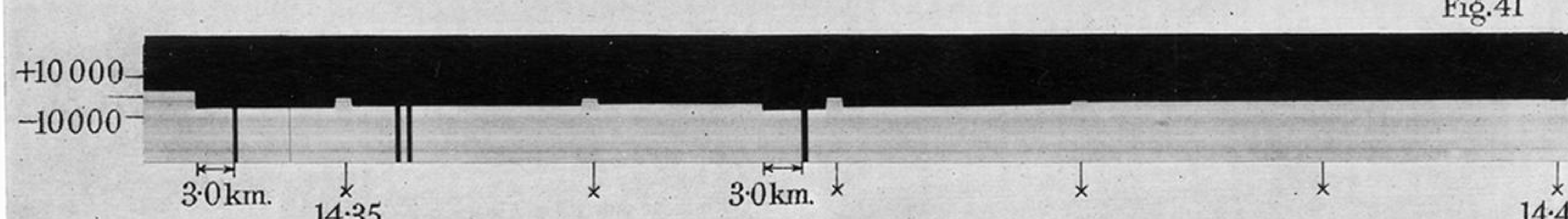


Fig. 41



June 6, 1931

Fig. 42

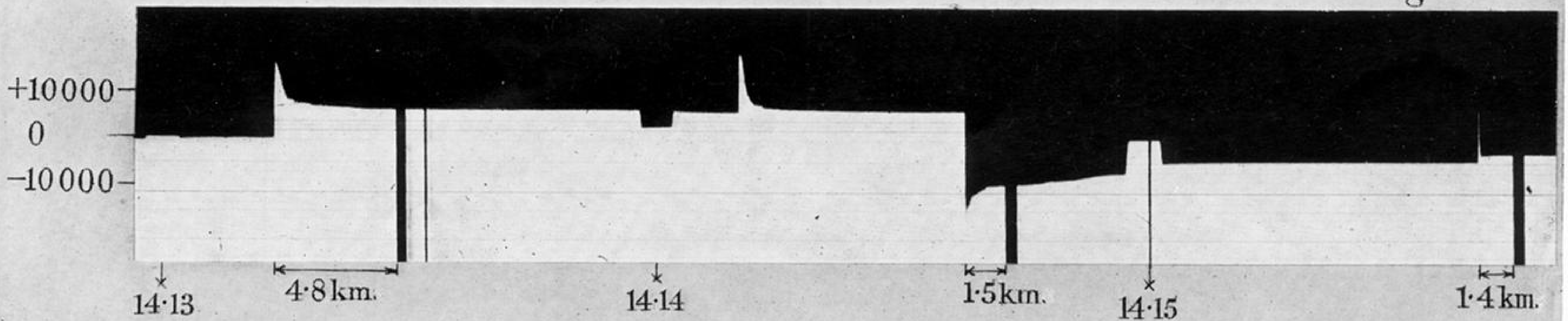


Fig. 43

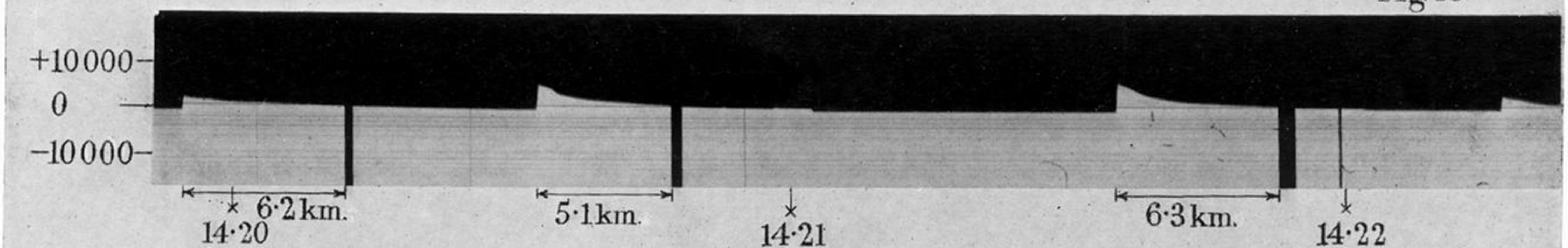
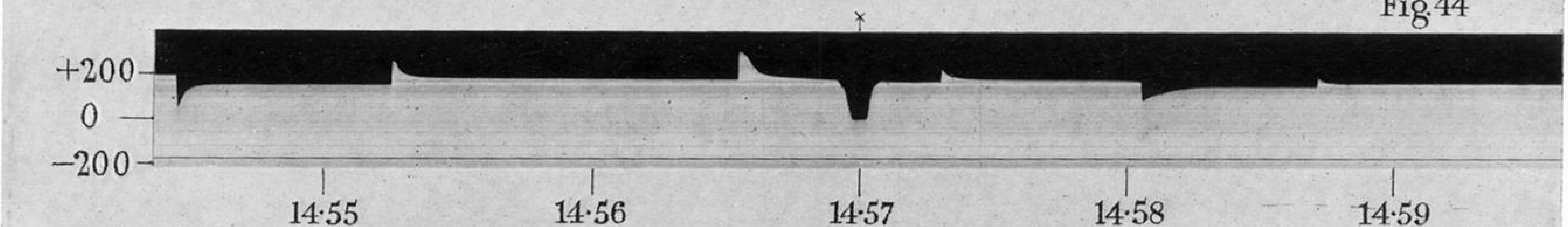


Fig. 44



July 26, 1932

Fig. 45

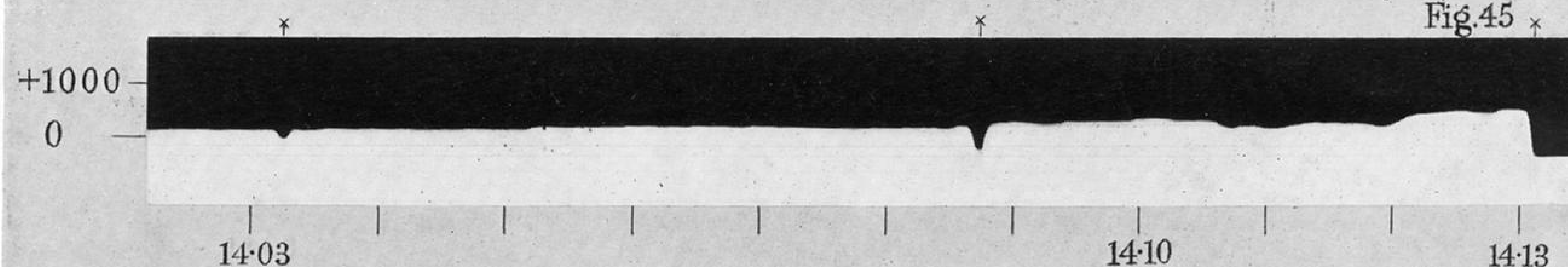
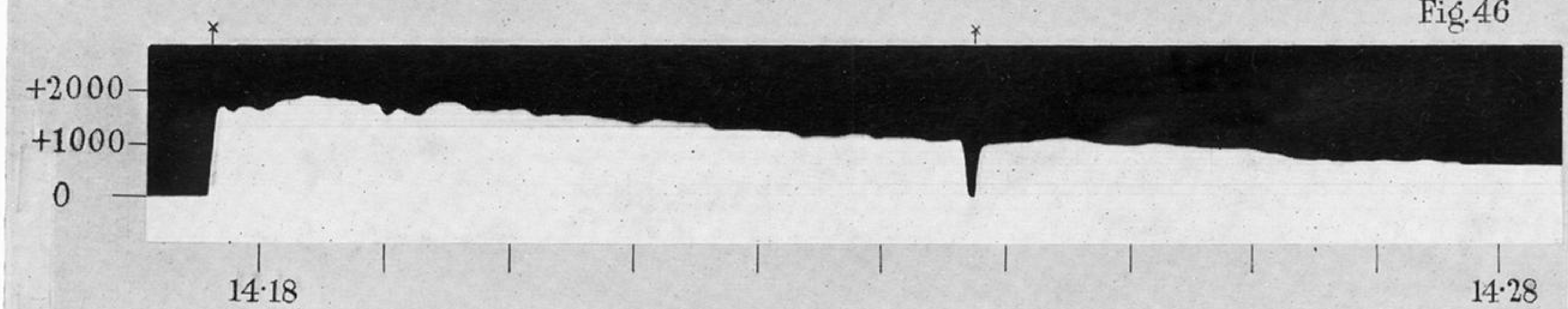
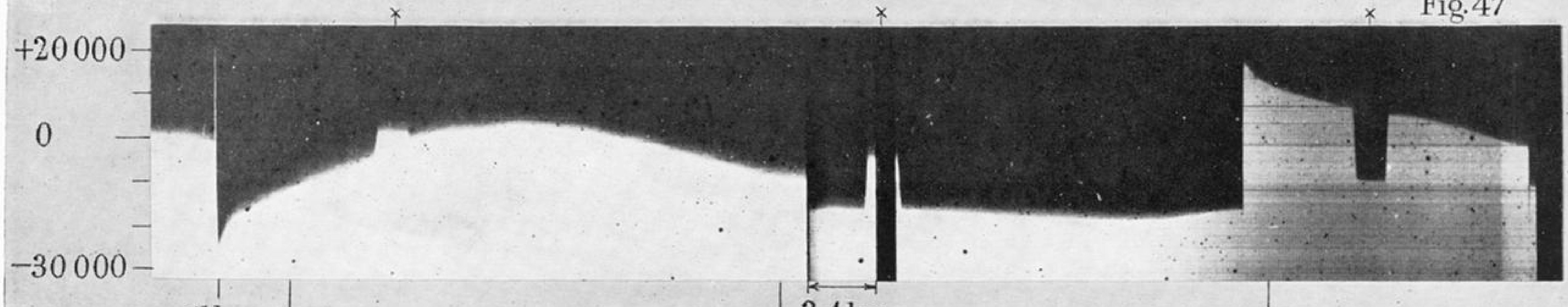


Fig. 46

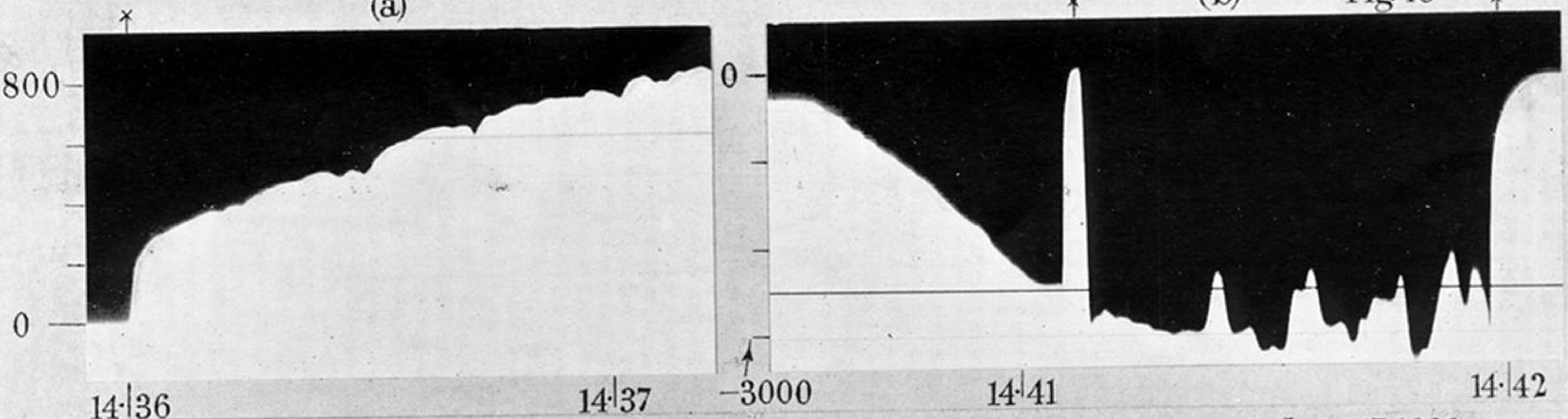


April 29, 1933

Fig. 47



May 9, 1933
Fig. 48



June 17, 1933
Fig. 49

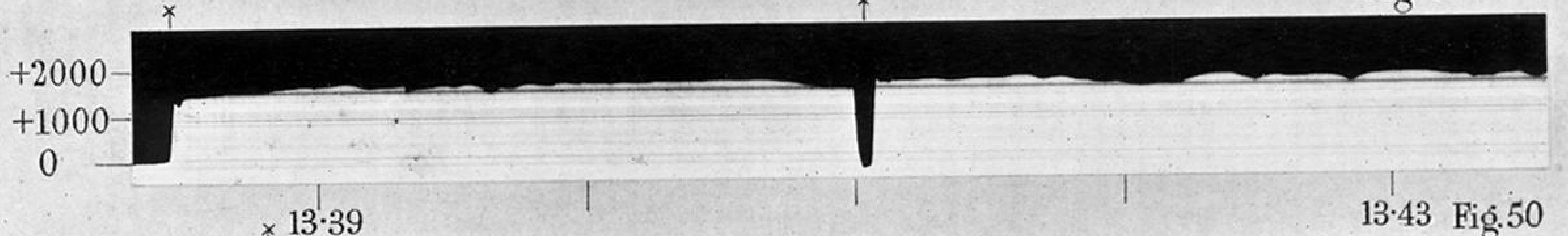


Fig. 50

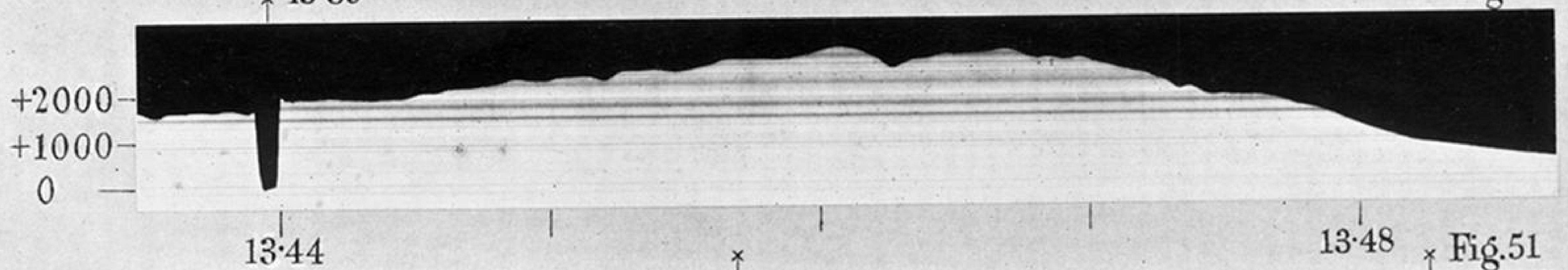


Fig. 51

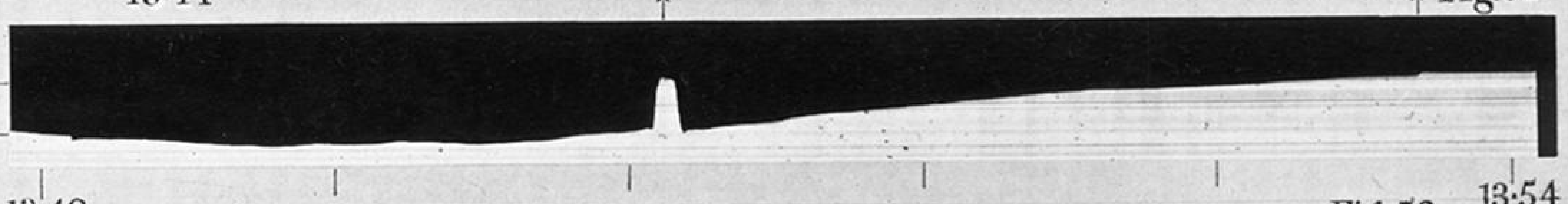


Fig. 52

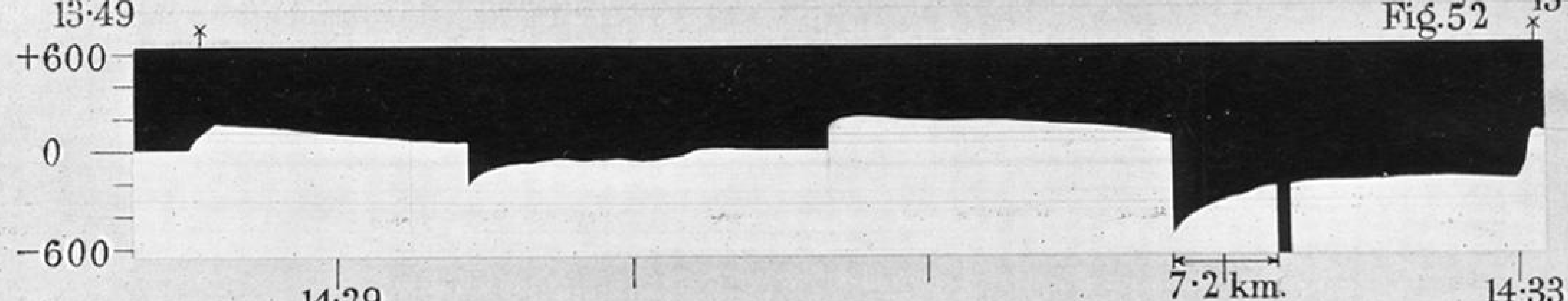


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Fig. 53

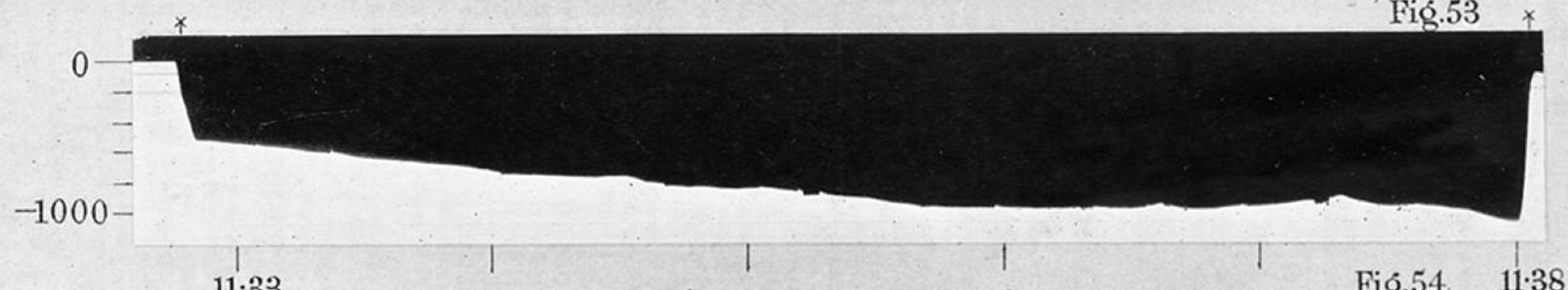


Fig. 54

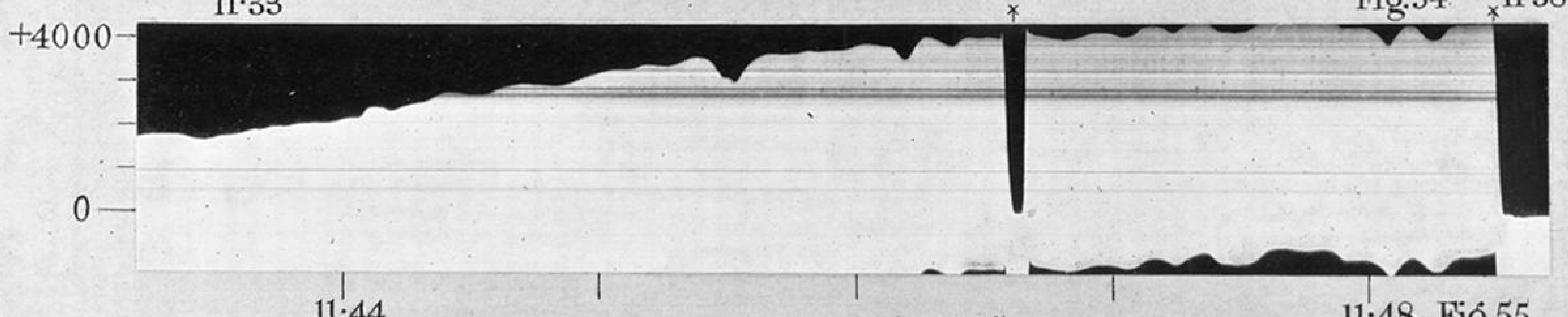
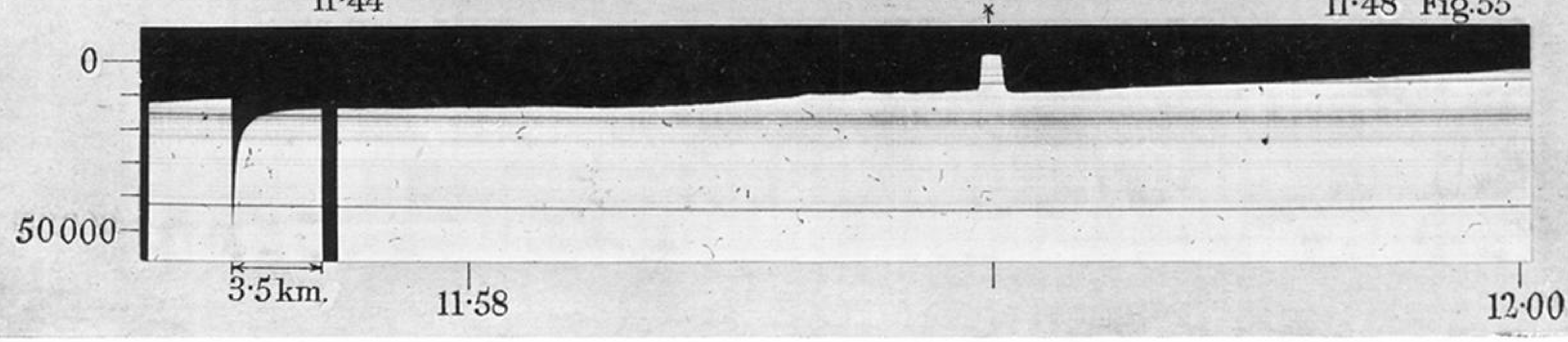
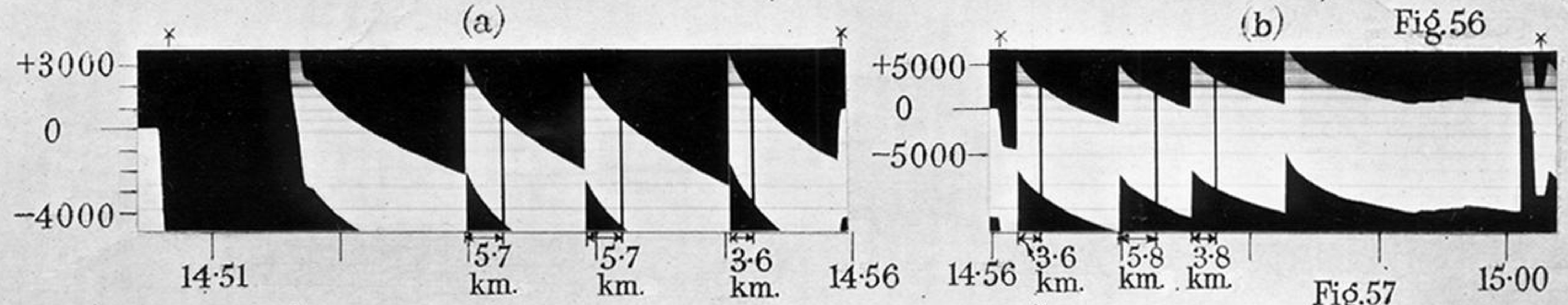


Fig. 55



June 19, 1933



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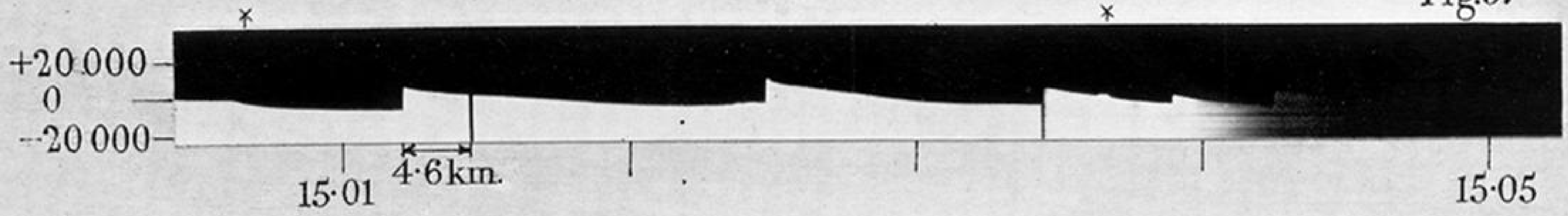


Fig. 57

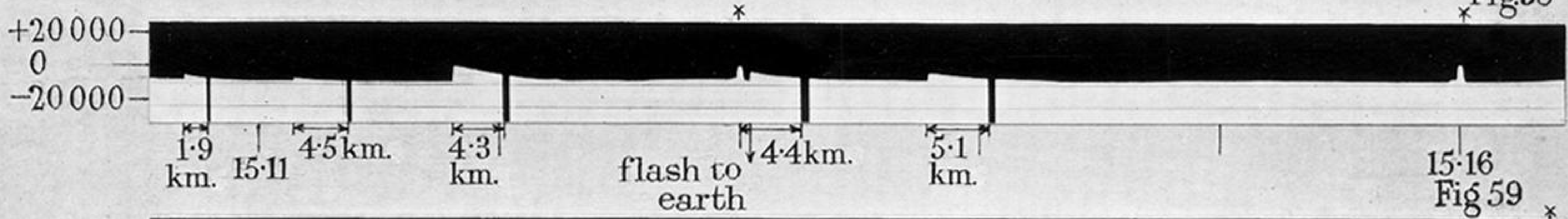


Fig. 58

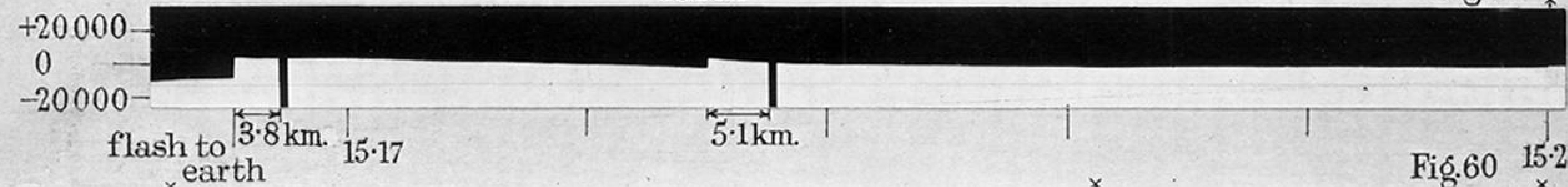


Fig 59

Fig. 60

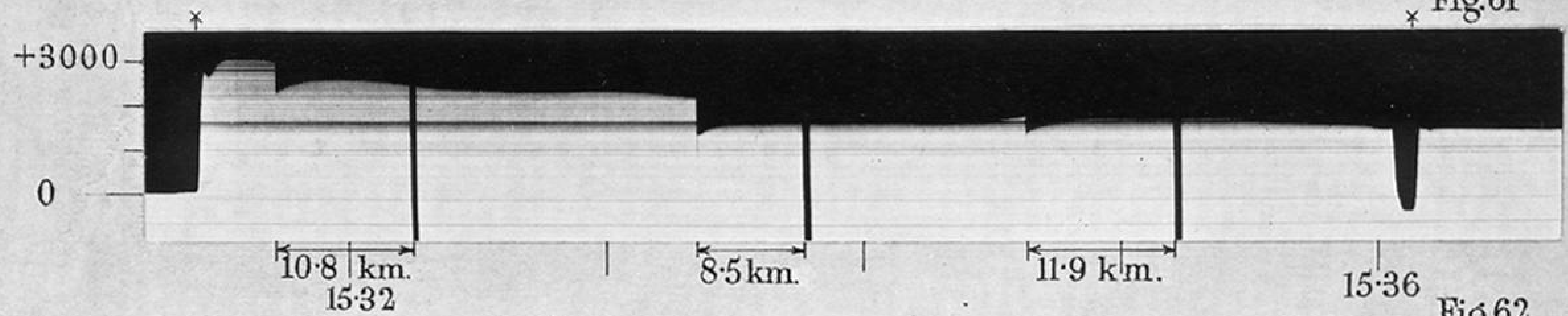
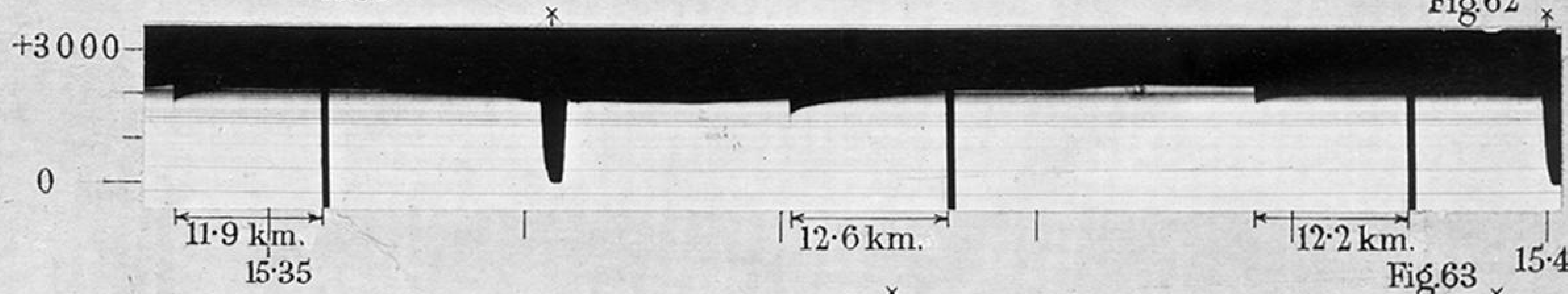


Fig. 61



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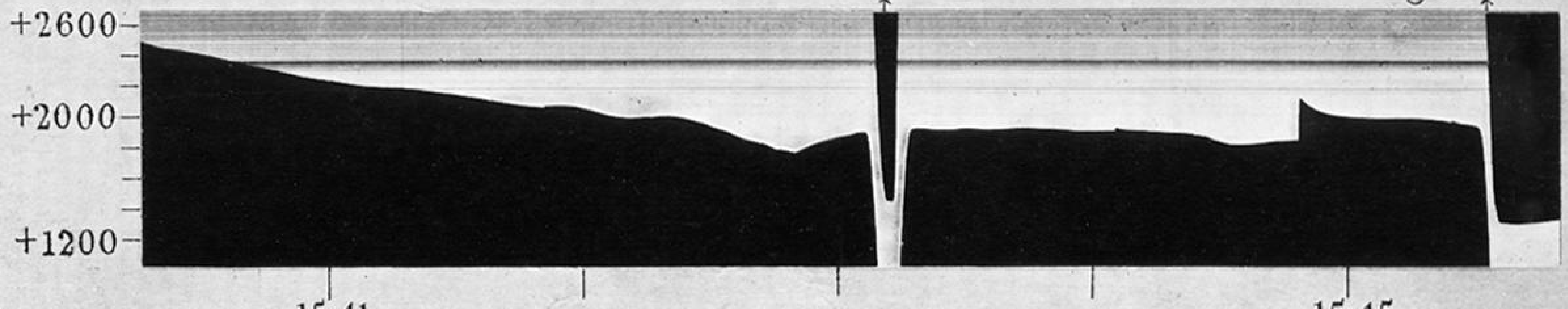

Fig. 63

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Fig. 64

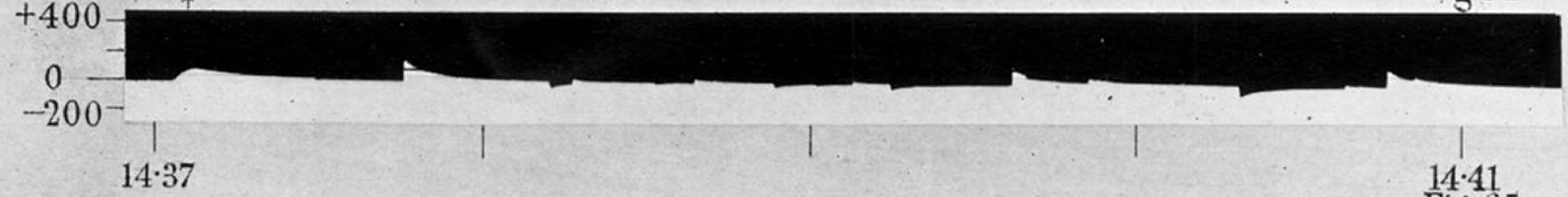


Fig. 65

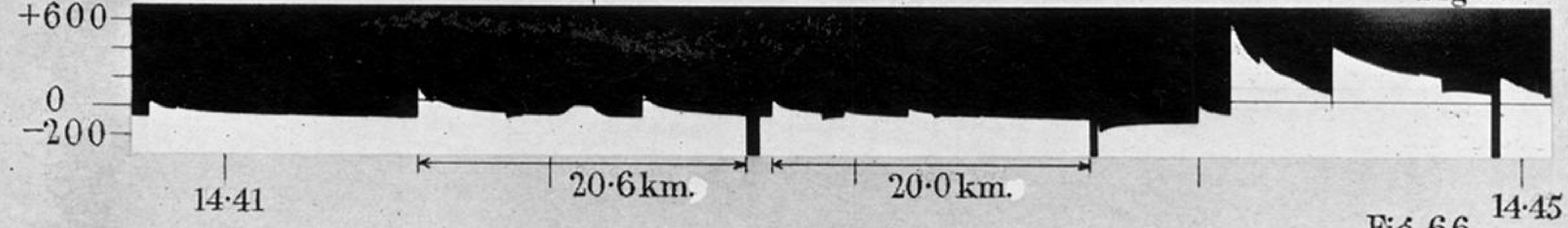


Fig. 66

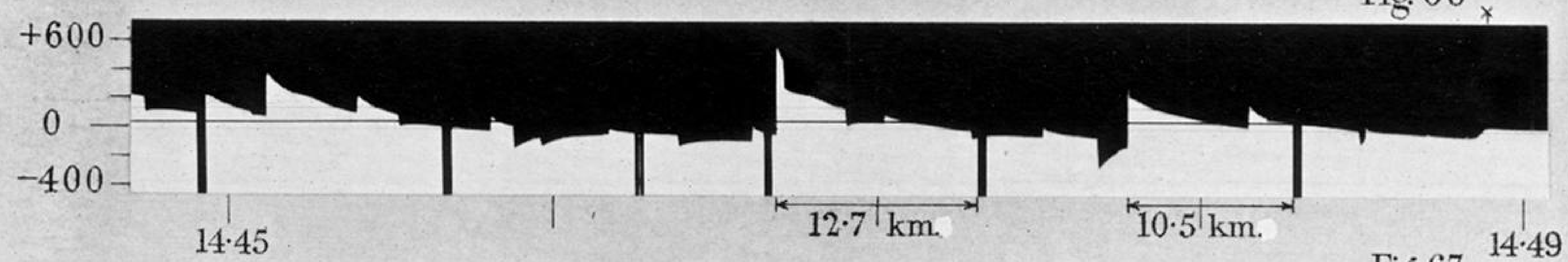


Fig. 67

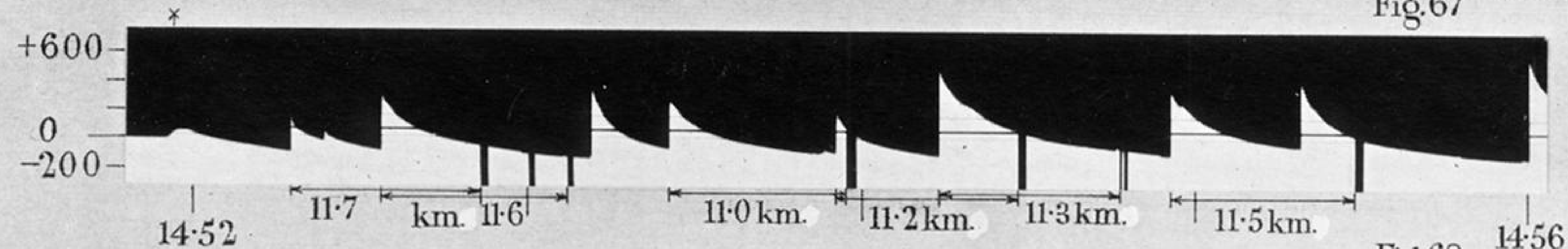


Fig. 68

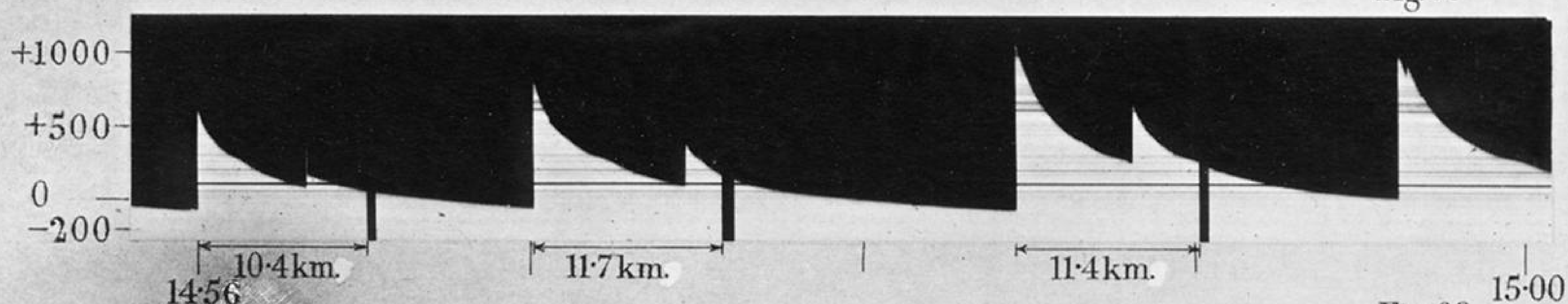


Fig. 69

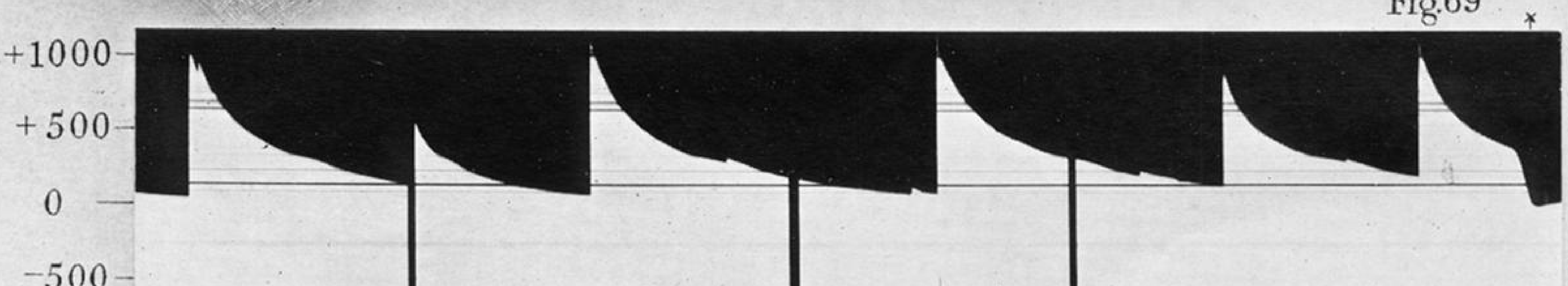
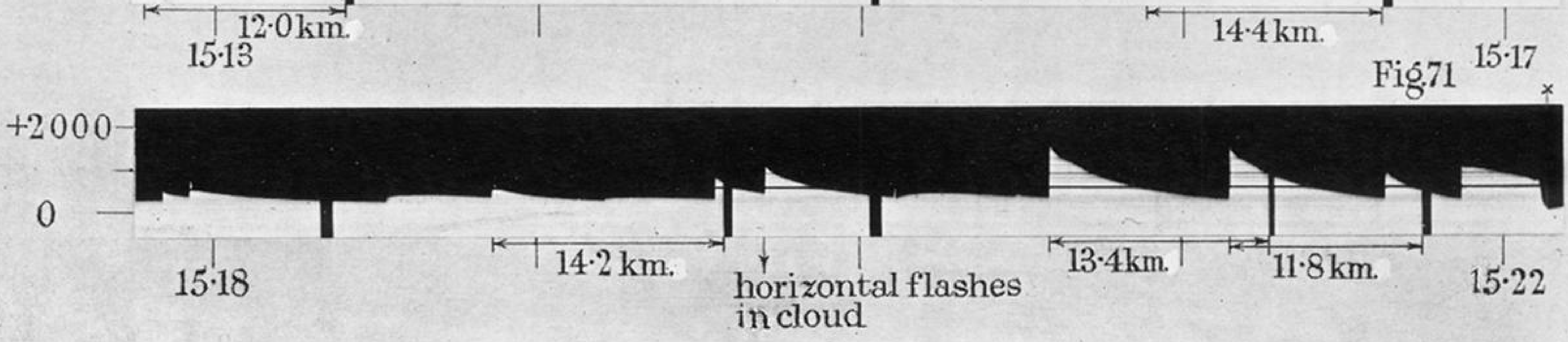


Fig 70

Fig. 71



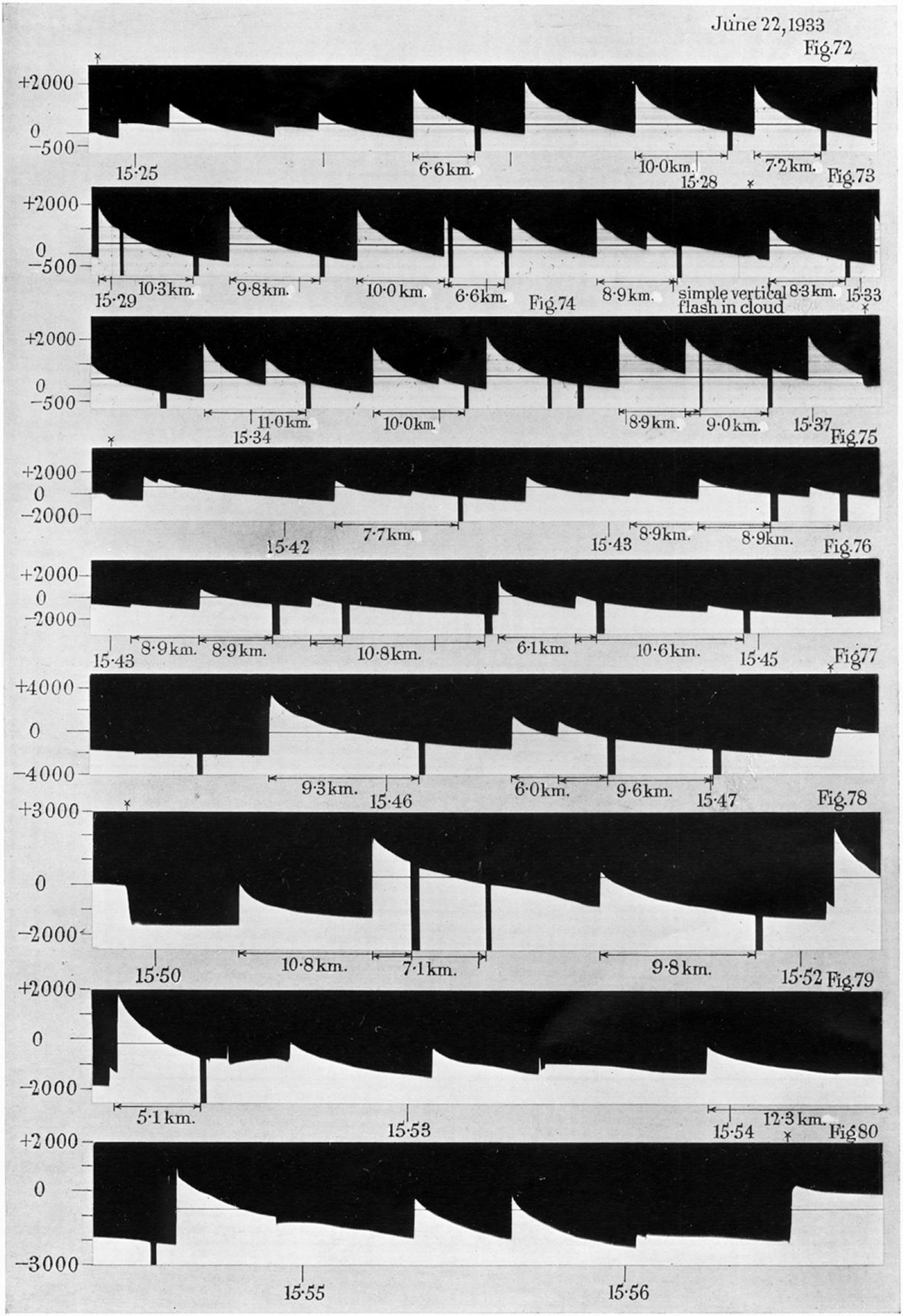

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Fig. 72
+2000
0
−500
15·25
6·6 km.
10·0 km.
7·2 km.
15·28
Fig. 73
+2000
0
−500
15·29
10·3 km.
9·8 km.
10·0 km.
6·6 km.
8·9 km.
simple vertical flash in cloud
8·3 km.
15·33
Fig. 74
+2000
0
−500
11·0 km.
10·0 km.
8·9 km.
9·0 km.
15·34
15·37
Fig. 75
+2000
0
−2000
7·7 km.
15·42
15·43
8·9 km.
8·9 km.
Fig. 76
+2000
0
−2000
15·43
8·9 km.
8·9 km.
10·8 km.
6·1 km.
10·6 km.
15·45
Fig. 77
+4000
0
−4000
9·3 km.
15·46
6·0 km.
9·6 km.
15·47
Fig. 78
+3000
0
−2000
15·50
10·8 km.
7·1 km.
9·8 km.
15·52
Fig. 79
+2000
0
−2000
5·1 km.
15·53
12·3 km.
15·54
Fig. 80
+2000
0
−3000
15·55
15·56

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Fig. 81

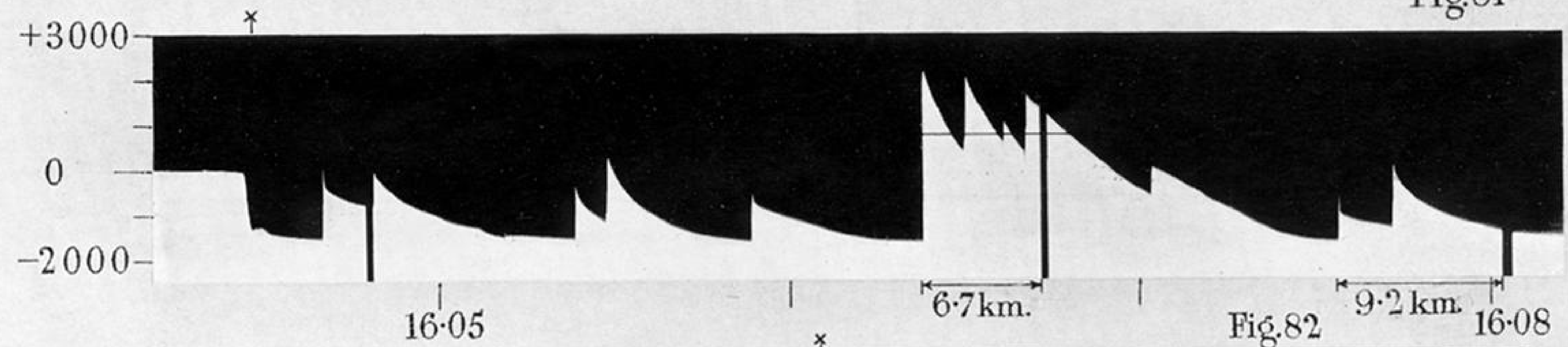

Fig. 82

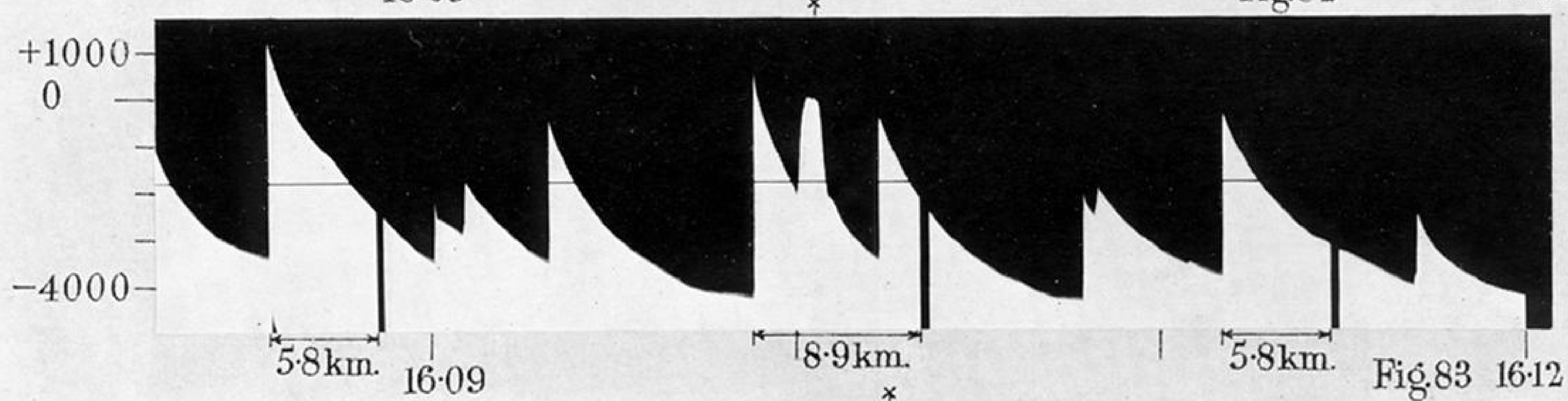

Fig. 83

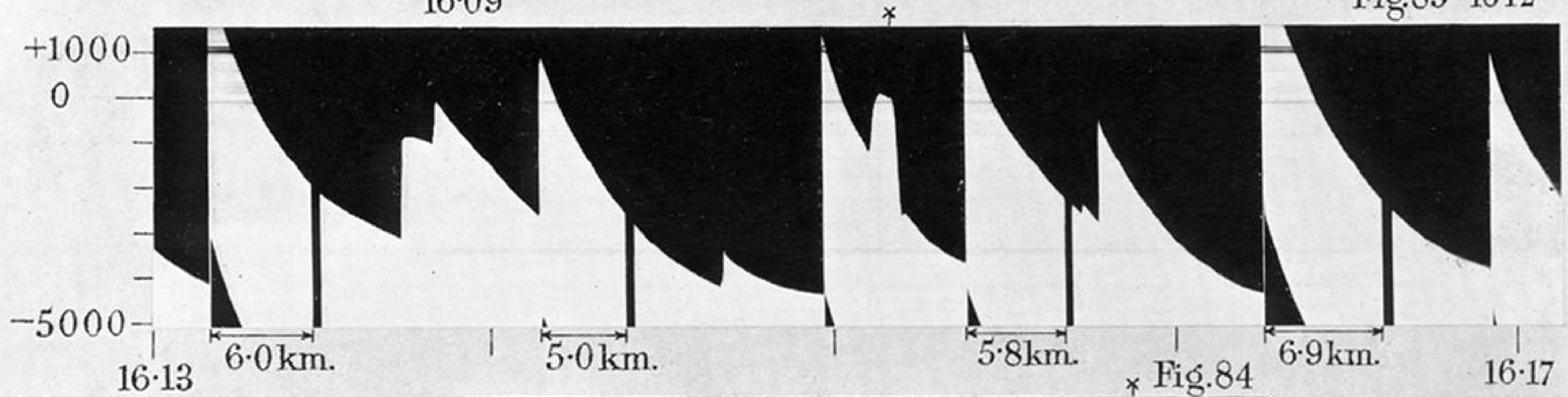

Fig. 84

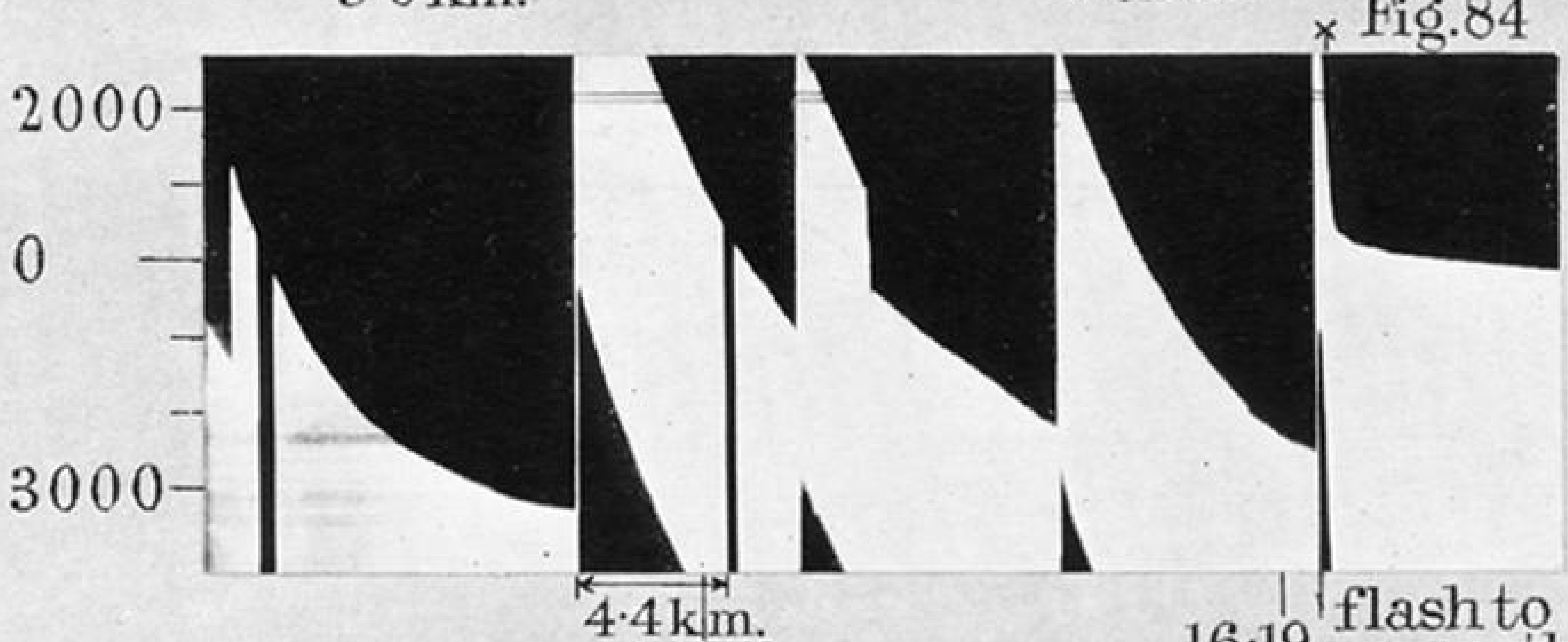

Fig. 85

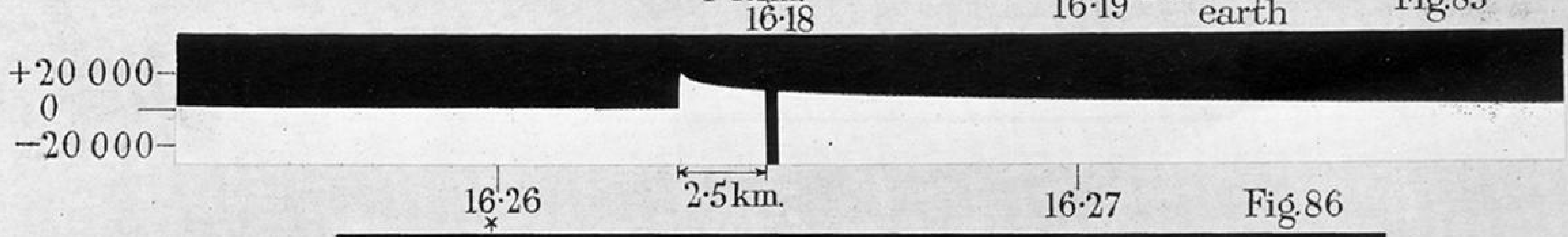

Fig. 86

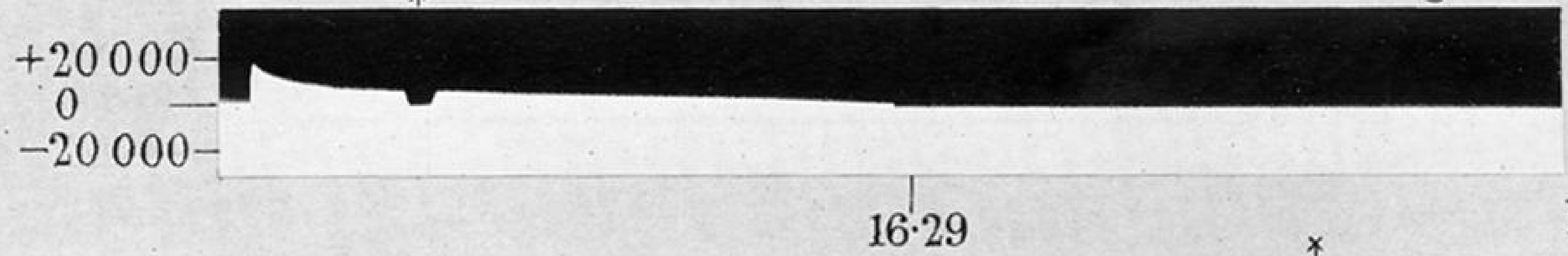

Fig. 87

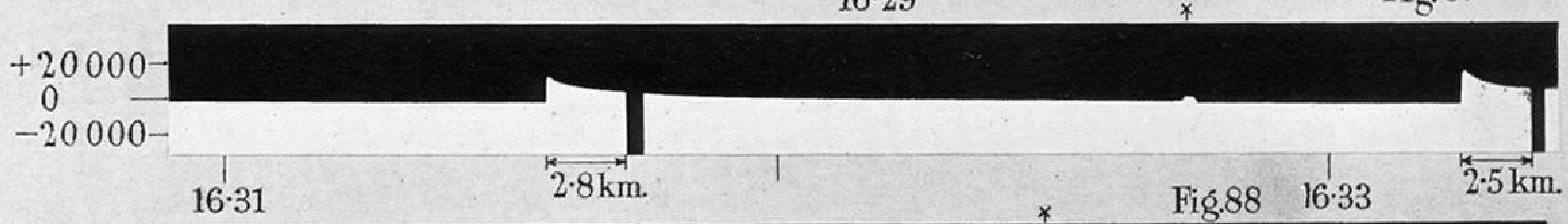

Fig. 88

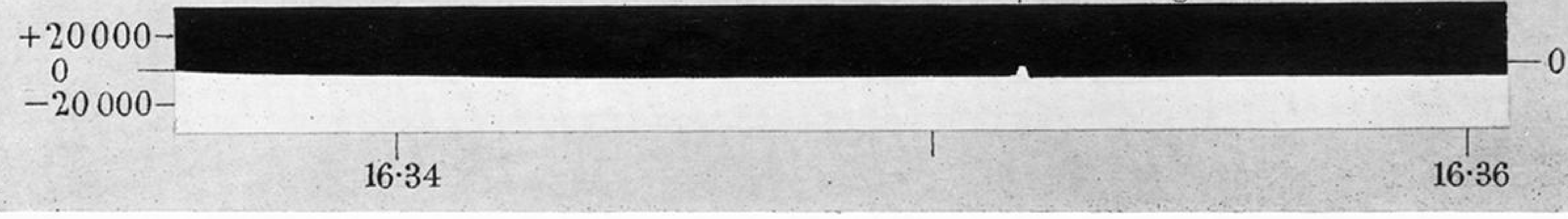

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Fig 89

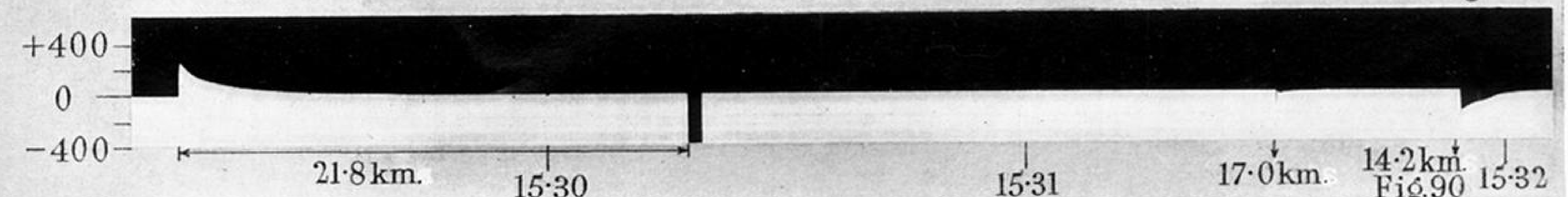

Fig. 90

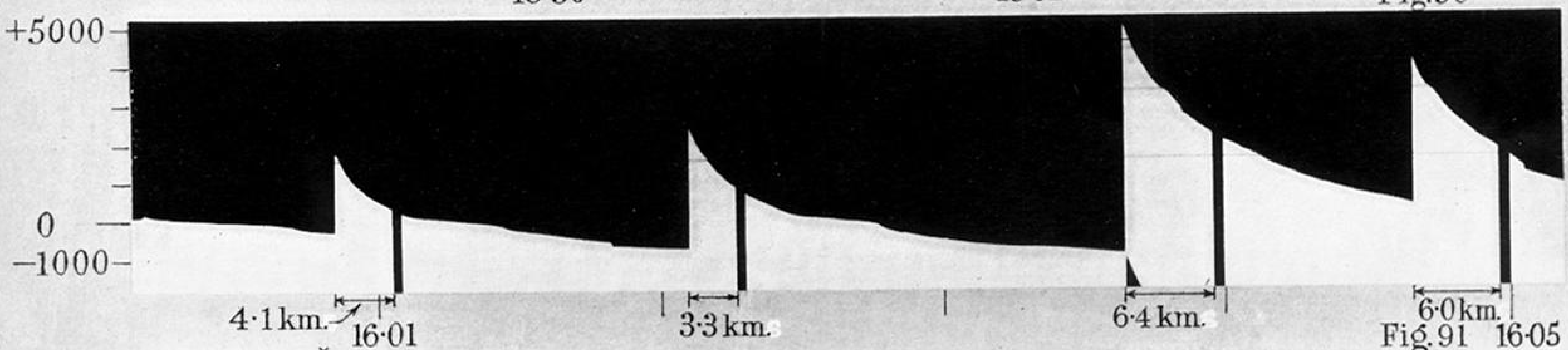

Fig. 91

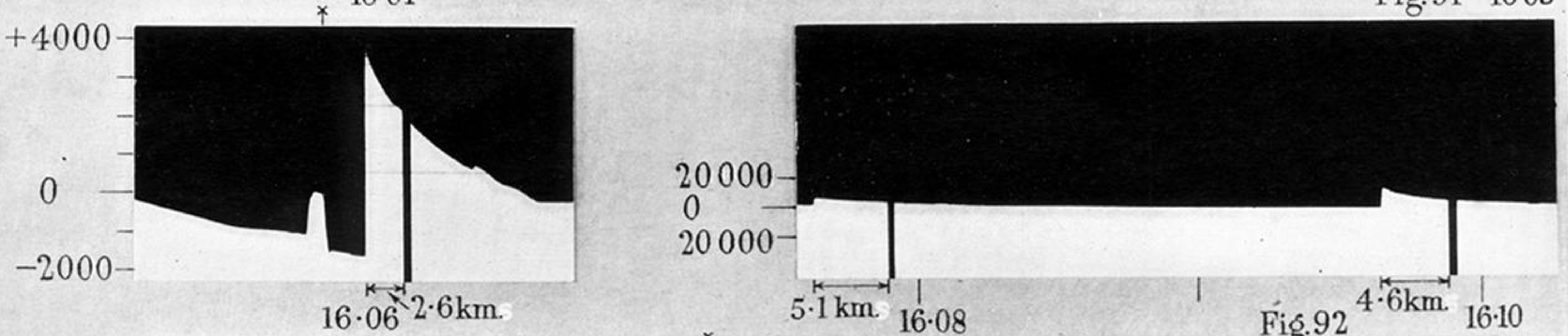

Fig. 92

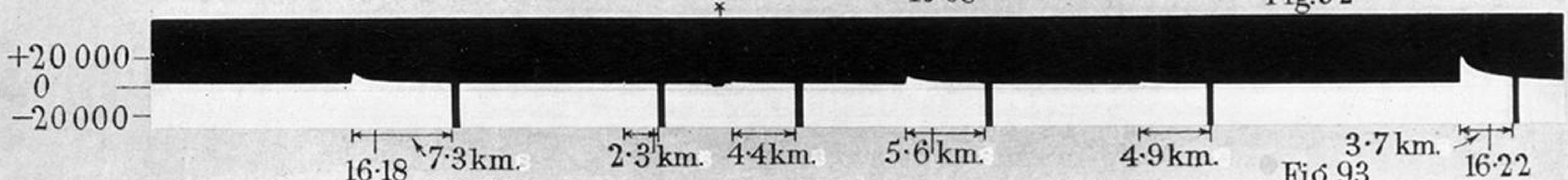

Fig. 93

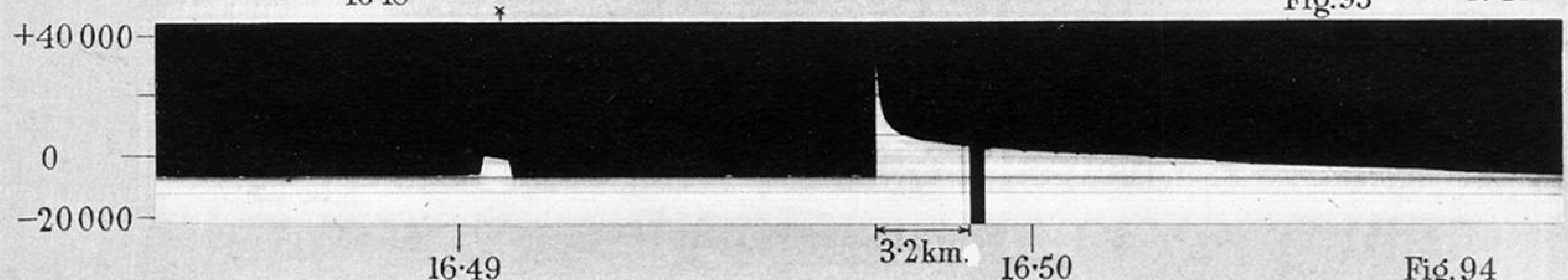

Fig. 94

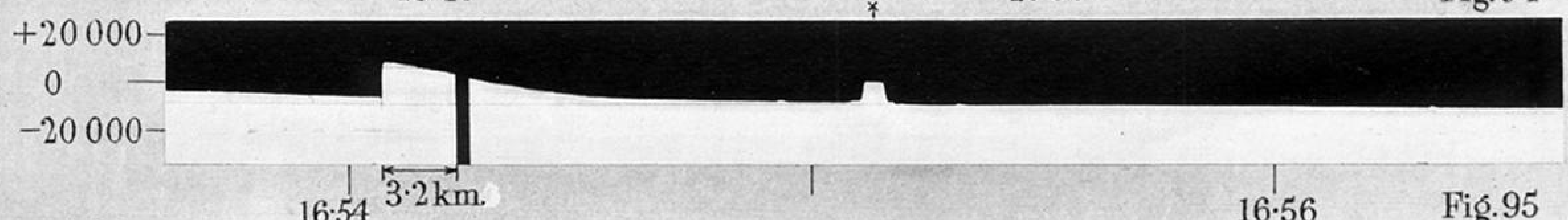

Fig. 95

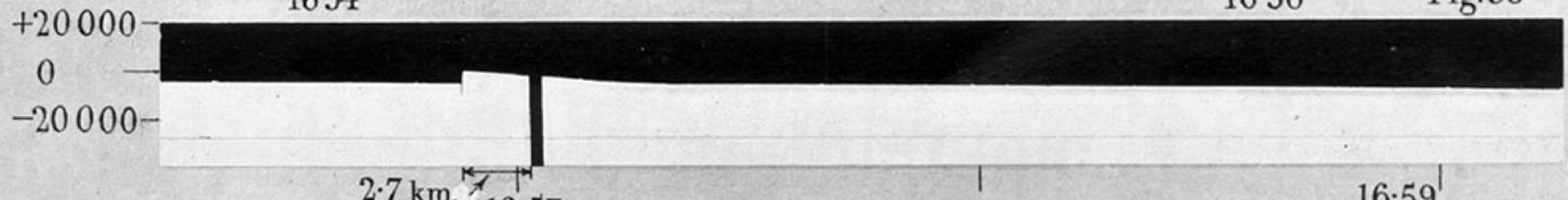

Fig. 96

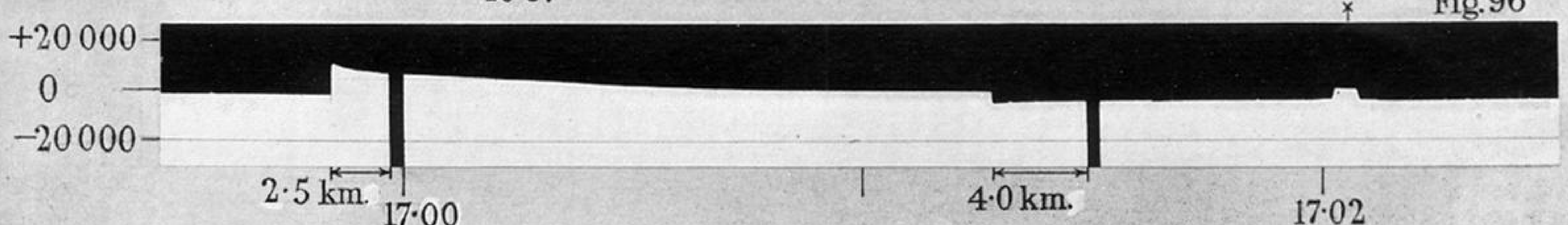

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Fig. 97

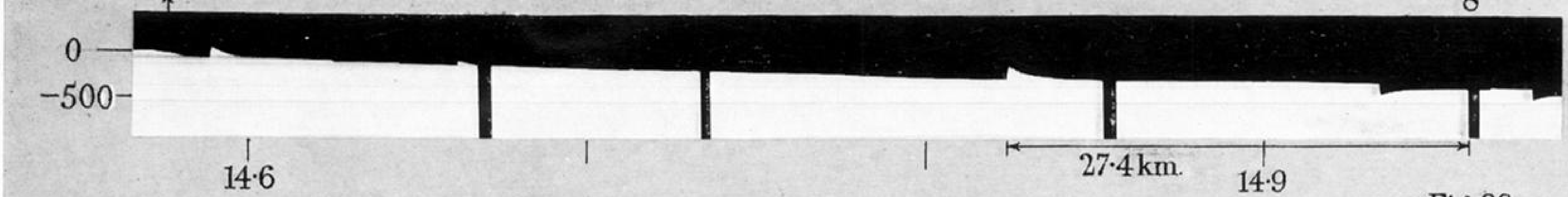


Fig. 98

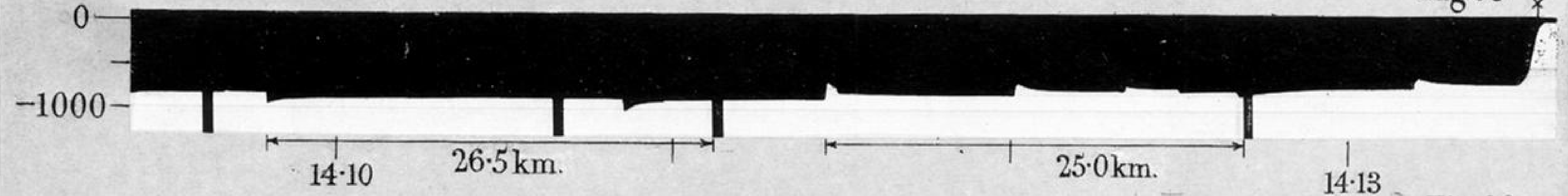


Fig. 99

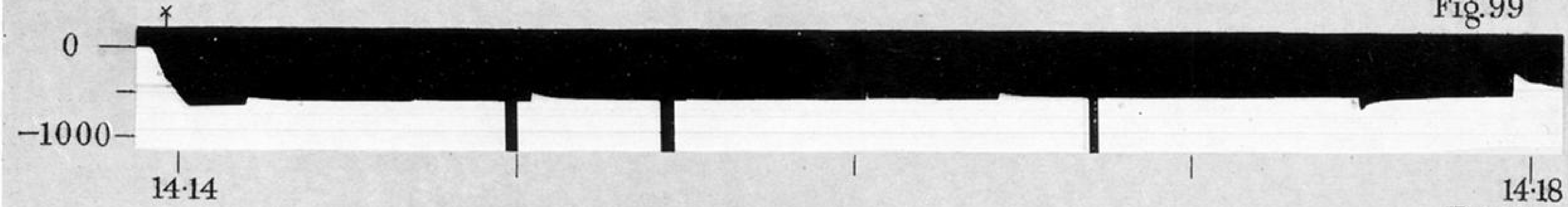


Fig. 100

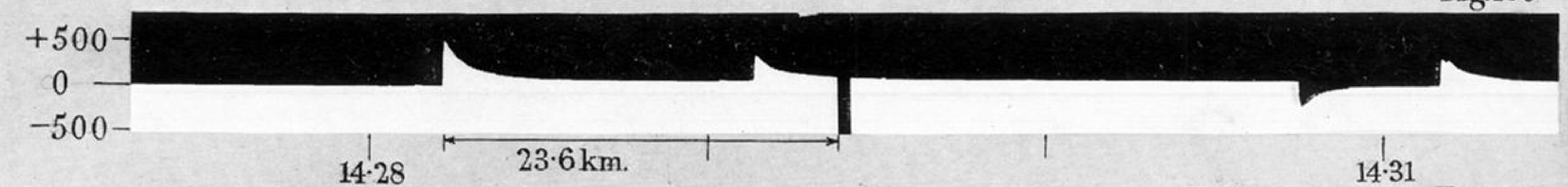


Fig. 101

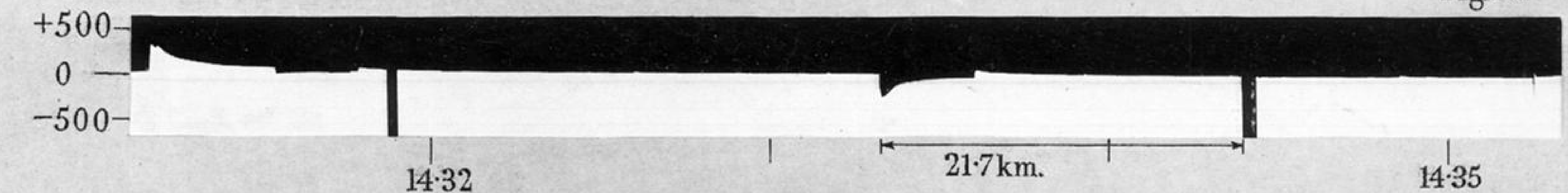


Fig. 102

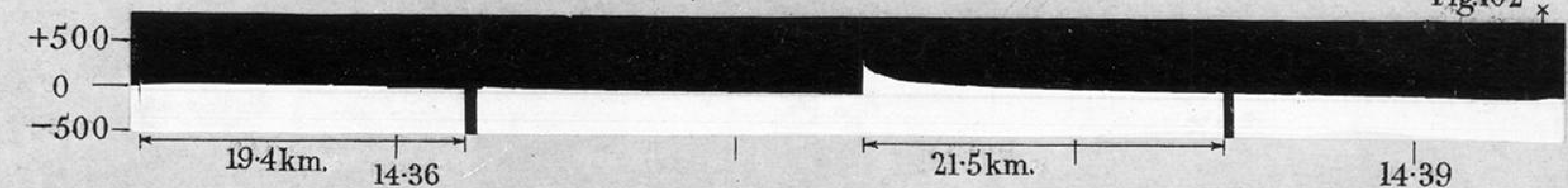


Fig. 103

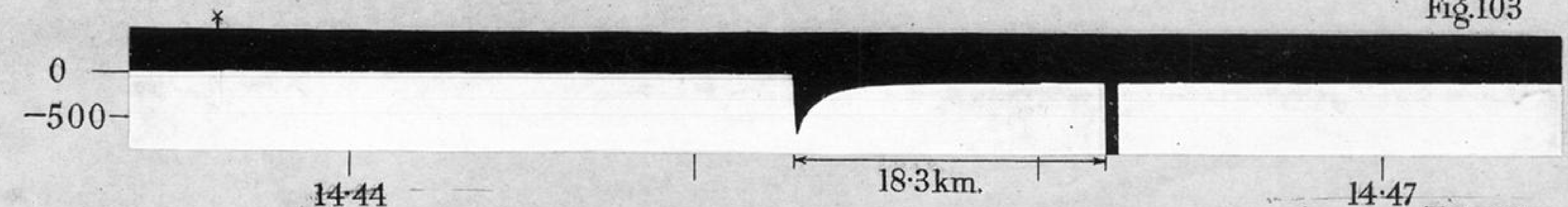


Fig. 104

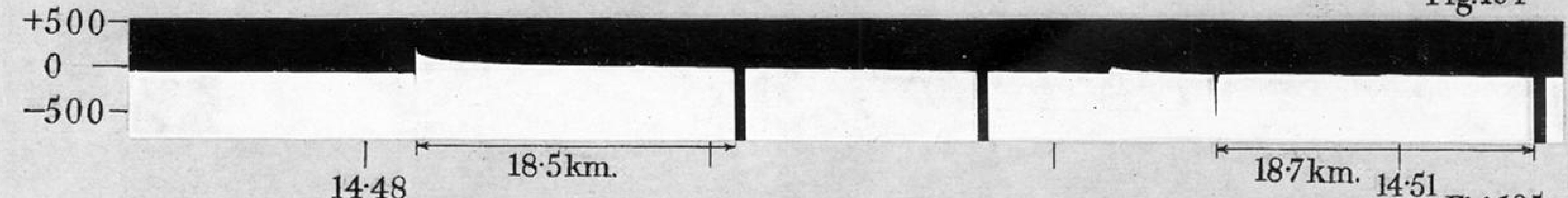
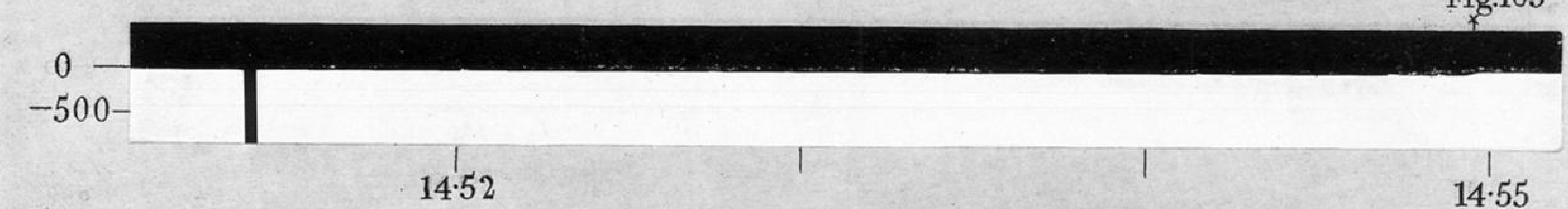


Fig. 105



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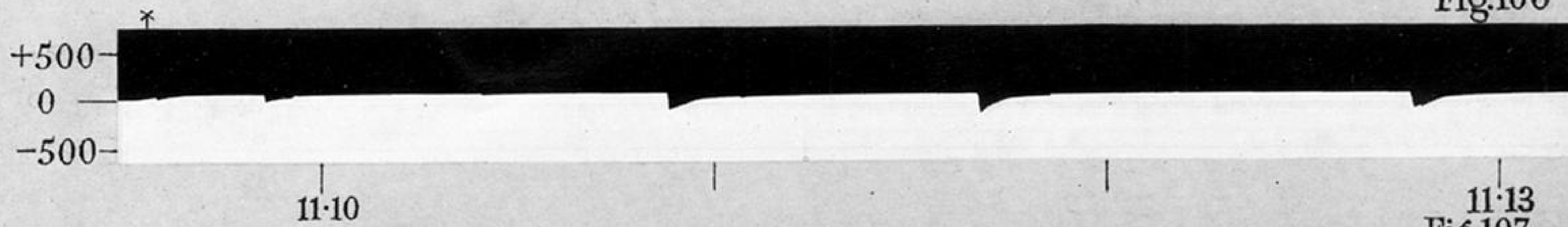

Fig. 106

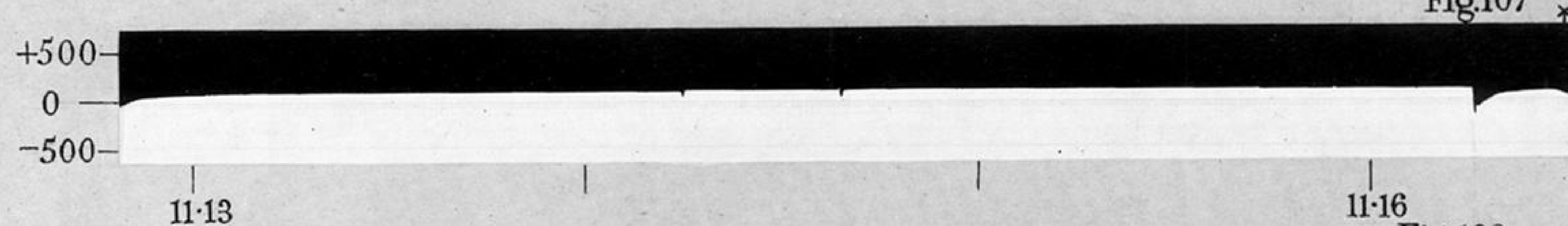

Fig. 107

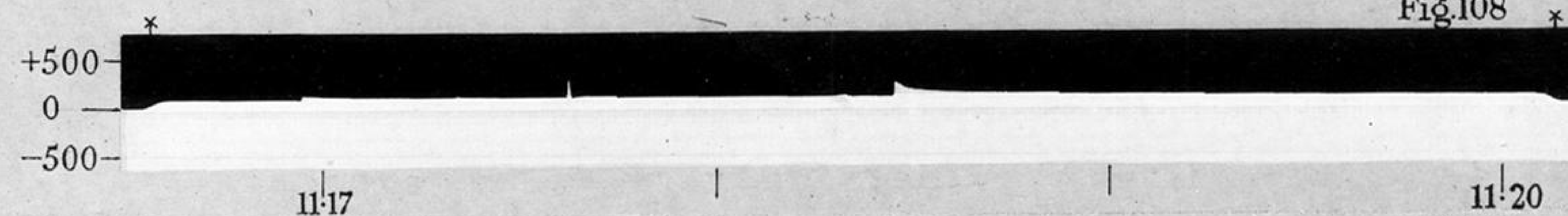

Fig. 108

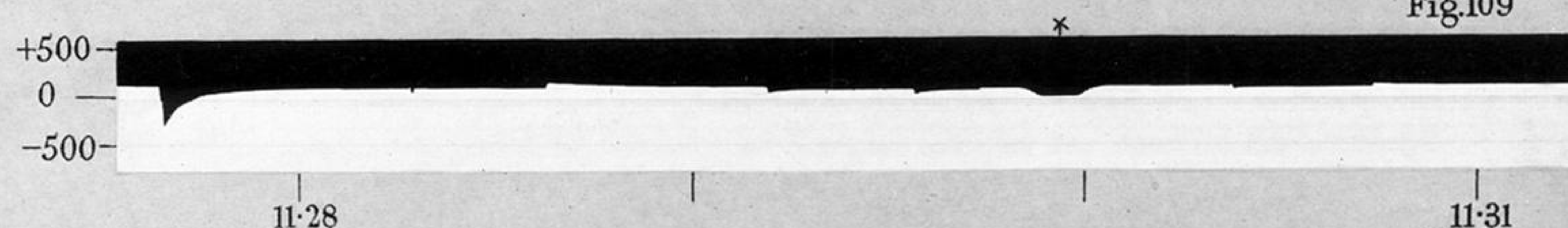

Fig. 109

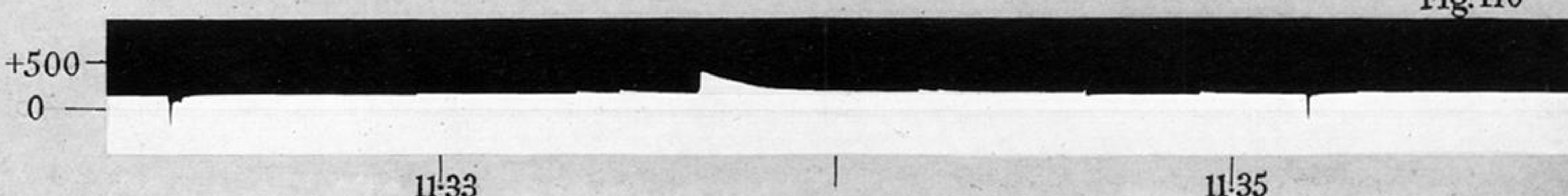

Fig. 110

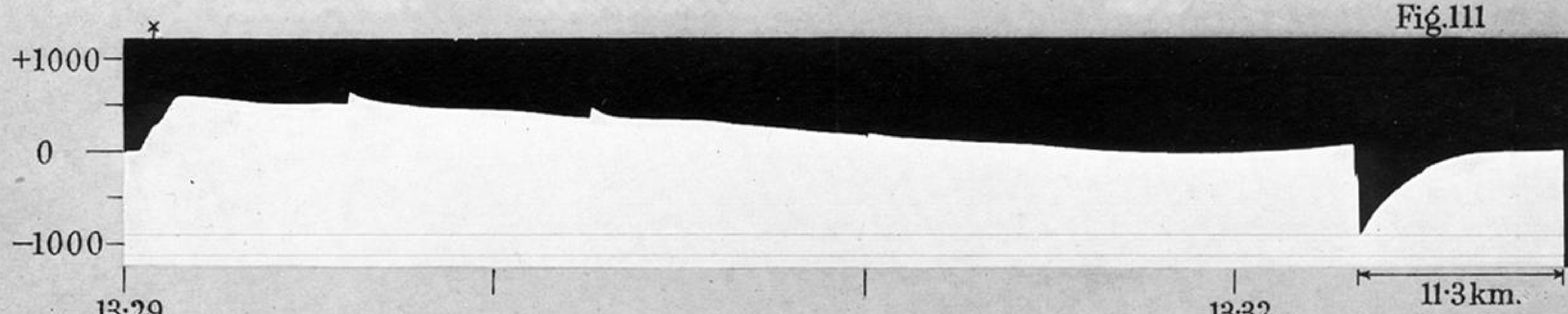

Fig. 111

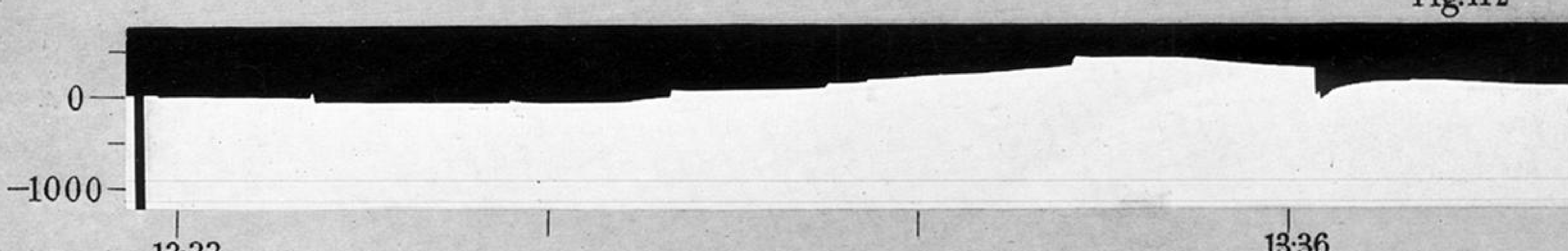

Fig. 112

Fig. 113

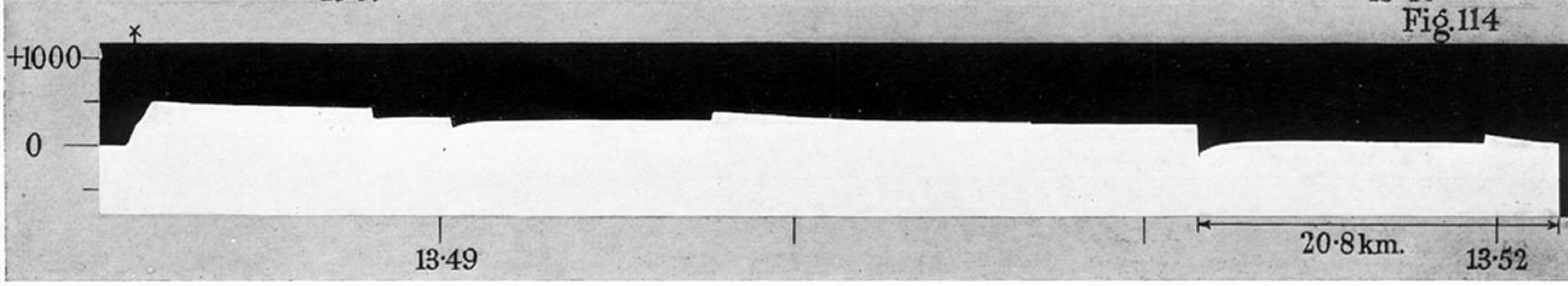

Fig. 114

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Fig. 115

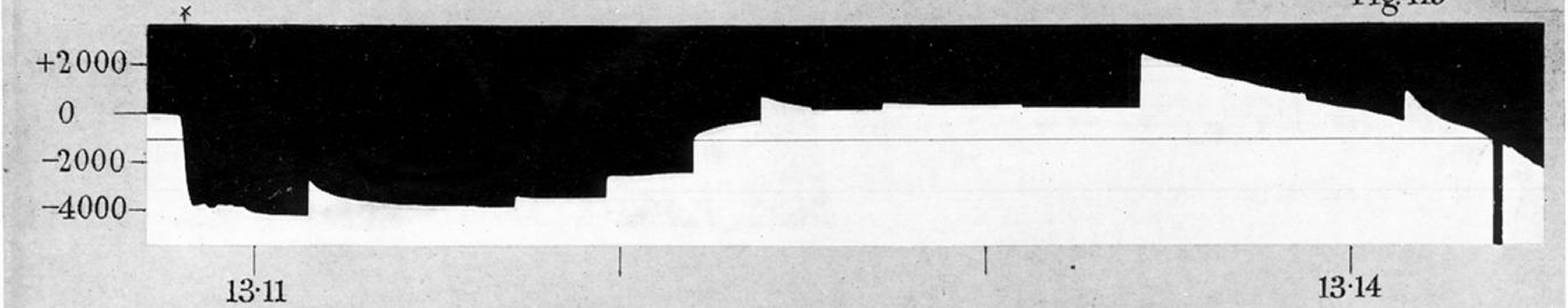


Fig. 116

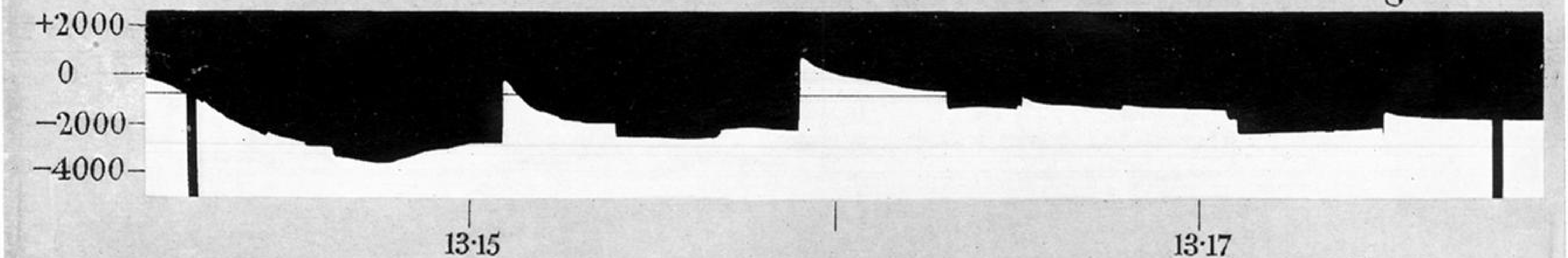


Fig. 117

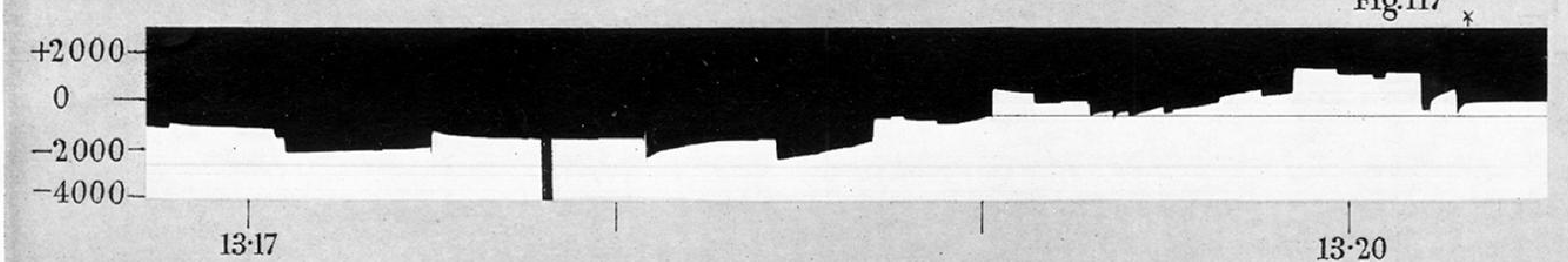


Fig. 118

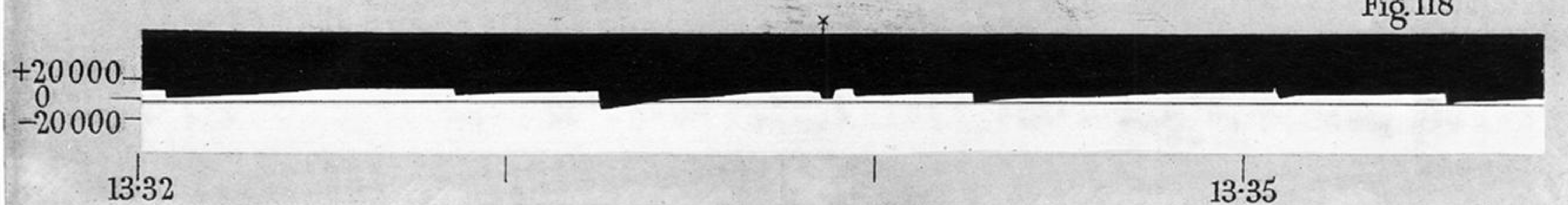
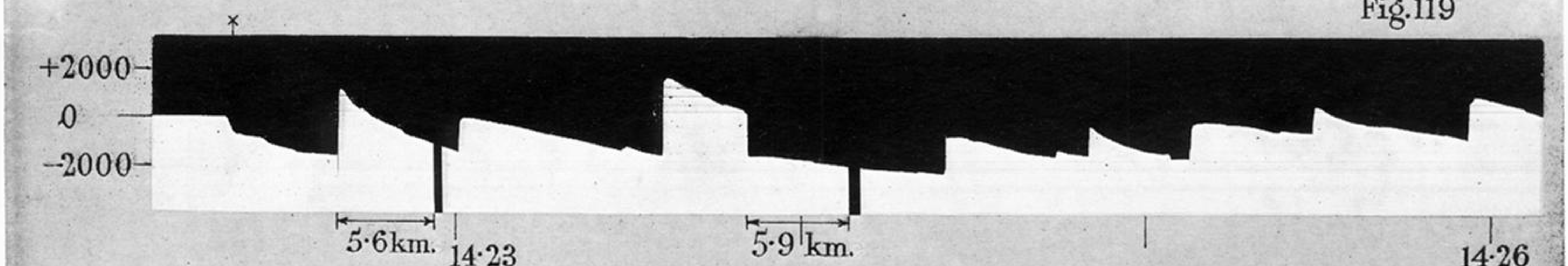


Fig. 119



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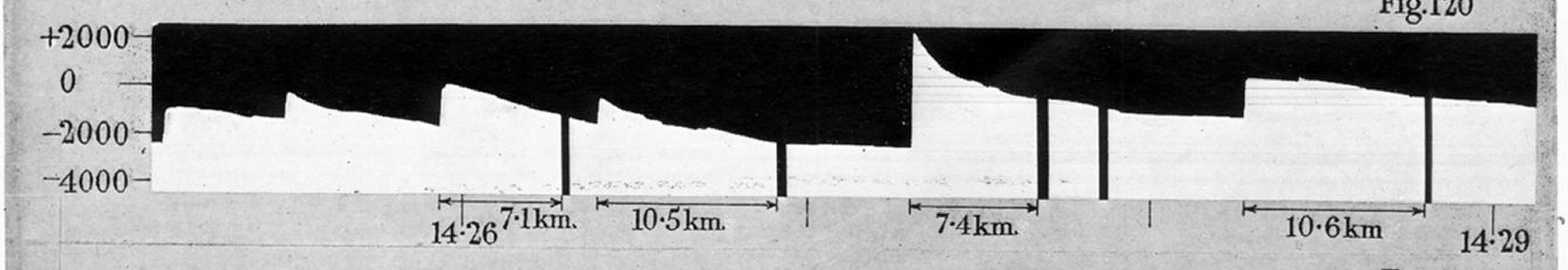

Fig. 121

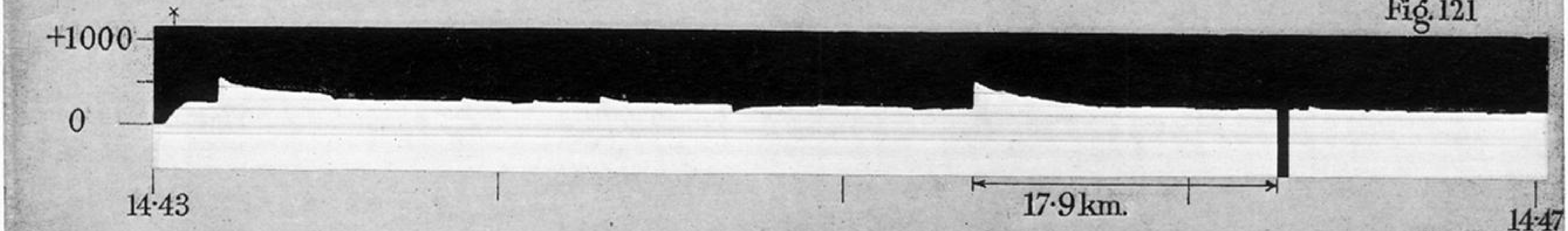

Fig. 122