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THESIS

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DOCTOR OF PHILOSOPHY.

BY

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SUBJECT.

THE APPLICATION OF THE CATHODE RAY OSCILLOGRAPH TO THE DETERMINATION OF THE DIRECTION OF ARRIVAL AND THE WAVE FORM OF ATMOSPHERICS.

SUMMARY.

The thesis which follows is divided into two sections, each of which deals with a separate problem.

The first section is concerned with an account of the construction of a Cathode Ray Oscillograph Direction Finder on the lines developed by the Radio Research Station at Slough, and its application at Capetown to the determination of the direction of arrival of atmospherics over a period towards the end of 1935. The results of this investigation show that 89% of the thunderstorms reported by the meteorological report network were correctly located in bearing, while 53% of the bearings recorded by the instrument as coming from regions covered by the meteorological network were definately associated with thunderstorms. Bearings were obtained from sources over the Atlantic and Indian oceans, and their sources shown to be related to ocean depressions. It is pointed out that the investigation was of a preliminary nature, and that, in the near future, it is proposed to carry the investigation further by the establishment of two stations, at which cross bearings on such sources will be obtained.

The second section is concerned with the application of the Cathode Ray Oscillograph to the investigation of the changes in the electrical field which occur in the neighbourhood of a lightning flash, and the correlation of the oscillograph records of such changes with Boys' camera photographs of a near lightning flash.

An account is first given of the work of previous investigators in this field, and it is shown that the problems associated with a thunderstorm resolve themselves into three classes, which deal with (a) the generation of the cloud charge (b) the mechanism of a lightning flash (c) the

investigation of the field changes due to the flash at a distance from the source. The methods employed and the results obtained by previous investigators are discussed, particularly the methods in which use has been made of the Cathode Ray Oscillograph, and the results of the analysis of the Boys' camera photographs by Schonland, Malan and Collens.

The present investigation had a two-fold object. In the first place it was intended to obtain oscillograph records of the field changes due to a lightning flash in the proximity of the flash, to carry out an analysis of these records, and to compare and correlate the results with those from the analysis of the Boys' camera photographs. In the second place it was hoped to obtain a direct correlation of the two types of record by obtaining a Boys' camera record and an oscillograph record from the same flash.

The oscillograph unit was constructed along lines suggested by the staff of the Radio Research Station, Slough, and was similar to that employed by Appleton, Watson Watt and Herd for the delineation of the wave form of atmospherics with certain modifications. The whole outfit was mounted in a motor lorry, and the field work was carried out during the summer thunderstorm season of 1935-1936 at the Witwatersrand. Details are given of the apparatus and layout, and also of the methods employed in the field when the unit was in operation.

SUMMARY OF RESULTS OF INVESTIGATION.

In the present investigation the main consideration has been given to the records from ground flashes, since the Boys' camera records deal mainly with these. The photographs have shown that a ground flash is composite, consisting of one or more separate strokes, separated by variable time result in the appearance of radiation ripple on the record of the leader process. The results of the measurements of the frequency of the leader ripple found on the records are tabulated, and these measurements are shown to be in satisfactory agreement with the time intervals associated with the leader steps.

The magnitudes of the field changes to be expected from a lightning flash are considered theoretically, and the bearing of any tortuosity in the leader channel on the form of the oscillograph record discussed. It is shown that a reversal distance should exist, within which it may be expected that the oscillograph will register a reversed field change.

The magnitudes of the displacements on the oscillograph trace associated with each of the three stages of a lightning stroke are shown to be determined by the magnitude of the charge involved in each process. It is therefore possible, from the measurement of these displacements on the records, to obtain results indicating the relationship existing between these charges. The conclusions drawn from these results are that the first stage or leader process in a first stroke results in the lowering of the greater portion (about 70%) of the cloud charge involved in the complete stroke, and its distribution along the leader channel and branches in such a manner that the effective height of this charge is reduced to approximately one-half its former value. In the case of a subsequent stroke a smaller proportion of the total charge involved in the stroke is lowered by the leader process.

Results so far summarised have been derived from considerations of the main or normal type of oscillograph record appearing on the films. As mentioned previously, records of first strokes have been classified in various groups, and consideration is given certain types of record which differ from the normal. It is shown that these may be due, in certain cases, to flashes in which the first stroke has a leader velocity at a certain stage in its development very much below the average, and in other cases to the possible existence of air discharges.

The relationship which should exist between the distance of the flash from the oscillograph unit and the nature and magnitude of the resultant oscillograph record due to the flash is discussed. In the present investigation estimations of the distances involved were made by the observer during the course of the field work, but were naturally only approximate. The results of measurements from the records, and their relationship to the reported distances of the various flashes, are tabulated, and it is shown that the results appear to indicate abnormally low values for the field changes registered by the oscillograph for flashes near the unit.

A discussion follows of the radiation associated with subsequent strokes in a flash. It is shown that the records exhibit indications of changes occurring in the cloud immediately after a stroke has occurred, and the possible nature of these changes is discussed. It is shown that there is a progressively increasing time interval for these changes from stroke to stroke.

Certain other aspects of the results obtained from the examination of the oscillograph records are briefly discussed. It is shown that the films exhibit possible evidence of ionospheric reflection. In addition the general nature of the oscillograph records from distant flashes and from cloud flashes are indicated, although it is pointed out that these lie outside the scope of the present investigation.

In conclusion some account is given of a direct correlation between the oscillograph record and the Boys' camera photograph of the same flash.

INTRODUCTION.

The author has been, for a number of years, a member of the staff of the department of Physics of the Natal University College, and is stationed at Howard College, Durban. He obtained the degree of M.Sc. in Physics at the University of Capetown in 1926, and at that time became associated for the first time with the Director, Dr. B. F. J. Schonland, under whom the work, the subject of this thesis, has been undertaken. Subsequently the association was renewed, when the author was appointed a member of the Lightning Investigation Committee of the S. A. Institute of Electrical Engineers, of which Committee the Director is chairman.

As a member of this Committee the author had constructed, in the workshops of Howard College, a Boys' camera, of the same pattern as those used by the other members of the committee, and had attempted to collaborate with them in the Boys' camera photographic work. Being anxious to pursue this type of work further, he made arrangements to obtain leave of absence from his college duties to devote his whole time to this work for a definite period, and, at the commencement of 1935, was enrolled as a Ph. D. student at the University of Capetown.

At the time he entered the Physics Department at Capetown Dr. Schonland had just returned from an extended visit to Europe and the United States of America. During that visit he had had an opportunity of meeting and consulting most of the foremost workers in the field of Atmospheric Electricity. In particular he had spent a certain period with those at, and associated with, the Radio Research station at Slough. As a consequence of this visit, Dr. Schonland suggested that a fruitful line of investigation would be to employ the Cathode Ray Oscillograph in an examination of the nature of the changes occurring in the electrical field at any point, due to a lightning discharge, and, if it were possible, to correlate these changes with the photographic records of such discharges obtained by using the Boys' camera.

The investigation, as suggested, if carried out successfully promised to fulfil a twofold object. In the first place it would be both interesting and fruitful in itself, affording a promise of information which would both confirm and amplify the information already obtained from the Boys' camera work on the nature of a lightning discharge. In the second place it would provide a training in technique which, in the future, could be applied to a number of other problems. As a consequence of this investigation it was hoped that the author, on his return to Durban, would be trained and fitted to carry out further investigations in this and allied problems. This was important, as it was realised that, for many problems associated with the nature of atmospherics, the collaboration of two or more investigators working at different points was essential.

PRELIMINARY PERIOD

A preliminary period was spent in acquiring the necessary technique in the use of the oscillograph itself. Using as a guide the publication "The Cathode Ray Oscillograph in Radio Research" by Watson Watt, Herd and Bainbridge Bell, time was spent in constructing various types of time-base, and applying them to the oscillograph, on systems of time-base locking, and allied experiments with the instrument.

CATHODE RAY OSCILLOGRAPH DIRECTION FINDER.

As a first application, it was decided to apply, in South Africa, the methods developed by Watson Watt and his co-workers at the Radio Research Station at Slough for the determination of the direction of sources of Atmospherics, using the Cathode Ray Oscillograph Direction Finder. This was intended to be merely a preliminary investigation of the method, but it was hoped that it would serve a twofold purpose. In the first place, entailing as it did the construction and use of various stages of amplification and the matching of these stages both for gain and phase, it would provide very useful experience in this direction. Further, it would enable experimental work to be carried out in Capetown, where the almost total absence of thunder storms within audible or photographic distance made the main problem of investigation almost impossible. In the second place it was hoped that a preliminary investigation of this nature would indicate the advisability, or otherwise, of carrying out a fuller investigation at a later date. Should this preliminary work prove successful, it was intended, at a later date, to establish two stations at different points, which would then collaborate, and, by taking cross-bearings on some particular source, locate its exact position.

The necessary aerial coils, amplifiers and oscillator were constructed at the University of Capetown during the early portion of the year, and the apparatus was exhibited and demonstrated at the Annual Meeting of the S.A.Association for the Advancement of Science held at Paarl, Cape Province during July, 1935. A description of the apparatus was given in the form of a paper read before Section A of the Association.

(APPENDIX A)

Subsequently, the Direction Finder apparatus was assembled in a room on the top floor of the Physics block at the University of Capetown, and, during September and October 1935, a series of determinations was made with it of the bearings from Capetown of the chief sources of atmospherics. Readings were taken on different days, and at different periods of the day, and the results were plotted, and subsequently correlated with the positions of reported thunderstorms. These latter were obtained from the meteorological maps for the corresponding period of the investigation, which were kindly supplied by the Chief Meteorologists of the Union of South Africa and of Southern Rhodesia. A paper, embodying the results of this preliminary investigation, was read before the Royal Society of South Africa in October, 1935.

(APPENDIX B).

It is necessary to emphasize the preliminary nature of this investigation and report. It is fully realized that many aspects of the problem might, with profit, have received fuller and more careful consideration. It must be remembered however, that a limited period of time was available, and many details were either neglected or dealt with in as simple and short a manner as possible. This explains why no attempt was made to instal facilities to determinethe sense of the direction of arrival of the signals. Further it is realized that the method adopted for the determination of the input field strength could be greatly improved. Had this been intended as a complete investigation, these and certain other aspects would have received fuller consideration. However, with the approach of the thunderstorm season in the Transvaal, where it was intended to carry out the field work in the investigation of the field changes in the neighbourhood of a lightning stroke, it was essential to curtail the work with the Direction Finder, and to concentrate on the construction and testing of the apparatus necessary for this second undertaking.

The results of the investigation with the Cathode Ray Oscillograph Direction Finder clearly indicate that the method had succeeded in locating, with a satisfactory degree of accuracy, the bearings of thunderstorms as sources of atmospherics in Southern Africa. Moreover, the method seemed to provide a means for locating the positions of sources existing in localities inaccessible to the observers attached to the Meteorological Departments. In particular, its application to the detection and location of sources over the oceans bounding the sub-continent appeared to mark it as an important adjunct to the present methods employed in obtaining meteorological data for weather forecasting. Further, the rapidity of its working, and the elimination of delay in obtaining information by its use, indicated its value in the field of aviation.

As a result of this preliminary work with the Direction Finder, it is intended, in the near future, to establish two stations in South Africa, the one in Durban, the other in Johannesburg, at which Cathode Ray Oscillograph Direction Finders will be erected. The station at Durban will be erected at Howard College, and that at Johannesburg at the Bernard Price Institute of Geophysics. Certain of the necessary pieces of apparatus for this purpose have already been constructed, and at these stations it is intended to employ such improvements as Adcock aerials, sense direction finders and photographic recording of results. From these two stations it will be possible, by synchronisation of the readings, to obtain cross bearings on any particular source, and thus determine its exact location. When established and fully equipped, these two stations should make it possible to carry out a full investigation of the whole problem of the possibilities and limitations of the Cathode Ray

Oscillograph Direction Finder. Moreover, these stations will also provide a means for investigating the nature of the field changes at a point due to a distant lightning flash, and its attendant problems. If the position of the source be located with a certain degree of accuracy by the Direction Finder, the nature of the field changes can be correlated with the distance away of the flash, and any factors depending on this distance investigated.

PART II.

THE USE OF THE CATHODE RAY OSCILLOGRAPH IN THE INVESTIGATION OF THE ELECTRICAL FIELD IN THE NEIGHBOURHOOD OF A LIGHTNING FLASH.

REVIEW OF PREVIOUS WORK.

Before dealing with the methods employed and the results obtained in the investigations forming the subject of this section of the thesis, it is advisable briefly to review the methods and results of previous workers in this field.

The first important step towards the solution of the problem of the nature of lightning was made about the middle of the 18th century. This was the establishment of the close relationship which exists between a lightning flash and a spark discharge. It was Benjamin Franklin who first conceived the idea of a "lightning rod", and, in the hands of Dalibard, the first electrical sparks were obtained from such a rod in 1752. Later, with his well known kite experiment, Franklin was able to establish conclusively the electrical nature of lightning. It is interesting to note in passing that Franklin, as the result of a number of experiments, stated "that the clouds of thunder-gust are most commonly in a negative state of electricity, but sometimes in a positive state", and" for the most part, in thunderstrokes, it is the earth that strikes into the clouds, and not the clouds that strike into the earth".

From that time the whole subject of atmospheric electricity has attracted a number of different investigators, under whose labours the sum total of our knowledge of the subject has gradually advanced. It is unnecessary to trace in detail all this work. As may be expected, it has developed along different lines, investigations being carried out which deal with different aspects of the subject. They may in general be divided into three classes, as far as the lightning flash is concerned, although, as may be expected, they are not independent of each other.

One class deals with the explanation of the mechanism of the generation of the electrical charge in the cloud. The second deals with the mechanism of the lightning flash itself, the process in which occurs the rapid discharge or dissipation of the charge on the cloud. The third class deals with the changes which occur in the electrical field at points away from the cloud due both to the accumulation of charge on the cloud and to its discharge by the lightning flash. Although the present thesis in concerned with the last of these aspects, it is necessary to include in this review the other two, since one cannot be divorced from the others.

THE GENERATION OF THE CHARGE ON A THUNDERCLOUD.

More than one theory has been advanced to explain the generation of a charge on a thundercloud. Bearing in mind the necessity for some source of energy to exist in order to generate these charges, it may be noted that all the theories agree in ascribing this source to the Kinetic energy possessed by the air and other particles within and composing the cloud. It is in the explanation of the manner in which the movement of these particles brings about the charged nature of the thundercloud that the various theories differ.

Two facts about the atmosphere, even in fine weather, are well known. In the first place there exist charged particles or ions, both positive and negative, of varying size and mobility. These may be free electrons, or a gas molecule from which an electron has been ejected, or a dust or water particle to which one of these has become attached. In the second place there exists a vertical potential gradient in the atmosphere above the earth, such that the earth is negative with respect to the atmosphere above.

The particles composing a cloud vary considerably in magnitude, from the free electron to the largest drop or hailstone. Within the cloud there is in general a movement of particles in opposite directions, the smaller moving upwards to the top of the cloud, and the larger drops falling under the gravitational force with different velocities depending on their magnitudes. It is agreed that these particles acquire charges, and their movements in opposite directionscause a separation of charges of opposite sign, so that the cloud acquires the charges of opposite sign on the top and at the bottom, giving to it a dipole nature.

Various processes may be responsible for the charged condition of the moving particles. As has been mentioned, previously, there is always in existence ions of varying mobilities. These ions may act as neuclei for the condensation of vapour to form drops, which would then be charged. Again there may occur the selective capture of such ions by drops after their formation. Further, it has been shown experimentally that water drops, on collision, tend to become positively charged, and consequently give to the atmosphere around them a corresponding negative charge.

The particles, whatever their nature, composing the cloud have thus different ways in which they may acquire charges.

Two important theories have been advanced to explain the separation of the charges of opposite signs to the different parts of the thunderstorm cloud, giving to it its dipole nature. The one theory is due to G.C.Simpson, the other to C.T.R.Wilson. These theories both explain the separation of the charges of opposite sign, but the mechanism in the two theories is entirely different, and in certain important respects they lead to opposite conclusions.

The explanation advanced by Simpson is that, in the cloud, the wind enters the cloud from below, and passes upward into the cloud, with decreasing velocity. On the other hand rain drops fall, growing in size as they fall, from the upper portions of the cloud. He found that, in an ascending stream of air, there is a critical velocity (8 metres / second) through which drops cannot fall. Hence when the drops reach the point in the cloud where the wind velocity and turbulence is such that they cannot pass through that region, they become unstable and break up, the smaller drops being positively charged and the rising air acquiring a corresponding negative charge. In this way the lower portion of the cloud acquires a positive charge, and the upper portion a corresponding negative charge.

The explanation advanced by Wilson, on the other hand, is based on the behaviour of a drop falling in an electrical field such as is known to exist in the atmosphere. The rate of fall of the drop will depend on its size, and he suggests that the large drops will acquire a negative charge, while the minute droplets will have a positive charge. If a drop be considered falling through the normal potential gradient of the atmosphere, it will acquire a dipole structure due to this field, such that the lower front of the drop will be the positive pole. The lower portion will thus attract to itself any negative ions it may meet, and repel positive ions. Since the ions present in the cloud will be "large ions" of slow mobility, the velocity of the drops will be such as to preclude the upper or negative pole of the drop from attracting to itself the positive ions, and the drops falling to the lower portion of the cloud will acquire a net negative charge. In this way the lower portion of the cloud acquires a negative charge, and the upper portion a corresponding positive charge.

These two theories, both of which provide an explanation of the generation of the charge on the thundercloud, have this one important difference. The process suggested by Simpson leads to a cloud of negative polarity, the negative pole being on the upper portion of the cloud, while the process suggested by Wilson leads to a cloud of positive polarity. As will be seen later, clouds of both positive and negative polarity have been observed, so that it is probable that both types of process play a part in the generation of the cloud charge.

THE MECHANISM OF A LIGHTNING FLASH.

It has already been mentioned that Franklin established the close relationship between the electric spark and the lightning flash. It is well known that, before a spark can be made to pass between the poles of an induction coil, a critical potential (30,000 volts / centimetre at ordinary atmospheric pressure) is necessary. Hence for a lightning stroke to pass between cloud and ground, or any two points in the atmosphere, the potential must reach some critical value. This value will depend on the conditions existing at the time, but it is estimated to be at least 10,000 volts per centimetre under the most favourable conditions. Thus the process for the generation of the charge in the cloud

must proceed

must proceed until such a critical value is reached.

If the cloud be of negative polarity, as suggested by Simpson, the development of the flash would proceed along the following lines. The atmosphere between cloud and ground is known to contain electrons, and, the lower portion of the cloud being positively charged, it would attract these electrons. Under the high field they would advance with a velocity sufficient to ionise by collision, and thus form an electron avalanche. The slower moving positive ions would be left behind, and would thus form a projecting tongue or extension of the cloud towards the earth. This would in turn cause a further electron avalanche, and thus the tongue would extend further and further towards the earth. As the process necessitates secondary collisions, it would explain the high temperatures developed in the channel.

If the cloud be of positive polarity, as suggested by Wilson, the lower portion of the cloud would be negatively charged. When the critical potential was reached, electrons would proceed from the cloud, ionising a conducting path from cloud to earth.

The results of observations on the branching of electric sparks between the terminals of an induction coil seemed to lend support to the theory of the negative polarity of thunderclouds. It is an observed fact that, in such an electric spark, branching always takes place away from the positive pole, and, since lightning is always observed to branch downwards towards the earth and away from the lower portion of the thundercloud, Simpson concluded that this fact constituted a strong piece of evidence in favour of his theory The experiments of Schonland and Allibone, however, have shown that, if the positive pole be such as to contain a number of points (a state well represented in the case of the earth) it is possible to obtain branching in an electric spark <u>towards</u> the positive pole.

The application of photographic methods to the problem of the mechanism of a lightning stroke has provided a large amount of additional information on the process of its development. The early work of Walter was carried out with a camera moving under the action of a falling weight, and he applied it both to the electric spark and to the lightning flash. Later a great deal of work has been done in South Africa by Schonland, Collens and Malan, using a Boys' camera. As a result of their work and that of Walter mentioned above, the picture of the photographically visible stages in the development of the discharge is practically complete.

Briefly, this work has shown that a lightning flash is multiple in nature, consisting of a varying number of separate strokes, separated by definite time intervals of varying magnitude. Before the first stroke of the flash a faintly luminous leader proceeds in a series of steps from cloud to earth, with a slight pause after each step. The function of this leader is to ionise a conducting path between cloud and ground, and it is in this stepped leader process that the branches originate. Immediately the path is completed, the main stroke discharge takes place. This is recorded on the photographs as an intense luminosity which develops from the ground upwards to the cloud and along the branches. The intensity in the main stroke is not constant, but falls off as the stroke develops upwards, the variation in intensity being associated with the branches. After the first stroke is completed there is a pause, and then follow the subsequent strokes at varying intervals. Each of these consists of a leader, differing from that of the first strokein that it is not stepped but continuous, and very much more rapid, called a dart leader, followed by an intense return stroke. These follow the path of the first stroke, but without the branching Should the interval between two strokes be sufficiently long for the conducting channel to cool, then the stepped leader process which preceeds the first stroke may again function over part or all of the path.

The photographic records obtained by the use of the Boys camera have provided quantitative results of the time intervals of the various stages in the process of a lightning flash, and frequent reference will be made to them later in the discussion of the results obtained in the investigation of the changes in the field in the neighbourhood of a lightning flash as recorded on the Cathode Ray Oscillograph.

FIELD CHANGES IN THE NEIGHBOURHOOD OF A THUNDERSTORM.

A method which may be used to determine the electrical field at any point, and the changes which may occur in that field, was initiated by C.T.R.Wilson in 1916, and applied by him to the investigation of the field changes in the neighbourhood of a thunderstorm. The method is of particular interest in being the starting point of the modern study of this problem. The method employs a conductor, initially at zero potential when shielded from the field at the point under consideration. On exposure to the field, it will acquire an induced charge due to the field, and its potential will alter, and a measurement of this change will provide a means of measuring the field. This may be done by readjusting the potential of the conductor to zero by a variation of the capacity of a compensating condenser in the electrometer circuit. By the use of a capillary electrometer of a special type, this compensation may be made automatic, and at the same time, relatively rapid, and the movements of the electrometer used to determine field changes. The method has been applied, first by Wilson and later by others, to the investigation of the rapid field changes occurring in the neighbourhood of a thunderstorm due to lightning flashes. By adopting a photographic method of recording the movements in the electrometer' permanent records of these changes have been obtained. The method was first applied to conditions in South Africa by Schonland and Craib, and later by Halliday, and, as a result of their work, certain important facts have been established

It has been clearly established that the very large majority of the storms investigated were from clouds of positive polarity, and further, the experimental data obtained in the investigations have provided quantitative results from which it is possible to determine the magnitude of certain of the electrical quantities involved in thunderstorms and lightning discharges.

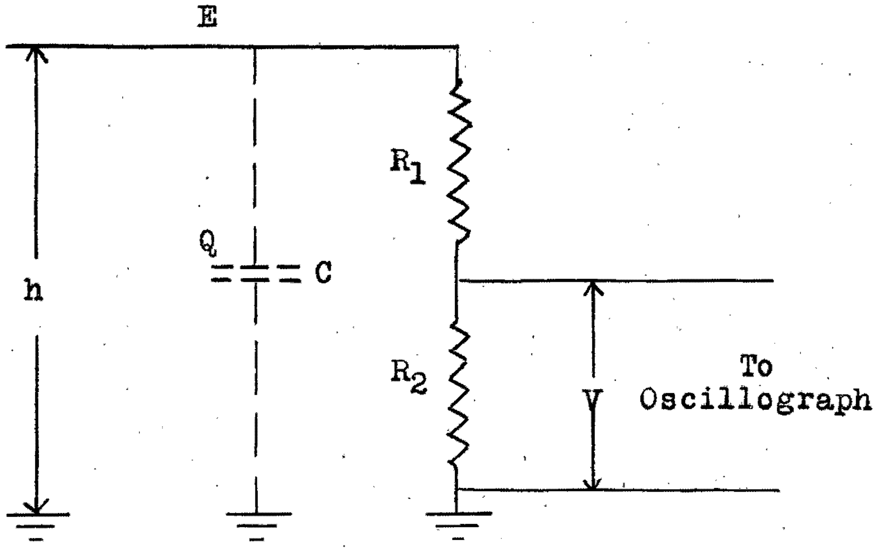
Various other methods have been employed to study the changes taking place in the field at any point due to a lightning discharge, all of which follow in principle the lines indicated above. They use an exposed conductor or aerial, which is connected, through some sensitive recording instrument, such as a string galvanometer or oscillograph, to earth. Field changes in the neighbourhood of the conductor or aerial induce charges on the conductor, and the instrument provides a means of recording the resulting currents in the system due to the field changes taking place in the space in which the conductor is situated. The value of records thus obtained depends, to a large extent, upon the properties of the recording instrument, and its method of response to the rapid changes in the electrical field. In this connection it may be observed that the capillary electrometer, used in the original investigations previously mentioned, had only sufficient sensitivity to record the total field change due to a complete lightning flash, and thus provided little information of the stages in the development of the flash itself. Thus the further methods, which have been developed later, have all been in a direction towards increasing the sensitivity of the recording instruments used, and particularly their rapidity of response to rapid changes in the field. For this reason the Cathode Ray

Oscillograph commends itself as an ideal recording instrument. Unlike other instruments with mechanical moving parts, the cathode ray, even in the gas-focussing, type of tube has a negligible inertia, and gives a rapid response to changes of potential of relatively high frequency on its working plates. In the gas-focussing type of tube the limit is set by the focussing positive ions, and is in the neighbourhood of 10^5 cycles per second. Since its inception, and application to this problem, a big advance has taken place in our knowledge of field changes, not only in the neighbourhood of a lightning flash, but at relatively large distances from it, in the investigation of the form of atmospherics. Thus the well-known work of Appleton, Watson-Watt and Herd on the nature of Atmospherics, and of H. Norinder on the nature of lightning discharges, uses as a recording instrument the Cathode Ray Oscillograph.

As an example of work in which mechanical recording instruments were employed, reference might be made to the work of H. Noto in Tokyo in 1929. This was intended as an investigation of "Electrical oscillations in the atmosphere". In this work an antenna was stretched above the laboratory, and then connected through a Dufeur oscillograph to earth. A spot of light, after reflection from the vibrator of the oscillograph, was arranged to fall on a cinematograph film driven at a constant cpeed, and thus a record was obtained of the field changes at the aerial. The period of the vibrator is given as 1/160th second.

A great deal of work on the nature of lightning discharges has been carried out by H.Norinder at the University of Uppsala using as a recording instrument a high velocity Cathode Ray Oscillograph of special design, the beam of which impinges directly on a photographic plate, and thus provides a permanent record of any fluctuations in the path of the beam. To avoid fogging, the beam is initially deflected in such a manner as to be screened from the plate, and the aerial impulse is used as a relay to trip the screening device, and permit the photographic recording device to function. To obtain a two-dimensional record of field changes, the usual device is employed, the aerial impulses being employed to activate one set of deflecting plates of the oscillograph, and a time base applied to the other set.

The manner in which the field changes in the neighbourhood of the aerial are related to the changes in potential at the oscillograph plate may be seen from the diagram of the circuit he employed.



C is the effective capacity of the system.

h is the effective height of the aerial

E is the potential gradient in volts / metre.

R_1 is the damping resistance.

R_2 is the resistanceacross which voltage changes are measured.

Q is the charge induced on the aerial system.

If i be the current through R_1 and R_2,

$$h.E + Q/C = i(R_1 + R_2).$$

or

$$E = \frac{1}{h}\left[-\frac{Q}{C} + i(R_1 + R_2)\right].$$

Now $i = -\frac{dQ}{dt}$ and $i = \frac{V}{R_2}$, so that $di/dt = \frac{1}{R_2}\cdot\frac{dV}{dt}$.

Therefore

$$\frac{dE}{dt} = \frac{1}{h}\left[-\frac{1}{C}\cdot\frac{dQ}{dt} + (R_1 + R_2)\frac{di}{dt}\right].$$

$$= \frac{1}{h}\left[\frac{V}{C.R_2} + \frac{R_1 + R_2}{R_2}\cdot\frac{dV}{dt}\right].$$

$$= \frac{R_1 + R_2}{h.R_2}\left[\frac{dV}{dt} + \frac{1}{(R_1 + R_2)C}\cdot V\right].$$

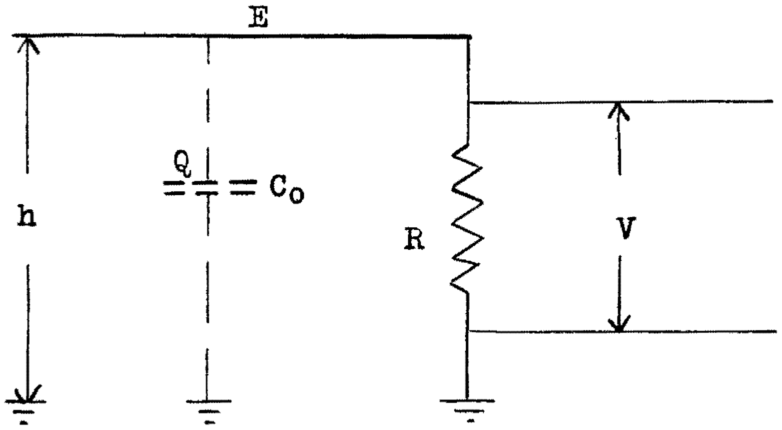
One disadvantage of this method is that, as may be seen from the above analysis, the record obtained on the photographic plate is one which shows the variation of dE/dt with time, and it is thus necessary to integrate if it be desired to know the variation of the actual field (E) with time. Further, as has already been pointed out, the Boys' camera results indicate that a lightning flash is a complex phenomenon, lasting a relatively long interval of time. With the limitations of the size of the plate employed in the investigation, a relatively slow time base must be used if a complete stroke record is to be included in one sweep of the time base, with consequent loss of resolution. If the period of the time base be shortened, greater resolution can be obtained, but subsequent portions of the record then become superimposed on one another, and, as a consequence, interpretation of the record becomes difficult. This objection is common to all systems of recording where a time base is employed with a fixed plate, and can only be obviated by the use of a moving film. However, with transient phenomena, the latter method must entail a certain amount of wastage, and the cost is often prohibitive. It is possible, by mounting the film on a drum revolving at constant speed, with a regular lateral displacement, to utilise the latter method, and at the same time to reduce wastage to a minimum.

The method employed by Appleton, Watson Watt and Herd was designed to delineate the wave form of atmospherics. As it is the method, with certain modifications, which has been adopted in the investigation forming the subject of this portion of the thesis, it will be considered in some detail.

Briefly the method consists of the examination, by means of a Cathode Ray Oscillograph, of the variation in the potential developed across a resistance or a condenser included in a damped aerial circuit, whose time constant is so small that it may be neglected in comparison with the duration of the atmospheric. When the variation across the resistance is considered the method provides a means for the measurement of the rate of change of the field (dE/dt), as in Norinder's method, whereas, when the variation across the condenser is considered, a direct measure of the field (E) can be obtained.

The relationship between the changes in the earth's field in the neighbourhood of the aerial and the variation in the potential applied to the working plates of the oscillograph in the two cases may be seen from the following diagrams.

CASE 1.



C_0 is the effective capacity of the aerial system

h is the effective height of the aerial.

E is the field change to be determined.

Q is the charge on the aerial.

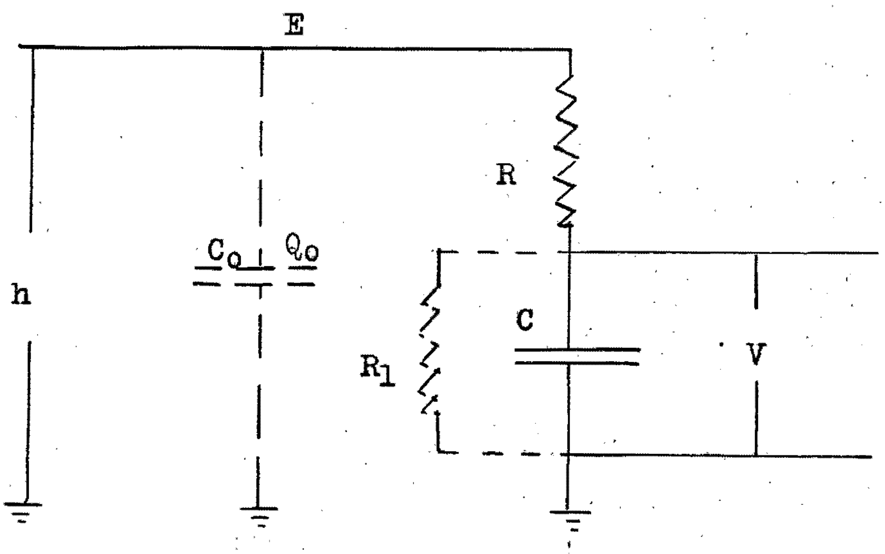
Then, since the potential of the aerial does not depart sensibl from its zero value,

$$hE + Q/C_0 = 0.$$

$$E = -\frac{Q}{h.C_0}.$$

$$\frac{dE}{dt} = \frac{1}{h.C_0}\cdot -\frac{dQ}{dt} = \frac{1}{hC_0}\cdot\frac{V}{R}.$$

CASE 2.



If V_0 be the potential at the aerial before the change,

$$V_0 + Q_0/C_0 = 0. \qquad \text{.........(1)}$$

Suppose the change results in a separation of charge, so that C acquires a charge Q.

Then, since the potentials of C_0 and C are stil identical,

$$V_0 + h.E + \frac{Q_0 - Q}{C_0} = Q/C. \qquad \text{........(2)}$$

From (1) & (2) $hE = Q/C + Q/C_0 = Q/C\left[\frac{C + C_0}{C_0}\right]$

But $V = Q/C.$

Hence $\underline{\underline{E = \frac{V}{h}\left[\frac{C + C_0}{C_0}\right]}}$

In the above analysis it has been assumed that, whenever changes occurred in the field in the neighbourhood of the aerial, they have been transient changes, which have left the aerial system in its initial state after the passage of the atmospheric. It is quite possible, however, and, in the neighbourhood of a thunderstorm, almost certain, that a permanent change in the field will occur, if the atmospheric be due to a lightning discharge. considering the circuit in Case (2) above, the result of a permanent field change would be that the induced charge on the aerial would be different before and after the disturbance. To obviate this difficulty, it is necessary to provide some leakage path for such a charge to escape, and this may be done by the inclusion of a resistance, R_1, across the condenser C.

It is clear that the time constant, C R_1, of this arrangement must be made sufficiently large so that it greatly exceeds the time of duration of the field change due to the disturbance, and thus R_1 must have a very high value. When such a permanent field change does take place, the oscillograph record will show an exponential trace of long duration, determined by the time constant of the arrangement.

Further, since the relationship between the field change, E, and the potential applied to the working plates of the oscillograph, V,

is given by

$$E = 1/h \left[\frac{C + C_0}{C_0} \right] V.$$

it is clear that, for any given field change, the magnitude of C will determine the magnitude of V. Hence, by a suitable adjustment of the value of C, field changes of considerable differences in magnitude may be made to give traces on the oscillograph of comparable size.

Before the potential, V, is applied to the working plates of the oscillograph, it is usually necessary for it to pass through one or more stages of amplification. In this connection it is important to notice that, when the oscillograph is connected across A B, it forms a resistance in parallel with R_1, across the condenser C, and thus effectively decreases the time constant, which, as we have already seen, must be maintained at a high value. A high valuefor the impedance between grid and filament of the first valve in the amplifier is thus essential. Further, it is essential that at no time should there be a flow of grid current in this first valve, Any such flow will give to the upper plate of the condenser C a charge, and, as we have already seen, any such charge will appear to indicate a permanent change in the earth's field. For this reason it is necessary to use a "power valve" in the first stage of the amplifier.

Arrangements were made by Appleton, Watson Watt and Herd whereby the response of the oscillograph to impulses of the known constants could be tested. A condenser of known capacity was charged and discharged through a known resistance and inductance, and, by a suitable adjustment of values, various types of impulse, from the aperiodic to the damped oscillation of high frequency, could be obtained. By means of a coupling resistance in the aerial circuit, any such impulse could be introduced into the aerial circuit, and the oscillograph record compared with the values calculated from the constants.

In carrying out their investigations on the nature of atmospherics, Appleton, Watson Watt and Herd applied the impulse from the aerial system to one set of working plates of the oscillograph, and a linear time base to the other, and examined the resultant oscillograph trace visually. The linear time base they found most satisfactory was the "ticking grid", the linear stroke being obtained by the discharge of a condenser through a saturated diode, and the almost instantaneous return stroke by the charging of the condenser by an oscillating valve.

J.E. Cairns, using substantially the same method as that just described, carried out, in 1927, an investigation into the wave form of atmospherics at Watheroo, Western Australia.

In a letter to "Nature", in 1933, F.W. Chapman, working in collaboration with Professor Appleton, describes a photographic method of recording the oscillograph trace. The oscillograph fluorescent screen has a long afterglow, and the camera shutter is tripped by a thyratron actuated by a small fraction of the initial voltage due to the field change. In this way records may be obtained of transient phenomena without wastage of photographic material.

SUMMARY OF CONCLUSIONS DRAWN FROM PREVIOUS WORK ON ELECTRICAL FIELD CHANGES.

The original Wilson method for the investigation of the field changes in the neighbourhood of a thunderstorm was first applied to South African thunderstorms by Schonland and Craib. As has already been mentioned, the method provides information of the resultant field due to a complete lightning flash, and thus, in the main, besides quantitative data on the magnitudes involved, determines the polarity of the cloud itself. The result of their work furnished conclusive evidence of the fact that thunderclouds are predominantly of positive polarity. Schonland, as the result of investigations on some fifty storms, was able to show that more than 90% of the observed changes due to ground flashes gave results indicating positive polarity in the cloud.

Subsequently Halliday, using, the same method in Johannesburg, obtained results indicating an even higher percentage. He was also able to obtain a correlation of the field change due to a flash with a photographic record of the flash itself in certain cases. His photographs showed that, in certain cases, the flashes were "double", in that a discharge to earth from a cloud and a discharge within the cloud itself occurred almost simultaneously. The majority of his correlated records which seemed to indicate negative polarity in the cloud were of this type, when the criterion of polarity was based on the ground flash alone. This result is not inconsistant with the actual positive polarity of the cloud, should the field change due to the discharge within the cloud predominate at the recording point.

As was previously indicated, the work of Appleton, Watson Watt and Herd was intended primarily as a study of Atmospherics and their method was designed to provide a delineation of their wave form. The work was carried out under the programme of the Radio Research Board, and covered a period of a year or more during 1922-1923. During this period over eight thousand individual records were obtained, some in England, others in the tropics at Helwan, near Cairo, and at Khartoum. The oscillograph traces were examined visually, and records kept of their characteristics. A statistical analysis of the records showed that they could be classified in two main groups, designated Aperiodic and Quasiperiodic. These two main classes were further subdivided to show the sign of the field change associated with the atmospheric, whether or not a semi-permanent change of field had occurred, the rounded or peaked nature of the oscillograph trace, the relative duration of the growth and decay periods in the aperiodic type and the sequence of opposite peaks in the quasiperiodic. The analysis showed that the aperiodic were three times as numerous as the quasiperiodic, and that predominantly positive discharges were one and a half times as numerous as negative.

The field strengths of the atmospherics and their periods of duration were also examined statistically, and the results of such examination summarised. This summary shows that the mean aperiodic atmospheric had a peak field strength of 77 millivolts/metre, and a duration of 2245 micro-seconds, and the mean quasiperiodic atmospheric had a peak field strength of 156 millivolts/metre, and a duration of 3125 micro-seconds.

It was also observed that, besides the main field changes composing the atmospheric, there was often present a fine structure or "ripple". This ripple had an amplitude which reached about 10% of the fundamental amplitude of the atmospheric, and the ripple most frequently occurring had a frequency of about 100 micro-seconds.

Included in the observations were determinations of the net field changes of the earth's electrical field due to thunderstorms, obtained by the use of the cathode ray oscillograph, and also by using a capillary electrometer and a string electrometer. From the results of these determinations it was found that the preponderance of positive or negative field changes depended on the distance of the storm from the recording apparatus. A theoretical discussion of these results showed that, with thunderstorms up to considerable distances the most frequent type of cloud was one of positive polarity. Thus the conclusions arrived at from the work of Schonland and Halliday previously discussed agreed with the results from this investigation.

The particular form which the atmospheric wave form trace might be expected to assume was also discussed from a theoretical point of view. Using the fundamental equations of Clark Maxwell for the transmission of Electrical impulses through space, it can be shown that the expression for the field at any point due to a lightning discharge at a distance r from the point is

$$E = \frac{1}{r^3}\cdot M + \frac{1}{cr^2}\cdot\frac{dM}{dt} + \frac{1}{c^2 r}\cdot\frac{d^2M}{dt^2}$$

Since the three terms, known as the electrostatic, induction and radiation terms respectively, depend to a different degree upon r, the nature of the oscillograph trace will differ with distance. Thus, for small values of r, the electrostatic term is the important one, while at great distances the radiation field predominates. A comparison between the theoretical wave form and that actually recorded leads to the conclusion that one must look to thunderstorms up to considerable distances, as important sources of typical atmospherics. Further, from the actual records obtained, it may be concluded that lightning is not in general freely oscillatory, since such records are either aperiodic or quasiperiodic.

The work of Norinder deals mainly with the interpretation of the oscillograph records to explain the mechanism of the lightning discharge. In a paper published in 1934 he used a time sweep of 10^4 micro-seconds, and also one of 10-20 micro-seconds. From the records he then obtained he concluded that a lightning discharge, observed as a distant flash, consisted of several partial impulses, following one another, with different time intervals between them. The time interval between consecutive partial discharges he gives as lying between the limits of 200 micro-seconds and 3000 micro-seconds, while the most frequent total duration of a partial impulse is from 200 micro-seconds down to 50 micro-seconds. A comparison of these figures with those of Appleton, Watson Watt and Herd, given above seem to indicate that his partial impulse must be associated with the fine structure or ripple previously discussed. In a later publication the results are given of an anglysis of field changes due to atmospherics. These he finds are of two types, "clicks" and "grinders", names used to distinguish their effects in a radio receiving set. The oscillograph records show that the clicks are distinct from the types obtained directly from lightning discharges. The clicks are single disturbances of duration of the order of 100 micro-seconds, whereas lightning flashes were found to consist of repeated discharges of this type. He attributes the clicks to very short electrical discharges within adjacent parts of a thunderstorm, a phenomenon not usually detectable visually. The grinders, on the other hand, have a duration comparable with that of a lightning flash, and he concludes that they are due to distant lightning flashes. Their wave form differs from that obtained for near lightning flashes, and the theoretical consideration of the variation of wave form with distance is considered, on similar lines to those of Appleton, Watson Watt and Herd previously mentioned. He concludes from this analysis that atmospherics could be derived from lightning discharges of known forms.

Appleton and Chapman have recently published a further paper on "The Nature of Atmospherics". In this they report certain modifications introduced into the apparatus formerly used by Appleton, Watson Watt and Herd, in an attempt to remove certain weaknesses in the technique of the former work.

The exposed conductor they used consisted of a Wilson sphere, the down lead from which was carefully screened, and an electrometer triode was used as a connecting link between aerial system and amplifier. The amplifier itself was resistance-capacity coupled, and the excursions of the oscillograph spot were recorded photographically by the afterglow method to which previous reference has been made.

The results they obtained show in the first place that there was a tendency for discharges to occur in groups, so that these results again confirm the deductions from the Boys' camera records of the composite nature of a lightning flash. The employment of a faster time base indicated that the decay of the moment of a thundercloud occurs in stages. The first stage is relatively slow, (0.01 second) and, during its progress, the moment of the cloud is reduced by 30 - 50 %. The second stage is very rapid (40 - 80 micro-seconds), and practically the whole of the remainder of the moment is then destroyed. These stages are identified with the leader and return stroke processes shown in the Boys' camera photographs. A certain fine structure is found on the records of the first stage which is identified with the branching and discontinuous nature of the first leader as shown in the Boys' camera photographs.

Finally, consideration is given to the change in the form of the oscillograph trace with increasing distance of the flash, such change being due to the relative variations in the magnitudes of the electrostatic and radiation fields with distance.

METHOD OF PROCEEDURE AND DESCRIPTION OF APPARATUS.

As has been previously indicated, the object of the present investigation was to examine, by the use of the Cathode Ray Oscillograph, the changed in the electrical field in the neighbourhood of a thunderstorm due to a lightning discharge, and, if possible, to correlate such changes with the Boys' camera photographs of the lightning flash. Owing to the frequency of thunderstorms on the Witwatersrand, and the success that had been achieved by the Boys' camera operators there, it was decided to carry out the field work in Johannesburg during the summer season of 1935-36. The method used was substantially that of Appleton, Watson-Watt and Herd, except that it was decided to take photographic records of the oscillograph trace, using for this purpose a revolving drum camera. The apparatus was of the form developed by the Radio Research Board at Slough.

It was fortunate that the investigations, carried out by the Lightning Investigation Committee of the S.A.Institute of Electrical Engineers, on the development of a lightning flash, using the Boys' camera, had preceded the present investigation, as the experience gained thereby was found to be of a considerable benefit. This experience had clearly shown, amongst other things, that success with the camera work depended on the operator possessing the maximum of mobility, and it was early realised that, in the present investigation, mobility was even more essential. In South Africa, owing to the rapid changes in temperature that occur, it is found that thunderstorms develop, often with very little if any, warning, in a very short time, and travel over the country at a speed of 20-30 miles per hour. The direction in which they travel depends on the ground contours beneath the storm and other factors, such as the prevailing winds in their vicinity, and often cannot be foretold. In the photographic work it had been found necessary to keep a careful lookout for storms, with the camera outfit ready loaded in a motorcar, so that it could be rapidly transported in any required direction to some suitable position at which the storm might be intercepted in its course, and the necessary exposures made. Even under these conditions it was found that journeys were often fruitless, and the percentage of successful photographs was small. In this connection mention must be made of the valuable assistance rendered by Mr. H. Collens. His unique knowledge of the behaviour of thunderstorms in the vicinity of Johannesburg, and his experience with the Boys' camera, were of inestimable value in the present investigation.

Profiting by this experience, it was decided to make the experimental outfit in the present investigation as mobile as possible, by mounting it complete in some vehicle. The problem was a formidable one, for, where the Boys' camera operators had found it possible to use an ordinary motorcar, since its purpose was purely one of transport to a suitable site for photography, it was now necessary to transport the oscillograph, camera and all the auxiliary apparatus. In addition the outfit had to be self-contained, and all sources of supply of power for the oscillograph, amplifier unit and drive for the recording camera had to be included. These had to be so arranged that, immediately on arrival at the required location, the outfit could be put into commission. In short, the problem resolved itself into that of designing a portable, self-contained laboratory and dark-room on wheels. Fortunately The

Victoria Falls and Transvaal Power Company were kind enough to place at our disposal a Reo Speed Wagon, which had formerly been used by the linesman of the company when executing repairs on their power lines, and this was found to be satisfactory for the purpose.

Since it had been decided to use photographic recording of the oscillograph trace, it was first necessary to render the body of the lorry light-proof, so that records could be made of both day and night storms. To accomplish this all openings and windows in the body were closed with covers of cardboard and American cloth. A double curtain of black material was hung from the roof down to the floor in front of the double doors at the rear of the lorry giving access to the interior. With the doors closed, the interior thus became a light-tight room some 8 feet long, 5 feet wide and 5 feet high.

Inside the body were fitted two tables, stretching the full width of the lorry, the one flush with the front of the lorry, the other separated from it by about 3 feet. This allowed sufficient space for one observer, if necessary, to take up a position in comfort between the two tables, while a second observer could be stationed behind the rear table. The front table carried the oscillograph and the amplifier units, and the rear table carried the camera outfit, the motor for the camera drive, the control panel for the oscillograph, and all switches controlling the motor and amplifier. All these units were mounted on spongy rubber and kept in position by battens. This was done to prevent any damage during transit, and to obviate vibration from the motor affecting other portions of the outfit.

The accelerating voltage for the oscillograph was obtained from a bank of High Tension batteries, and these were mounted on a box which formed part of the original fittings of the lorry and ran its length at one side under the tables. These batteries were so arranged that, by a series of switches, the voltage applied to the oscillograph could be varied from 500 volts, for visual observation, to 2,000 volts for photographic recording. Under the front table, on the floor of the lorry, were fixed several large capacity lead cells. These provided the power for the camera motor and for heating the filaments of the amplifier valves. The anode voltage for these valves was obtained from High Tension batteries which were also situated under the front table. Projecting through the floor of the lorry, under the front table, was an earth wire, attached dirextly to the chassis of the lorry, and this provided a common point to which the various earth connections in the outfit could be made.

Stretched above the roof of the lorry was the aerial. This consisted of a length of copper wire, 8 feet in length, standing 13 inches above the roof of the lorry, and carried by thin metal supports at each end. These supports were rigidly attached to the roof but were fully insulated from it by sulphur ring insulators. Mounted on these supports were thin metal cowls, so that the insulation received complete protection from rain. The front support projected through the insulator into the body of the lorry, and from it a short lead ran directly to the input terminal of the amplifier unit, which, as is shown later, embodied in its design the damping resistance and condenser of the aerial-earth circuit.

The internal arrangements in the lorry were such that it was possible for a single operator, by taking up his station behind the rear table, to control each unit of the complete outfit, and so, if necessary, to make a complete record single handed. As a general rule it was found the spot on the fluorescent screen a horizontal deflection. Flexible leads from the terminals on the tube holder led to terminals on the back of the panel, to enable all connections to the oscillograph to be made to these terminals. The ebonite panel was mounted in the oscillograph box, made of wood covered with sheet metal, so that, when mounted, the oscillograph tube was completely shielded. The front of the box had a circular opening, exposing the fluorescent screen, and thus enabling photographs of the excursions of the spot to be taken. Mounted in the box were fixed condensers, from which leads led to terminals on the panel. In this way any E.M.F. under investigation could be applied either directly to the working plates or through these condensers. The necessary leaks from working plate to gun, to preclude accumulation of charge on the working plate, were also included in the general assembly.

THE CAMERA AND ITS MOTOR.

The camera used to record the oscillograph fluctuations was adapted from an Ottway drum. mThis is a cylindrical drum 10cms. in width and 1 metre in circumference with a horizontal axis mounted in bearings. Below the drum shaft was a second shaft, on which was cut a thread of uniform pitch. A train of gear wheels and clutch were so arranged that, with the clutch engaged, it was possible togive to the drum, in addition to its axial rotation, a uniform horizontal traverse of about 0.6 millimetres per revolution. The drum was rigidly mountedin a large cubical box, with a removable lid such that, with the lid in place, the whole box was light tight. Projecting from one side of the box was the driving shaft of the drum, and from the opposite side, the clutch handle. The latter was so constructed that it could be used to reset the drum to its zero position after it had completed its traverse.

The camera lens was mounted in a rigid metal support attached to the metal frame carrying the drum shaft bearings so that its position relative to the drum face remained constant, and protruded from the front of the camera box. The lens used was a speed Anastigmat Cine Lens of focal length 2 inches (f/1.5) supplied by J.H.Dallmeyer Ltd, London.

The camera itself was mounted at such a distance from the Fluorescent screen of the oscillograph that the image was reduced about 10 diameters. The film used in the camera was supplied by Messrs. Kodak, Ltd., direct from their factory in U.S.A., and the emulsion was that used by them for sound recording. The films were supplied by the manufacturers cut in suitable lengths just to fit the camera drum with a short overlap. The process of loading the film in the camera was very simple. The camera top was removed, the film wound evenly and tightly round the drum, and the two ends, with the slight overlap, fastened to the drum by means of a spring clip. Spare films were carried in special light tight cylinders in the lorry, and the whole process of removing a used film and reloading could be performed in a few seconds.

From the above description it is clear that, with a stationary oscillograph spot, a complete traverse of the camera drum would produce a film record consisting of a continuous spiral trace of pitch 0.6 millimetres, and such a trace would completely fog the film. To overcome this difficulty, and bearing in mind that it was only necessary to record deflections of the oscillograph spot, a mask was mounted in front of the oscillograph screen. The mask covered the whole of the fluorescent screen, except for a narrow horizontal slit approximately 5 millimetres in width at the height of the oscillograph spot. Across this slit, immediately in front of the undeflected spot, a narrow band was placed, just sufficient to mask the spot when in this position. In this way the undeflected spot and all diffused light from the screen were screened from the camera lens, and the film record was one of the oscillograph deflections alone.

To drive the camera drum it was necessary to use a direct current motor which could be driven from lead batteries in the lorry, while at the same time maintaining constant speed under load. Fortunately the load imposed on the motor by the camera drum was small, and this did not prove difficult. A reduction gear was included to obtain a drum speed of one revolution per second. The maximum writing speed of the film employed was found to be about 10^5 centimetres per second, and, with the reduction of ten diameters from screen image to film image previously mentioned, experience showed that this drum speed was about the maximum permissible to obtain a satisfactory record of the fine structure of the oscillograph trace. This motor was connected to its batteries through two switches, one outside and the other inside the camera . The former was used to start the motor, while the latter was so arranged that, when the drum reached the end of its traverse, it broke the motor circuit, and thus prevented any damage to the camera due to over run.

THE AMPLIFIER UNIT.

The amplifier unit employed in this investigation is shown diagrammatically in Figure 1., and follows the lines of that described by Appleton, Watson Watt and Herd and shown in Figure 3, page 621, of their publication, to which reference has been made. As previously mentioned, the damping resistance in the aerial circuit and the "potentiometer" condenser were included in the amplifier unit. The high resistance across this condenser had a value of 10 megohms. The capacity of the lorry aerial was measured experimentally, and found to be 0.000025 microfarads. It has been shown previously that, if C_0 be the capacity of the aerial and C that included in the aerial circuit, the relationship between the field changes in the neighbourhood of the aerial (E) and the change in voltage across C (V) is given by

$$E = \frac{V}{h}\left[\frac{C+C_0}{C_0}\right].$$

From the low value of C_0 for the lorry aerial, in the case of distant storms it was found necessary to increase the aerial capacity in order to obtain measurable records on the oscillograph. This was done by introducing an extension from the aerial on the lorry to an upright erected in the ground some distance from the lorry. With this extension in position the aerial capacity was measured and found to be 0.000123 micro farad. For nearer storms, if the field change was sufficiently large to deflect the spot off the screen the value of V could be reduced and brought within measurable limits by increasing C. As indicated in the wiring diagram, awitching arrangements were introduced to enable records to be made either of E or of dE/dt, although, in the present investigation, results were confined to a determination of E.

The amplifier itself consisted of three stages, resistance capacity coupling being employed between the stages. The first stage consisted of a power valve, L.S.5. to obviate any possibility of grid current and a resultant charge on the plate of C. Since this provided small amplification, the second stage contained a valve of high amplification factor, L.S.5.B. The third stage contained an L.S.5 valve, to provide for the large voltage changes applied to the oscillograph plates. A potentiometric input to the grid of the second valve provided another means of regulating the gain in the amplifier.

Before the amplifier was incorporated in the general circuit, it was submitted to a series of tests to determine whether its inclusion would introduce serious distortion of the impulse between aerial and oscillograph. This was done by following the method outlined by Appleton, Watson Watt and Herd, and mentioned previously, where impulses of known constants are applied through the amplifier to the oscillograph, and the trace thus obtained compared with the values calculated from the constants. In this way it was found that the amplifier introduced no serious distortion of any kind over the range in input volts for which it was later used.

A determination of the amplification factor of the amplifier has also been made under working conditions and when mounted in the lorry. The value is found to be 260. This determination was very kindly carried out by Mr. L. Katz.

GENERAL OUTLINE OF THE INVESTIGATION.

When the present investigation was first suggested, it was intended to have a twofold object. In the first place it was hoped that, with the oscillograph outfit in the field in the Witwatersrand area during the summer storm season, it would be possible to obtain a number of oscillograph records of the field changes in the neighbourhood of a lightning flash, and, by visual observation of the nature of the flash, classify these generally as due to ground flashes or cloud flashes. Thesescould then be examined in the light of the photographic records of lightning flashes which had previously been obtained by the use of the Boys' camera. The analysis of the Boys' camera records had been carried out by Schonland, Collens and Malan, and that analysis provided a general picture of the sequence of events over a complete ground flash. The relationship between this general picture and the general picture derived from the oscillograph records of field changes due to ground flashes would then provide additional information on the mechanism of the discharge. In the second place it was hoped that it might be possible to obtain, simultaneously, an oscillograph record of the field changes due to a ground flash and a Boys' camera record of the same flash, and thus to correlate directly the two methods of investigation. The value of such a correlation is obvious. From it could be seen the direct relationship between the photographically visible sequence of events and the field changes, and it would indicate clearly the limitations of each method.of analysis.

In practice the first of these objects did not prove very difficult, once the outfit had been assembled in the lorry. During 1935-36 season the number of suitable storms was below the average of previous seasons, but in spite of this handicap, a number of records were obtained, both during daylight and at night, at varying distances from the lightning discharge. A report on these records forms the subject of this section of the thesis. The second object, the direct correlation of Boys' camera and oscillograph records, proved very difficult. This was to be expected, for not only were the inherent difficulties of obtaining a Boys' camera picture present, but in addition it had to be obtained during the run of the oscillograph film and at night. The lorry outfit, by reason of its bulk, was of necessity not as mobile as the camera outfit, and in addition where the camera could be kept trained on a storm cloud until a flash took place, the oscillograph was limited to the time taken by a drum traverse. In fact, during the whole period of the investigation, such correlation was only obtained on one occasion, when simultaneous records of three flashes were obtained..

GENERAL PICTURE OF GROUND FLASH FROM BOYS' CAMERA RECORDS

Before considering the oscillograph records obtained in the present investigation it is necessary to outline the general picture of the sequence of events in a ground flash as obtained from the Boys' Camera Records. This is given by Schonland, Malan and Collens as follows:-

"Each lightning flash to ground consisted of a series of separate strokes ranging in number from 1 to 27. The time of separation was very variable, even in the same series, and values of 0.0006 second to 0.53 second have been found.

The first stroke of each series differs from the others in two respects, which make it easy to identify. It is usually much more intense than the succeeding strokes and is always much more heavily branched.

Each stroke is composite, and consists of a leader portion travelling from cloud to ground and a main return portion moving faster and more brightly in the reverse direction. The leader to the first stroke consists of a series of streamers moving downwards in a step-by-step manner, and is hence referred to as "stepped". The length of each step is about 50 metres, and after completing a step the tip of the streamer appears to pause for a time of the order of 100 micro-seconds, whereupon the streamer extends still further, the new step being much brighter than the rest of the streamer.

The prolific branching of the main part of the first stroke of a series arises solely from downward branching of the stepped leader which precedes it. The course followed by the steps decides the path which is followed generally by all the strokes making up the flash and the zig-zag nature of the channel arises from changes in the direction adopted by successive steps. The leaders to the subsequent strokes of the series are in general of the dartlike character previously described. They follow the path blazed by the first leader, but usually do not branch. When branches are formed by either first or successive leaders they are subsequently more brilliantly illuminated during the return stroke.

Occasionally, however, when there has been an unusually longinterval before the occurence of a "subsequent" stroke, the lower end of the usual dart leader becomes stepped like the leader to a first stroke. This type of leader is termed "dart-stepped".

The second, upward moving, return portion of each stroke follows directly upon the arrival of the leader part at the ground. In the course of its journey the return part branches outwards and downwards along the forks blazed by the leader._____ The very bright luminosity of the return stroke has its longest duration and greatest intensity at the ground and often shows a marked decrease in intensity at successive branches from the bottom upwards.

The first-leader process involves the formation of a conducting channel along which flows electric charge from the cloud region tapped. Its progress is slow compared with that of the other and later processes involved in the discharge, and it always occurs in a step-wise manner. In the course of its downward movement the leader branches outwards into regions where a local concentration of space-charge may be presumed.......The advancing leader with its branches constitutes an actual downward movement of part of the cloud-charge, which is distributed over the whole conducting system, and in particular over the branches, at the moment the leader hits the ground. The leader process thus effectively lowers a portion of the cloud-charge into the air. When this charged system is placed in good conducting connexion with the earth, a rapid flow of charge takes place, on a scale and at such a rate as is exhibited by the main return stage of the stroke. The frequently observed concentration of the energy of the return stroke upon the lower two-thirds of the channel and its branches as well as its decrease in velocity as it passes the branches offers evidence that the leader process often lowers into the air the greater part of the cloud charge tapped. An exactly similar effect is observed in subsequent strokes; the downward moving leader again charges up the channel, and the return stroke intensity and duration indicate by the manner in which they fall off with height above the ground that the leader process has drained the cloud region it taps of most of the available charge".

GENERAL FORM OF OSCILLOGRAPH RECORD FOR A GROUND FLASH TO BE EXPECTED FROM A BOYS' CAMERA PICTURE.

From the quotation from Schonland, Malan and Collens in the last section we may deduce the type of oscillograph record that might be expected from the general picture of the field changes accompanying each stage in the process of the lightning discharge. As they point out, the first stage or leader process effectively lowers the greater portion of the cloud-charge from the cloud region tapped into the air. This will result in a decrease in the moment of the cloud charge. The duration of this change depends on the time of duration of the leader process, and is much longer for first than for subsequent strokes. The second stage, or main return stroke, consists of the rapid flow of this charge from the air to earth, and a further rapid decrease in moment.

There still remains the residual charge in the cloud region tapped by the flash, and it is reasonable to suppose that the main return stroke does not cease immediately it reaches the cloud base, but proceeds a certain distance further into the cloud, draining this space of its charge. This process may very well occur without being recorded on the Boys' camera photographs, except as a continuation of return stroke luminosity. Such a process would result in a still further decrease in moment.

Thus the changes in moment would take place in three stages:-

(a) Leader Change of duration depending on the type of leader.

(b) Main Stroke Change, very rapid.

(c) Residual charge change, of indeterminate duration, but very probably slower than (b).

As has been mentioned previously, the equations for the propagation of an Electro-magnetic disturbance in space give the following relation between the change of moment (M) in the cloud and the corresponding field change (E):-

$$E \doteq \frac{1}{r^3}\cdot M + \frac{1}{cr^2}\cdot\frac{dM}{dt} + \frac{1}{c^2r}\cdot\frac{d^2M}{dt^2}$$

where M is the moment at a time (t - r/c) seconds.

The three terms on the right hand side of the equation were called the Electrostatic (E_s), Induction (E_i) and Radiation (E_r) terms respectively. It was pointed out that the relative values of these three terms depended on the value of r, the distance from the source at which the field change is measured. For small values of r the Electrostatic term is the most important, whereas for large values of r the Radiation term predominates. In general however we see

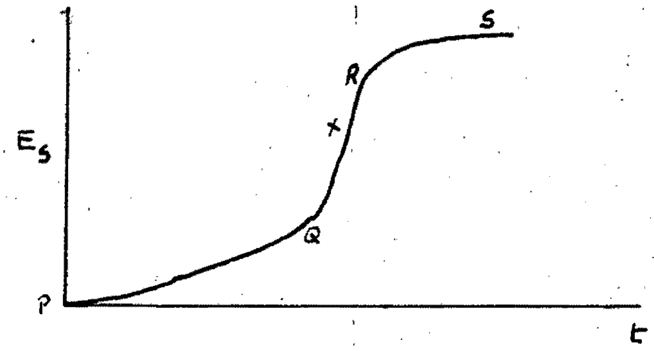
E_s is proportional to M

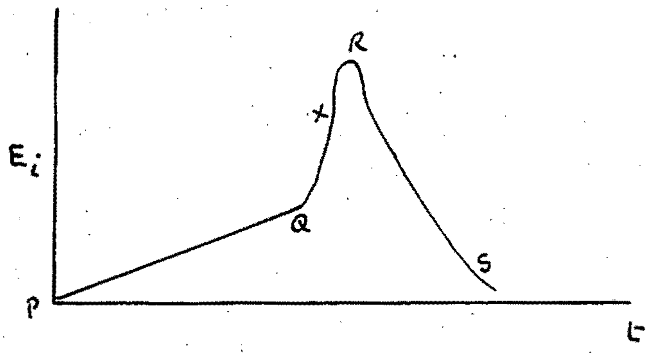
E_i is proportional to dM/dt

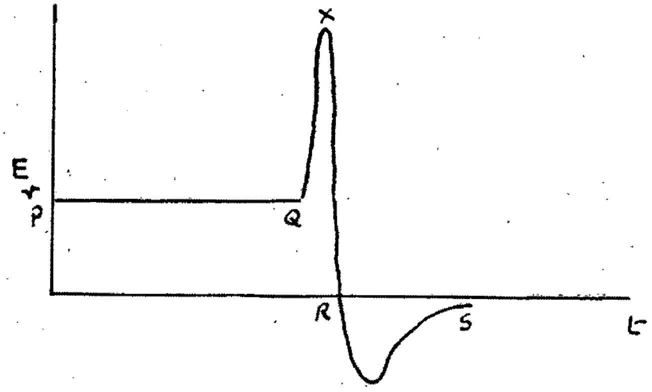
E_r is proportional to d^2M/dt^2

It is now possible to obtain a graphical representation of the changes to be expected in E_s, E_i and E_r with time during the three stages in a complete lightning stroke previously indicated.

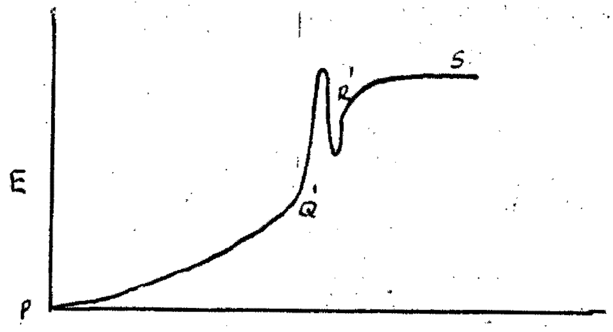
This will be as follows:-



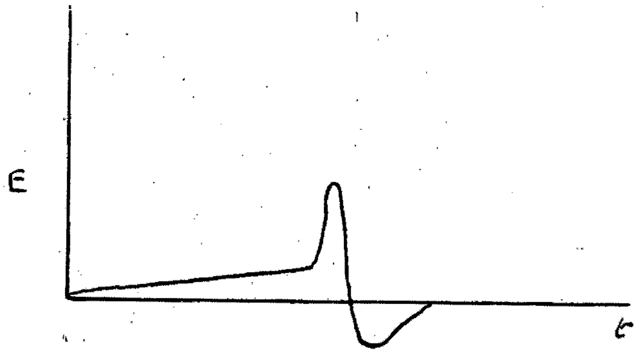




The actual oscillograph record to be expected may be obtained by combining these three, the relative values of E_s, E_i and E_r depending on the value of r. For a near flash, in which E_s predominates, the record should take some such form as follows:-



On the other hand, for a distant flash, in which E_r predominates, the record should take some such form as follows:-



The above analysis is obviously only a first approximation, and will be considered in greater detail later. No allowance has been made for the high resistance leak across the plates of the condenser in the aerial circuit, so that the final value of E indicates the net field change due to the flash. Further, no allowance has been made for any abrupt changes in the moment during any of the stages, such as the stepped nature of the leader process in the first stroke of a series. Any such changes will appear on the oscillograph record as a fine structure or ripple superimposed on the general form given above. The effect of the leak resistance will be to superimpose on the general curve an exponential, decay curve, so that the final position of the oscillograph spot will again be at zero.

GENERAL CHARACTER OF THE OSCILLOGRAPH RECORDS.

It has been pointed out previously that, whenever the oscillograph was in operation in the neighbourhood of an active thunderstorm, an external observer was, if possible, employed to enable a record to be made of the visual nature of the flash. This enabled the oscillograph records to be arranged in two general classes as being due either to ground flashes or to cloud flashes. An examination of the records themselves shows that each class is distinct in type, differing in many essential features from each other. After a little experience it was possible to differentiate between records of ground flashes and cloud flashes from an examination of the record alone, without reference to the report of the visual observer. This proved to be very useful where the services of an observer were not available, or where a record was obtained, as sometimes occurred, when the flash itself had escaped the notice of the observer. In all cases, however, visual correlation was sought, and, where no such correlation was available, the record was classified as "probable ground flash" or "probable cloud flash" from its general form.

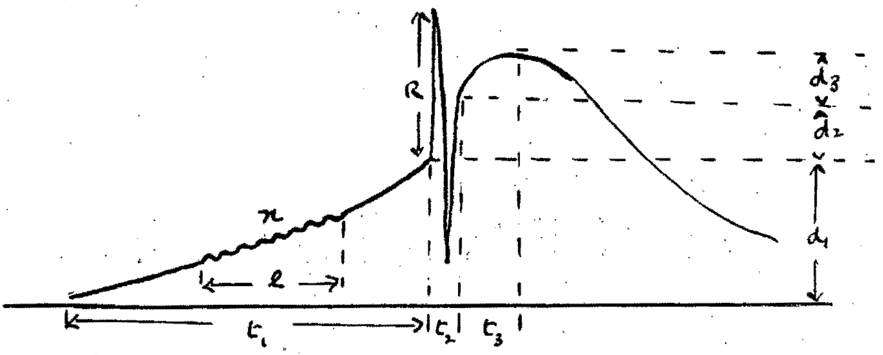
The Boys' camera records deal almost exclusively with ground flashes, and for this reason, in the present investigation attention has been directed particularly to the oscillograph records obtained from such flashes. A number of records of cloud flashes were obtained; in fact, as may be expected, they were as numerous as ground flashes, in spite of the fact that the oscillograph was seldom put into operation except to obtain records from a cloud active in ground flashes. Some typical records of cloud flashes will be given later, and their general form indicated. It must be remembered, however, that the primary object of the investigation was to obtain a comparison between oscillograph and Boys' camera records, and for such a comparison cloud flashes were unsuitable.

Dealing only with records of ground flashes, the oscillograph records show that each ground flash consisted of a series of separate strokes, ranging in number from 1 to 20. The following is typical of the type of oscillograph record obtained for a complete flash to ground.

The time of separation, measured from the field change due to the return stroke (QR in the diagram in the previous section) was found to be very variable, the smallest value found being 0.012 second and the largest 0.569 second, neglecting single stroke flashes.

The form of the oscillograph trace for a complete stroke in any flash was found to agree generally with that predicted in the previous section from the Boys' camera analysis. In general the three stages of field change due to the leader, main stroke and residual charge were clearly indicated, and this enabled a statistical analysis of their various characteristics to be made.

Certain symbols have been adopted to designate the various quantities obtained from the records for this statistical analysis, and these are clearly indicated in the following diagram, typical of a common form for first strokes.



The field changes associated with the three changes are given by d_1, d_2 and d_3, and the duration of those changes by t1, t_2 and t_3. It must be remembered that the oscillograph trace is not confined to one term in the equation for E, but the resultant of the Electrostatic, Induction and Radiation terms, hence allowance must be made for this in the analysis.

RESOLVING POWER OF OSCILLOGRAPH.

Before proceeding to a discussion of the results obtained from the analysis, it will be advisable to indicate the resolving power of the apparatus in time. As stated previously, it was found that, in order to obtain clear records, the maximum writing speed of the film was a little more than 1 drum revolution per second. Assuming a speed for the drum of 80 revs. per minute, with its circumference of 1 metre, each centimetre length of film corresponds in time to 0.0075 second. Film measurements could be made with an accuracy of 0.1 millimetre, which gives a resolving power in time of 75 micro-seconds. A comparison of this figure with the corresponding value in the Boys' camera analysis, where the resolving power in time was 0.6 micro-seconds, indicates the limiting value of the type of oscillograph used in the investigation. It is fully realised that, for an analysis as detailed as that obtained from the Boys' camera records, it is necessary to employ a cathode ray oscillograph of the type employed by Norinder. The resolving power of the gas filled type of oscillograph used in the present investigation, however, is sufficient for the analysis of the general field changes which occur.

NUMBER OF STROKES IN A FLASH AND INTERVAL BETWEEN STROKES.

The total number of records available for analysis in the present investigation where the records showed a definite ground flash or a "probable ground flash", was 65. A certain number of these were from distant flashes, in which the E_r term predominated, and hence the analysis of these presented difficulties when an analysis of the E_s changes alone were being considered. However, all records can be utilised for the present portion of the analysis, since all indicate the

the total duration of the complete flash, the number of strokes in each flash, and the time intervals between strokes.

TABLE I.

DISTRIBUTION OF STROKES IN NUMBER PER FLASH.

Number of strokes per flash	CASES RECORDED BY	
	Oscillograph	Boys' camera
1	11	32
2	8	5
3	12	4
4	7	5
5	7	8
6	2	2
7	3	1
8	4	2
9	5	1
10	3	1
11	1	-
12	1	-
13	-	1
15	-	1
20	1	-
27	-	1

Table I shows the distribution of the number of strokes per flash from the oscillograph, compared with the results from the Boys' camera analysis. The latter table is taken from the paper by Schonland, Malan and Collens, Progressive Lightning II." It will be noticed that the oscillograph records show a larger proportion of multiple stroke flashes than do the Boys' camera records. There are two possible explanations for this fact. In the first place it may be that the nature and size of the thunderclouds dealt with in the one investigation tended to provide a greater proportion of multiple flashes. On the other hand it may be that, on the oscillograph records, there has been a tendency to consider two flashes with a small time interval between them as one and the same flash. This is quite possible, when it is remembered that the oscillograph records all field changes due to discharges anywhere in its neighbourhood. Thus, as is invariably the case on the Witwatersrand, if there be two or more thunderstorms active in the same neighbourhood at the same time, the oscillograph records the field changes from all the storms as the flashes occur, whereas the Boys' camera only records the flash from the cloud on which the camera is trained. In addition the one correlated record previously mentioned provides evidence of a further possible explanation. The Boys' camera record in this case indicates that the cloud on which the camera was trained gave several different flashes along different paths during the time the camera plate was exposed.

TABLE II.

TIME INTERVALS BETWEEN STROKES.

INTERVALS RANGING BETWEEN	NUMBER RECORDED BY	
	Oscillograph	Boys' camera
0.001 sec. and 0.002 sec	1	1
0.002 " " 0.005 "	2	6
0.005 " " 0.01 "	6	9
0.01 " " 0.03 "	55	28
0.03 " " 0.05 "	84	22
0.05 " " 0.07 "	48	11
0.07 " " 0.09 "	19	15
0.09 " " 0.11 "	8	4
0.11 " " 0.15 "	12	6
0.15 " " 0.23 "	3	1
0.23 " " 0.32 "	2	3
0.32 " " 0.42 "	3	1
0.42 " " 0.53 "	-	2

Table II shows the distribution of the time intervals between strokes as recorded on the oscillograph, compared with the Boys' camera results, taken from the same paper. The agreement is excellent, and the oscillograph records show that the time intervals between the separate strokes of a series varied from 0.0019 second to 0.413 second with a most frequent value for this interval of 0.033 second.

TABLE III.

DISTRIBUTION OF TIME OF TOTAL DURATION OF MULTIPLE FLASH.

DURATION RANGING BETWEEN	NUMBER RECORDED
0 and 0.1 sec	12
0.1 sec. and 0.2 sec.	13
0.2 " " 0.3 "	10
0.3 " " 0.4 "	7
0.4 " " 0.5 "	7
0.5 " " 0.6 "	5

Table III shows the distribution of the total time occupied by a complete flash, when the flash is multiple in that it contains more than one stroke. There is no similar table for comparison in the publication of Schonland, Malan and Collens, cited above, but McEachron and McMorris, in an article published in the General Electric Review of October, 1936, in which they discuss the results of some Boys' camera investigations carried out by the writers in America, include information on the total duration of multiple flashes. A comparison between the results shown in Table III, expressed in the form adopted by McEachron and McMorris, and the results given by these writers in their publication, is shown in Figure 3

RELATIONSHIP BETWEEN TIME INTERVAL AND INTENSITY.

In their publication cited above Schonland, Malan and Collens examined the relation between the intensity of a stroke and the time interval before its occurence. They were able to show, from the Boys' camera records, that those strokes which have an intensity greater than the first stroke in the flash were those in general which occurred after a longer interval of waiting than the average. An examination of the oscillograph records has been made bearing on this point. The relationship between the interval before a stroke and the total field change due to the stroke or to any particular stage in the stroke has been examined, but so far no correlation has been obtained. The intensity of the stroke may depend on the time occupied in the return stroke, but the resolving power of the cathode ray oscillograph apparatus in time, as has already been pointed out, is not sufficient for this to be examined.

THE FIRST STROKE OF A SERIES.

An examination of the first strokes in the oscillograph records obtained of the 65 ground flashes indicated that these could be classified into certain types. These types differed from one another in several important respects, and the first stroke of a flash often enabled that flash to be classified. The Boys' camera photographs had established the fact that the first stroke in any flash differed from subsequent strokes in that its leader process was much slower, and at the same time stepped, and this was confirmed by the oscillograph records. The oscillograph records, however, also indicated that these first strokes differed amongst themselves, not only in the magnitudes of the various stages composing the record, but in the general form it assumed.

As might be expected, in the case of near flashes, the most common type of first stroke occurring conformed to the general picture previously derived from the theoretical consideration of the Boys' camera picture. Similarly the general type of record from a distant storm conformed to the general picture derived for it. In the general analysis of first strokes, six types or classes have been adopted, and Figure 2 indicates the general form of the record for each class.

The distribution of these six types over the 65 records is shown in Table IV.

TABLE IV.

Type α	27	Near Flashes
Type β	13	
Type γ	2	
Type δ	5	
Type D	13	Distant Flashes
Type Dα	5	

TIMES ASSOCIATED WITH TYPE α FIRST STROKES

Since the Type α is the most common type of first stroke occurring in the majority of cases, it must be considered as the normal type of oscillograph record for a first stroke from a flash occurring near the recording instrument. An analysis of the oscillograph records of all first strokes of this type should therefore provide a means of correlating the oscillograph records with the general picture of the first stroke as derived from the Boys' camera photographs. Reference will be made later to the other types of first stroke, and their oscillograph records analysed. An attempt will be made to explain their divergence from the main α type.

The diagram of the Type α first stroke in Figure 2 has been utilised to indicate the various quantities for which measurements have been obtained from the oscillograph records. The results from these measurements have been used in a statistical analysis of the various quantities.

TIMES OF THE LEADER PROCESS (t_1).

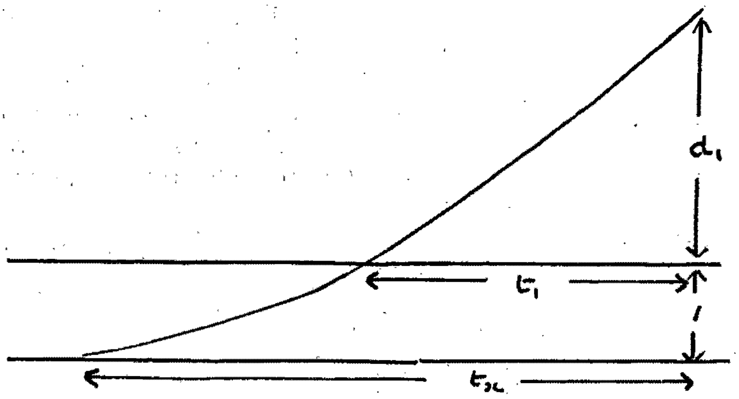
The leader process in a first stroke is a stepped process, and hence its effective velocity is considerably less than the actual velocity of the streamer producing each step. The time t_1 will represent the total time occupied by the leader process.

It will be remembered that, in the actual photographic process of recording the fluctuations of the oscillograph spot, a mask was introduced in front of the oscillograph screen to avoid fogging the film. Any deflection of the spot would mean that the spot must be deflected beyond the mask before its trace was registered on the film. An examination of the films shows that the width of this blank area on the film due to the mask was on the average 0.2 m.m. Hence, when measurements are made on the films, it is necessary to make allowance for this mask effect, and this is done by the addition of 0.1 m.m. to any measurement made from the zero base line.

The mask effect will affect the values of t_1, in that the actual length measured on the film of the recorded leader trace will be too short. A correction may be introduced based on the following consideration:-

It may be assumed as an approximation that the slow leader will give a parabolic trace on the film . The validity of this assumption is considered later.

Hence it may be assumed that $d = k.t^2$, and that d is measured in 0.1 m.m.



$$\left.\begin{aligned} d_1 + 1 &= K.\, t_x^2 \\ 1 &= K\,(t_x - t_1)^2 \end{aligned}\right\}$$

$$\frac{t_x - t_1}{t_x} = \frac{1}{\sqrt{d_1+1}}$$

$$t_x = \frac{\sqrt{d_1+1}}{\sqrt{d_1+1} - 1} \,.\, t_1.$$

Applying this correction to the measured values of t_1 obtained from the films, we obtain the distribution curve for t_1 shown in Figure 4.

RESULTS OF ANALYSIS OF t_1 TIMES. (fig. 4)

The values of t_1 range from 2.86×10^{-3} second to 38.37×10^{-3} second with a most probable value of about 18×10^{-3} second.

The analysis of the Boys' camera has shown the effective velocities of stepped leaders. The mean value is given as 3.8×10^{7} cms/sec., although it is pointed out that about half the values listed lie between 1.0 and 3.0×10^{7} cms/sec. The most probable length of time for the stepped leader to traverse 1 Kilometre of air is given as 7×10^{-3} sec., the range being from 10×10^{-3} to 0.8×10^{-3} second. If we assume the effective height of a cloud to be 3 Kilometres, these figures would give a most probable valuefor t_1 of 21×10^{-3} sec., with a range from 30×10^{-3} to 2.4×10^{-3} sec.

The agreement between the two sets of records is sufficiently close, if it be remembered that both investigations are dealing with a comparatively small number of flashes, and that the value of t_1 will depend on the length of the flash.

TIMES FOR THE LEADER PROCESS IN SUBSEQUENT STROKES.

The original analysis of the oscillograph records showed 65 flashes classified as ground flashes. If from these be excluded all records of distant flashes, where the leader process time is difficult to determine from the records, and all flashes consisting of a single stroke, it is found that the total number of subsequent strokes available for analysis is 207.

The examination of the oscillograph records of these subsequent strokes, as far as leader records are concerned, indicates that on 73 of them the leader is not recorded, whereas, on the remaining records, the leader times are distributed as indicated in Table V.

In considering the results recorded in this table certain factors must be borne in mind. In the first place, as has previously been pointed out, there is the possibility that two or more flashes, with a short time interval between them, possibly from different thunderclouds, have been classified together as a single flash. It might be thought that the stepped nature of first stroke leaders would preclude this possibility, but the low resolving power of the oscillograph might result in the ripple not being recorded. In addition it must be remembered that the Boys' camera photographs have shown that certain of the dart leaders, especially on long leaders and with a long interval preceding the stroke, become stepped towards their ends, so that the presence of ripple indications on the latter portion of a leader trace would not necessarily indicate that it was a first stroke leader. This might very well afford one explanation of certain of the long leader times for subsequent strokes appearing in the table.

In the second place it will be remembered that the e effect of the mask over the oscillograph screen results in the first portion of the leader trace making no record on the film. If the field change at the aerial associated with the leader process be small, and it is usually smaller in subsequent strokes than in first strokes, it may fail to be recorded on the film. This may very well afford one explanation of the 73 records which contain no leader trace.

In addition it may be pointed out that Table V includes the results from all the records examined. Some of these are by no means good records photographically, and many of the abnormal values appearing in the table may be attributed to poor records. They have been included in the table for the sake of completeness, but in drawing conclusions from the table they may be largely discounted.

TABLE V.

DISTRIBUTION OF LEADER TIMES (t_1) FOR SUBSEQUENT STROKES.

Duration in 10^{-4} sec.	Number of Strokes.
No Leader Recorded	73
From 0 to 2.5	13
" 2.5 " 5	20
" 5 " 7.5	11
" 7.5 " 10	9
" 10 " 15	6
" 15 " 20	7
" 20 " 25	4
" 25 " 30	4
" 30 " 35	4
" 35 " 40	2
" 40 " 45	6
" 45 " 50	5
" 50 " 60	7
" 60 " 70	5
" 70 " 80	2
" 80 " 90	4
" 90 " 100	7
" 100 " 120	8
" 120 " 150	5
" 150 " 180	3
Greater than 180	2

RESULTS OF ANALYSIS OF t_1 TIMES FOR SUBSEQUENT STROKES.

From the results recorded in Table V it may be seen that the duration of the leader process in subsequent strokes, where such a process is recorded on the oscillograph film, covers a range from 1×10^{-4} sec. to 240×10^{-4} sec., with a mean value of 27×10^{-4} sec., and a most probable value in the neighbourhood of 5×10^{-4} sec.

Schonland, Malan and Collens, in their analysis of the Boys' camera records, give a table showing the distribution of dart-leader velocities. This table shows these velocities to range from 1×10^{8} cms/sec. to 23×10^{8} cms/sec., with a mean velocity of 5.5×10^{8} cms/sec. and a most probable value of 2×10^{8} cms/sec. Assuming a track length of 3 Kilometres (Probably an underestimate of the actual length of the average path) these figures would give, as the duration of the leader to a subsequent stroke, a range from 1.3×10^{-4} sec. to 30×10^{-4} sec. with a mean duration of 5.45×10^{-4} sec., and a most probable duration of 15×10^{-4} sec.

The fact that the correlation between the oscillograph results and the Boys' camera results is not as striking as in the case of first stroke leaders has already been in some measure explained, and was to be expected. The results are of the correct order, and clearly indicate that the leader process to a subsequent stroke is of much shorter duration than that to a first stroke. A comparison between Table V and Figure 4 makes this clear.

TIMES OF THE RETURN STROKE PROCESS (t_2)

The return stroke is associated with the destruction of the charge lowered in the leader process, and takes place immediately a conducting path to earth is established. In comparison with the leader process in first strokes, it is very rapid, and this brings t_2 very nearly within the order of the resolving power in time of the oscillograph records. This, as has been noted previously, is about 75 micro-seconds. Where it has been possible, the value of t_2 on the oscillograph records has been determined, and the distribution curve for t_2 for type α first strokes is shown in Figure 5.

RESULTS OF ANALYSIS OF t_2 TIMES

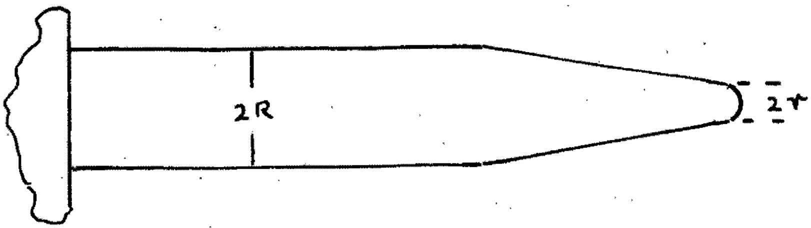
The values of t_2 range from 86 micro-seconds to 487 micro-seconds, with a most probable value of 165 micro-seconds.

The analysis of the Boys' camera records shows the velocities in the main return strokes with a range of variation of from 2.0 to 14.4×10^9 cms/sec. with a most frequent value of 3.5×10^9 cms/sec. Assuming, for the purposes of comparison, a return stroke of length 3 Kilometres, these figures would give a most probable value for t_2 of 86 micro-seconds, with a range of variation of from 21 micro-seconds to 150 micro-seconds.

Although the agreement in the values of t_2 from the two methods is not very close, it is of the correct order, and, bearing in mind the resolving power of the type of oscillograph employed, more cannot be expected. In addition it is interesting to note that the oscillograph records indicate higher values for t_2 than those obtained from the Boys' camera. The Boys' camera, however, only records the main stroke in the air beneath the cloud, and the record ceases immediately the cloud is reached. There is no reason to suppose, however, that the main return stroke does not penetrate into the cloud, and any such penetration, while it will not be recorded on the camera photograph, will affect the oscillograph record. Thus it is natural to expect that the value of t_2 from the oscillograph record will in general be higher than that deduced from the Boys' camera record.

THEORETICAL CONSIDERATION OF THE LEADER PROCESS.

As a first approximation the downward moving leader may be considered as moving from cloud to earth in a vertical line with constant velocity v cms/sec. Such a process will charge a length of channel of radius R, the channel ending in a tip of radius r.



At any moment the whole channel will not be at uniform potential, since there must be a fall of potential along its length. Hence the charge per unit length is not constant, but decreases as the distance from the cloud increases. The essential condition for the leader to advance is that the critical breakdown field must be maintained in front of the tip. Hence the radius of the tip must be such as to provide this critical field. The channel radius, on the other hand, will increase until it reaches such a value that the field at the sides of the channel is less than this critical breakdown field. As a first approximation, however, we may assume an average charge per unit length on the channel of q, with a charge Q on the tip.

The conduction current from the cloud flowing along the channel will then be qv, since the channel increases in length by v cms. each second. The convection current carried by the charge Q on the tip may be obtained by considering the charge Q carried on a length r of the tip. This passes any plane perpendicular to the channel direction in a time r/v sec. Hence the convection current will be Qv/r.
Equating the conduction and convection currents we have :-

$$Qv/r = qv \qquad \text{or} \qquad Q = qr.$$

Now the radius of the tip, r, must lie between 0.1 cm. and 10 cms., hence Q and q are of the same order. Since the total length of the channel is in general of the order of

10^5 cms., the charge on the tip, Q, is negligible in comparison with the total charge on the channel. Hence any effect which the charge Q may have on the electric field during the leader process may be disregarded.

Suppose the effective height of the cloud be h_1. At a time t after the start of the leader process the channel will be carrying a total charge qvt at a mean height above the ground of $(h_1 - \frac{1}{2}vt)$.

The moment of this leader charge is $2qvt\ (h_1 - \frac{1}{2}vt)$

The field produced at a point on the ground a distance L from the point vertically under the leader will be

$$\frac{2qvt\ (h_1 - \frac{1}{2}vt)}{\left[L^2 + (h_1 - \frac{1}{2}vt)^2\right]^{3/2}}$$

i.e. $$\frac{2qvt\ (h_1 - \frac{1}{2}vt)}{L^3}$$ if L is very much greater than ~~H~~ h_1.

The charge qvt was originally at a height h_1 above the ground, and then produced a field at this point

$$\frac{2qvth_1}{L^3}$$ if L is very much greater than h_1

Hence the field change after a time t due to the leader process will be

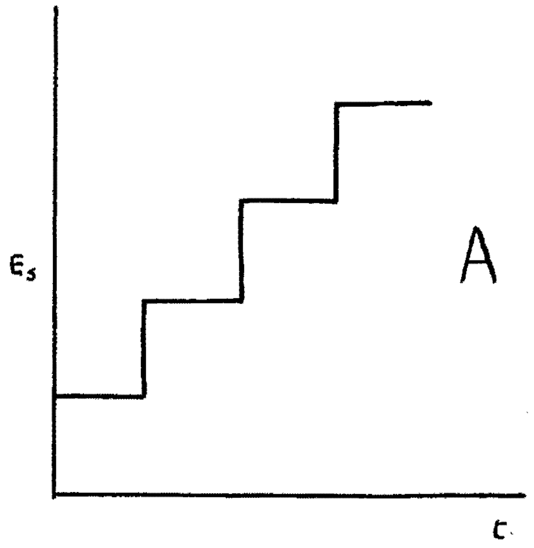
$$\frac{2qvt.\frac{1}{2}vt}{L^3} = \frac{qv^2t^2}{L^3}$$ (positive if q be negative)

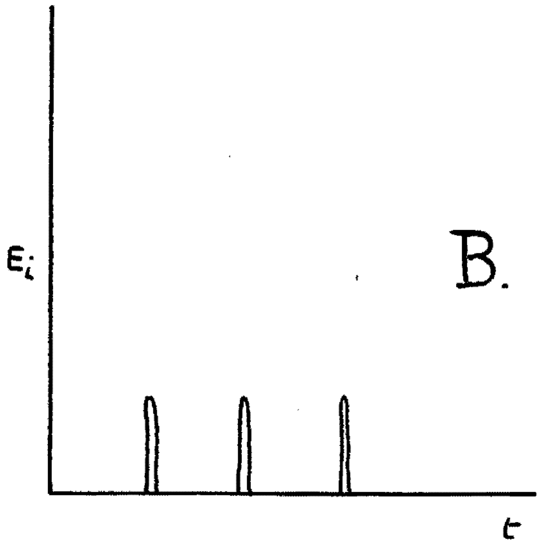
i.e $$\underline{\underline{d_1 = \frac{qv^2t^2}{L^3}}}$$

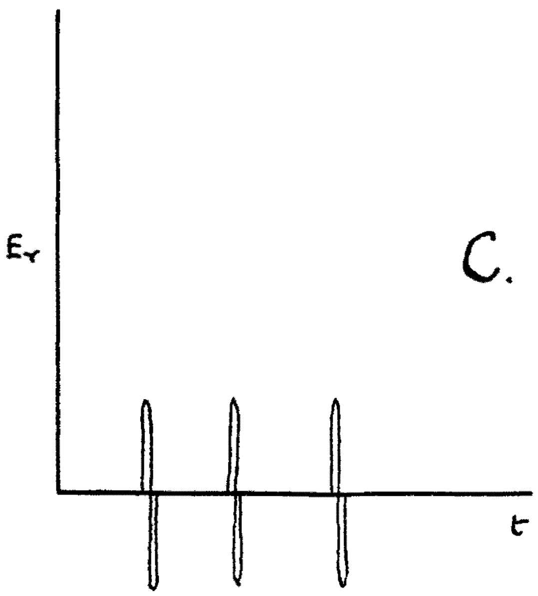
If we assume as a first approximation that, for a particular leader, q, v and L are constant, $d_1 = kt^2$. Thus the form taken by the oscillograph record of such a leader process will be a parabolic curve concave upwards. For first leaders v must be taken as the effective velocity of the downward movement, and for subsequent leaders it will be the actual velocity of the dart The oscillograph records show the trace of the leader field chang on the films following this parabolic curve in certain cases.

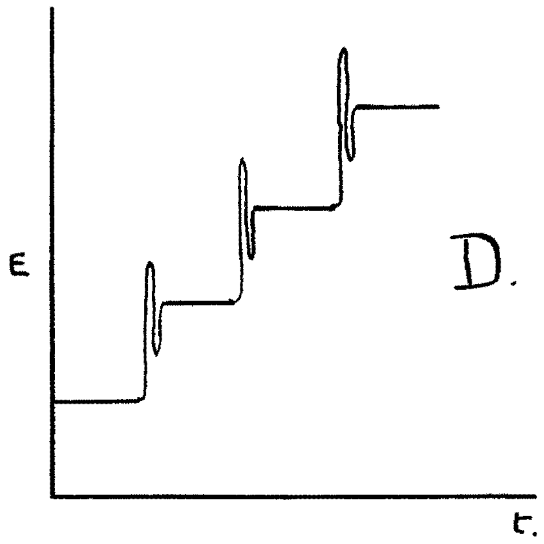
THE LEADER PROCESS IN FIRST STROKES.

The Boys' camera records have shown that the leader process in the first stroke of a flash is executed discontinuously, at intervals of from 96 micro-seconds to 16 micro-seconds. The actual value of v while a step is in progress is very high, about 5 x 10^9 cms/sec., so that the change in moment due to the step takes place in a very short interval of time. Between consecutive steps in the leader process there is a pause.









The changes in the Electrostatic field (E_s) due to the leader process may be represented graphically as in Figure A.

With rapid changes of this type taking place in E_s , they will involve consequent changes in E_i and E_r, and these may be represented graphically as in Figures B and C respectively.

The relative amplitudes of E_i and E_r will depend on the distance of the oscillograph from the flash. From the general equation for the field change

$$E = \frac{1}{r^3} \cdot M + \frac{1}{cr^2} \cdot \frac{dM}{dt} + \frac{1}{c^2 r} \cdot \frac{d^2M}{dt^2}$$

it is clear that the ratio of the scale of ordinates of B to A will increase linearly with distance, and that of C to A will increase as the square of the distance. Figure D gives a possible combination of E_s, E_i and E_r.

From the above considerations it may be pointed out that the oscillograph trace of a first leader will be such that the radiation ripple is likely to be small or absent on near flashes, and large on distant flashes. Further, with a near flash E_i may be expected to exceed E_r in effect, and thus thecleader ripple should show pulses rather than waves.

The low resolving power of the oscillograph employed in the present investigation precludes a full examination of all the points involved in the field changes due to the stepped leader process. It is possible, however, on a good photographic record of a first leader, to detect the presence of ripple on the leader trace, and to calculate the frequency of the ripple. In the next section the results from such an examination are indicated. For this purpose there have been included in the examination all records available of both Type α and Type β first strokes on which measurements on the ripple could be made.

TABLE VI.

MEASUREMENTS ON FIRST LEADER RIPPLE.

FLASH	TYPE	Suitability for Ripple measurement	Length of film on which ripples were counted	Number of Ripples Counted	Average Ripple Frequency	Ripple Amplitude as compared with total electrostatic field change due to flash.	
			0.1 m.m.		x 10^3	Mean	Peak.
J.2	α	s.p.	17	10	6.8	-	-
J.3	α	p.	30	21	8.1	-	-
J.5	β	s.p.	21	13	7.1	-	-
R.1	α	f.	18	14	7.7	0.105	0.368
R.2	γ	g.	30	34	11.3	0.157	0.684
X.1	α	s.p.	21	17	10.8	0.138	0.482
X.3	β	f.	35	32	12.2	0.025	0.123
Y.1	β	f.	30	25	11.1	0.034	0.171
Z.2	γ	g.	48	40	11.1	0.067	0.199
Z.3	α	s.p.	14	11	10.5	0.05	0.1
A.L.2	β	s.p.	15	11	9.8	-	-
A.P.1	β	g.	35	31	11.8	3.6	12.6
A.Q.1	β	g.	39	30	10.2	0.147	0.353
A.Q.2	β	g.	24	22	12.2	0.121	0.525
A.Q.3	β	f.	59	42	9.5	0.038	0.155
A.R.2	α	p.	21	16	10.1	0.094	0.25
A.R.4	α	p.	49	36	9.8	0.056	0.22
A.S.2	β	p.	22	15	9.1	0.16	1.59

MEASUREMENTS ON FIRST LEADER RIPPLE.

Table VI gives the results of measurements made on the oscillograph records of first strokes which show leader ripple with sufficient distinctness to allow of measurements being made.

The symbols in Column 3 have the following meanings:-

s.p.	poor record with some portions only having a suspicion of ripple.
p.	poor.
f.	fair.
g.	good.

It will be noticed that Columns 4 and 5 have been compiled when working at the limit of the resolving power, and hence the results can only be relied on to furnish an order of magnitude.

Certain of the records are classified as good, and, if these alone be considered, they give a mean value for the ripple frequency of 11.3×10^3. This result fixes the average time interval between successive steps in the leader process at 88.5 micro-seconds. If the results from the poorer films be included, they tend to decrease the average ripple frequency, and hence to increase the average time interval between successive steps. As has been mentioned above, the oscillograph, when recording these field changes due to the leader steps, is working at the limit of its writing speed on the film, hence the tendency will be for the film record to fail to record certain of the "steps", especially if the amplitude be large. Thus the number of ripples counted in a given length of film track will always tend to be less than the actual number of sudden field changes occurring over that interval of time, and progressively less the poorer the film record. It is therefore safe to assume that the above figure of 88.5 micro-seconds for the average time interval between successive first leader steps is too high, and the measurements shown in Table VI are in satisfactory agreement with the values found for the time intervals between the ends of successive steps in the stepped leader process as derived from measurements made on the Boys' camera photographs. Thus for a particularly clear photograph of a stepped leader (Flash 76) Schonland, Malan and Collens give the values of these intervals as varying from 96 micro-seconds to 16 micro-seconds, with a mean value of 52 micro-seconds.

It is natural to investigate the question of the occurrence of this leader ripple on every first stroke record. From the theory of leader propagation this should be the case. The films have been closely examined in this respect, and on the majority of the records of first stroke leaders the ripple can be discerned. In certain cases it is a mere discontinuity in the film trace, but, when the limits of resolution of the present method are considered, it is safe to assume that such ripple does exist on all leaders to first strokes.

FIELD CHANGES ASSOCIATED WITH TORTUOSITY OF LEADER CHANNEL.

It is necessary to consider the effect on the trace produced on the oscillograph record by the leader process of any sudden change in the direction of the downward moving leader. An examination of the photographic records of lightning flashes indicates that the path followed by a flash is not the straight vertical line between cloud and earth that was assumed as a first approximation when the case of the leader to a first stroke was considered. In practice the ionised path which the leader process establishes is usually a tortuous path in space.

In the first place the case of a straight channel, but inclined at an angle θ to the vertical, may be considered. As before, a constant track velocity, v, will be assumed, with a channel charge q per unit length.

After a time t the channel will carry a charge qvt at an effective height $h_1 - \frac{1}{2}vt.\text{Cos}\ \theta$

Hence the change of moment in the time t will be

$2qvt.h_1 - 2qvt.(h_1 - \frac{1}{2}vt.\text{Cos}\ \theta)$ i.e. $qv^2t^2.\text{Cos}\ \theta$.

And the field change at a point such that L is very much greater than h_1 will be given by

$$d_1 = \frac{qv^2t^2.\text{Cos}\ \theta}{L^3}$$

This expression, which holds as long as θ is constant, has one important application. Suppose that, at the start of the leader process, the channel be horizontal.

Then $\text{Cos}\ \theta = 0$ and $d_1 = 0$.

Hence if the leader to any flash start with a long horizontal portion, this will have no effect on the oscillograph, and, as far as the oscillograph record is concerned, the leader will only appear to commence at the time that the actual leader has completed the horizontal portion of its path and begins its vertical path. Thus for a leader of this type the leader time

t_1

(t_1) as indicated by the oscillograph record will be shorter than the actual duration of the leader obtained from measurements of a Boys' camera record of the flash.

An examination of a number of photographic records of lightning flashes indicates that this condition, a channel with a horizontal top, is sufficiently frequent to make the average time of duration of the leader process obtained from an analysis of the oscillograph records appreciably less than the same quantity obtained from an analysis of the Boys' camera records. In this connection it is interesting to remember the results obtained from the analysis of the leader process times of subsequent strokes obtained from the oscillograph records. These indicated that the times thus obtained were in general less than those obtained by Schonland, Malan and Collens from the Boys' camera records.

In the next place the case may be considered where the leader channel develops vertically for a time t, and then travels in a direction inclined at an angle θ to the vertical for a time t_1.

Making the same assumptions as before as to track velocity and channel charge, after a time $(t + t_1)$ the charge on the channel will be

qvt at an effective height $(h_1 - \frac{1}{2}vt)$
plus qvt_1 at an effective height $(h_1 - vt - \frac{1}{2}vt_1 \text{Cos}\,\theta)$

Hence the change of moment in a time $(t + t_1)$ will be

$$2qv(t + t_1)h_1 - \left[2qvt(h_1 - \tfrac{1}{2}vt) + 2qvt_1(h_1 - vt - \tfrac{1}{2}vt_1 \text{Cos}\,\theta)\right]$$

$$\text{i.e.}\quad qv^2(t^2 + 2t.t_1 + t_1^2.\text{Cos}\,\theta).$$

And the field change at a point such that L is very much greater than h_1 will be

$$d_1 = \frac{qv^2(t^2 + 2t.t_1 + t_1^2.\text{Cos}\,\theta)}{L^3}$$

Thus the change θ in the direction of the leader channel only affects the last term in the expression for d_1. If t_1 be small in comparison with t, then, even if the turn be horizontal, so that $\cos\theta$ is zero, this will make no practical difference to d_1 as long as it does not last for an appreciable time.

Suppose, however, that t_1 is equal to t, and at the same time the turn be horizontal, so that $\cos\theta$ is zero. Then the field change in time 2t with no horizontal turn

$$d_1 = \frac{4qv^2t^2}{L^3}$$

And the field change in time 2t with the horizontal turn

$$d_1' = \frac{3qv^2t^2}{L^3}$$

Hence $$\frac{d_1}{d_1'} = \frac{4}{3}$$

Since, however, the change due to the horizontal turn only occurs after a time t, the position will be

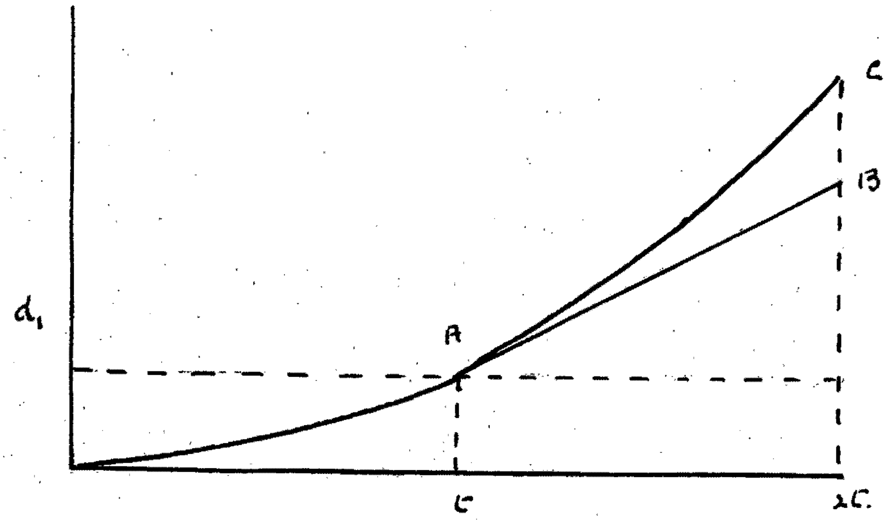
The field change in the time t to 2t with no horizontal turn will be $$\frac{4qv^2t^2}{L^3} - \frac{qv^2t^2}{L^3} = \frac{3qv^2t^2}{L^3}$$

The field change in the time t to 2t with the horizontal turn will be $$\frac{3qv^2t^2}{L^3} - \frac{qv^2t^2}{L^3} = \frac{2qv^2t^2}{L^3}$$

This gives the ratio for the time t to 2t

$$d_1 : d_1' \quad \text{AS} \quad 3/2.$$

Now it has been shown previously that, for a leader travelling along a vertical track, the graph of d_1 with time was a parabola. The case just considered becomes clear from the following figure.



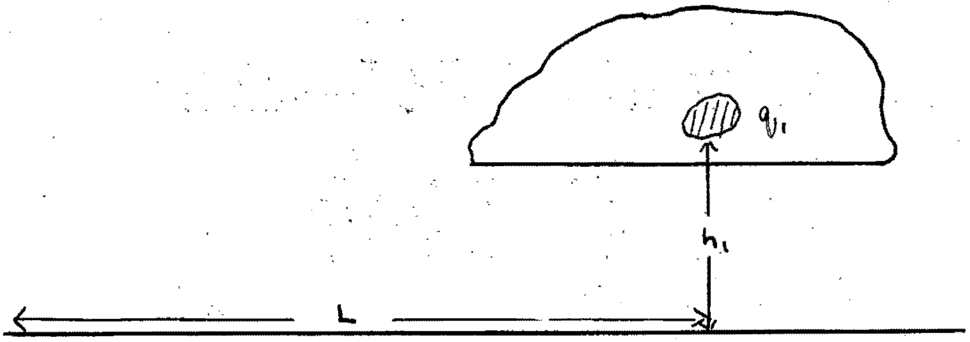
The curve for d_1 between t and 2t has a constant slope whose value depends on the time during which the horizontal path exists. Thus if the vertical channel makes the horizontal turn at the time t, the oscillograph trace at the point A will follow the straight line AB, whereas, with no turn in the leader channel, the oscillograph trace will follow the parabolic curve AC. It is clear from the figure that the change of direction in the channel will give no abrupt change of slope at the point A. in the oscillograph trace. Should any such abrupt change in the slope of the curve have occurred, it is clear that it would have given rise to radiation effects which might well be comparable with that associated with the steps in the first stroke leader process. Hence it is clear that in subsequent strokes, where the Boys' camera records show that the leader process is a rapid continuous dart process along the channel, even if the channel be a tortuous one, as is generally the case, the oscillograph trace may be expected to show no radiation ripple.

The Boys' camera records do indicate that, in certain cases of a long leader to a subsequent stroke, the leader becomes stepped near the end of its path, but the pause in such cases lasts for 5 ÷ 10 micro-seconds, and the consequent ripple structure is too fine to be recorded with the low resolving power of the present type of oscillograph.

THEORY OF THE CATHODE RAY OSCILLOGRAPH RECORD OF FIELD CHANGES.

Before considering the results of the analysis of the magnitudes of the field changes from the oscillograph records it is necessary to consider the matter theoretically. The general form of the oscillograph record to be expected from a lightning flash to ground has previously been considered, based on the sequence of events in the discharge process as revealed by the Boys' camera records. The question will now be considered in greater detail.

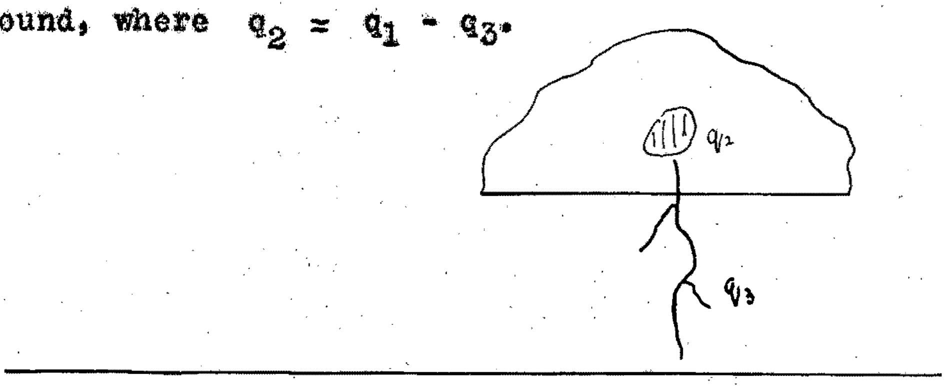
Suppose that a cloud carries a charge q_1 at a height h_1 above the ground, and that the field changes are being recorded at a point on the ground at a distance L from the point on the ground vertically under the cloud.



The moment of the cloud charge will be $M_1 = 2q_1h_1$

And the field at the point will be $E_1 = \dfrac{2q_1h_1}{(h_1^2 + L^2)^{3/2}}$

The leader stage means the lowering of a certain portion of the cloud charge, q_1, and distributing it along the channel and branches of the stroke. The nature and length of the branches will determine this distribution, and the effective height to which this charge is lowered. We may first estimate this height as being in the neighbourhood of $\frac{1}{2}h_1$ and in general as lying between $\frac{1}{4}h_1$ and $\frac{3}{4}h_1$ Suppose that the leader stage results in the lowering of a charge q_3 to an effective height $\frac{1}{2}h_1$ above the ground, leaving a charge q_2 in the cloud at a height h_1 above the ground, where $q_2 = q_1 - q_3$.



The moment at the end of the leader stage will be

$$M_2 = 2q_2h_1 + 2q_3 \cdot \tfrac{1}{2}h_1 = h_1(2q_2 + q_3)$$

And the field at the point under consideration at the end of this stage will be

$$E_2 = \frac{2q_2h_1}{(h_1^2 + L^2)^{3/2}} + \frac{q_3h_1}{(\frac{1}{2}h_1^2 + L^2)^{3/2}}$$

DISTANT FLASHES.

Suppose that $L \geqq 10$ Kilometres, while h_1 is 3 Kilometres, which may be taken as an average height for a cloud. Then we may neglect h_1^2 in comparison with L^2, and we have

$$E_1 = \frac{2q_1h_1}{L^3} \quad \text{and} \quad E_2 = \frac{h_1(2q_2 + q_3)}{L^3}$$

Consequently the change of field due to the leader process will be

$$d_1 = E_1 - E_2$$

$$= \frac{h_1(2q_1 - 2q_2 - q_3)}{L^3}$$

$$= \underline{\underline{\frac{h_1q_3}{L^3}}}$$

VERY CLOSE FLASHES.

Suppose that $h_1 \gg L$, so that L^2 may be neglected in comparison with h_1^2

We then have

$$E_1 = \frac{2q_1}{h_1^2} \quad \text{and} \quad E_2 = \frac{2q_2}{h_1^2} + \frac{8q_3}{h_1^2}$$

Consequently the change of field due to the leader process will be

$$d_1 = E_1 - E_2 = \frac{2q_1 - 2q_2 - 8q_3}{H_1^2} = \underline{\underline{-\frac{6q_3}{h_1^2}}}$$

In this case the field has <u>INCREASED</u>, due to the leader process. Hence there must be some reversal distance (L_0) at which the field change due to the leader is zero, i.e. where d_1 is zero. This will depend on the effective height of q_3, i.e. the manner in which the charge is distributed over the channel and branches.

<u>REVERSAL DISTANCE.</u>

First consider the three cases where the effective height of q_3 is $\frac{3}{4}h_1$, $\frac{1}{2}h_1$ and $\frac{1}{4}h_1$ respectively. Equating E_1 and E_2 :-

Effective Height = $\frac{3}{4}h_1$	Effective Height = $\frac{1}{2}h_1$	Effective Height = $\frac{1}{4}h_1$.
$\frac{2q_3h_1}{(h_1^2+L_o^2)^{3/2}} = \frac{2q_3\cdot\frac{3}{4}h_1}{[(\frac{3}{4}h_1)^2+L_o^2]^{3/2}}$	$\frac{2q_3h_1}{(h_1^2+L_o^2)^{3/2}} = \frac{2q_3\cancel{h_1}\cdot\frac{1}{2}h_1}{[(\frac{1}{2}h_1)^2+L_o^2]^{3/2}}$	$\frac{2q_3h_1}{(h_1^2+L_o^2)^{3/2}} = \frac{2q_3\cdot\frac{1}{4}h_1.}{[(\frac{1}{4}h_1)^2+L_o^2]^{3/2}}$
$h_1^2+L_o^2 = 1.212(\frac{9}{16}h_1^2+L_o^2)$	$h_1^2+L_o^2 = 1.588(\frac{1}{4}h_1^2+L_o^2)$	$h_1^2+L_o^2 = 2.52(\frac{1}{16}h_1^2+L_o^2)$
Let $L_o = xh_1$	Let $L_o = xh_1$	Let $L_o = xh_1$
$1+x^2 = 1.212(\frac{9}{16}+x^2)$	$1+x^2 = 1.588(\frac{1}{4}+x^2)$	$1+x^2 = 2.52(\frac{1}{16}+x^2)$
$\underline{x = 1.266}$	$\underline{x = 1.013}$.	$\underline{x = 0.745}$.
<u>FOR REVERSAL</u>	<u>FOR REVERSAL</u>	<u>FOR REVERSAL</u>
$\underline{\underline{L_o = 1.266\ h_1}}$	$\underline{\underline{L_o = 1.013\ h_1}}$	$\underline{\underline{L_o = 0.745\ h_1}}$

It follows that, for the average type of flash to ground, where the effective height of q_3 is approximately $\frac{1}{2}h_1$, the reversal distance is approximately h_1.

Since the field change at the reversal distance is zero, as we proceed from this point d_1 increases in value, but for a certain distance will obviously be less than $\frac{h_1 q_3}{L^3}$ (the field change as calculated for a distant flash)

As an example, consider the case where h_1 is 3 Kilometres and L is 7 Kilometres. In this case, assuming the effective height of the leader charge, as before, to be $\frac{1}{2}h_1$, we will have

$$d_1 = E_1 - E_2 = \frac{2q_3h_1}{(h_1^2 + L^2)^{3/2}} - \frac{q_3h_1}{(\frac{1}{4}h_1^2 + L^2)^{3/2}}$$

and, on substitution of the above values, d_1 has the value $\frac{q_3h_1}{(8.215)^3}$ instead of the approximate value $\frac{q_3h_1}{7^3}$

If we assume that h_1 is 4 Kilometres and that L is 7 Kilometres, then we find that d_1 is $\frac{q_3h_1}{(9.35)^3}$

Hence it follows that, with long flashes taking place near the site of the oscillograph, although outside the reversal distance, we should expect to obtain on the oscillograph record abnormally low values for d_1.

In general, however, if the flash be distant from the oscillograph anything beyond say 10 Kilometres, as is usually the case, the value of d_1 should represent $\frac{q_3h_1}{L^3}$

It must be remembered that the above analysis is based on the change in the cloud moment, M, and hence the value for d_1 that has been calculated refers only to the contribution of the electrostatic field (E_s) to d_1.

THE MAIN RETURN STROKE RECORD (d_2)

The main stroke stage represents the passage to earth of the charge which the leader process distributed along the channel and the branches, and this rapid process will be identified with the rapid field change indicated by d_2 on the oscillograph record.

First consider the case where the effective height of the leader charge at the end of the leader stage is $\frac{1}{2}h_1$, the most general case.

Then $d_2 = \dfrac{2q_3 \cdot \frac{1}{2}h_1}{(\frac{1}{4}h_1^2 + L^2)^{3/2}}$ and, if the flash be well beyond the reversal distance, so that L is very much greater than h_1

$$\underline{\underline{d_2 = \frac{q_3 h_1}{L^3}.}}$$

In the previous section it was seen that in such a case the value for d_1 was $\dfrac{q_3 h_1}{L^3}$

Hence, in general, it should be found that the values of d_1 and d_2 are approximately equal, or that the ratio $d_2 : d_1$ is approximately unity.

Next consider the two limiting cases, where the effective height of the leader charge after the leader process is complete is (a) $\frac{3}{4}h_1$ (b) $\frac{1}{4}h_1$.

From the photographic records it may be concluded that (b) is of rarer occurrence than (a).

EFFECTIVE HEIGHT $\frac{3}{4}h_1$

Assuming $L \gg h_1$

$$d_1 = E_1 - E_2$$

$$= \frac{2q_3 h_1}{L^3} - \frac{2q_3 \cdot \frac{3}{4}h_1}{L^3}$$

$$\underline{\underline{= \frac{q_3 \cdot h_1}{2L^3}}}$$

EFFECTIVE HEIGHT $\frac{1}{4}h_1$

Assuming $L \gg h_1$

$$d_1 = E_1 - E_2$$

$$= \frac{2q_3 h_1}{L^3} - \frac{2q_3 \cdot \frac{1}{4}h_1}{L^3}$$

$$\underline{\underline{= \frac{3q_3 h_1}{2L^3}}}$$

EFFECTIVE HEIGHT $\frac{3}{4}h_1$

Assuming $L \gg h_1$

$$d_2 = \frac{2q_3 \cdot \frac{3}{4}h_1}{L^3}$$

$$= \frac{3q_3 \cdot h_1}{2L^3}$$

Hence

$d_2 : d_1 :: 3 : 1.$

EFFECTIVE HEIGHT $\frac{1}{4}h_1$

Assuming $L \gg h_1$

$$d_2 = \frac{2q_3 \cdot \frac{1}{4}h_1}{L^3}$$

$$= \frac{q_3 \cdot h_1}{2L^3}$$

Hence

$d_2 : d_1 :: 0.33 : 1.$

Hence, on the oscillograph record for any ground flash well beyond the reversal distance we should expect the ratio $d_2 : d_1$ to lie between 0.3 and 3, with a usual value not far from unity, the mean of the distribution curve for this ratio lying above, rather than below, unity.

Once again itvmust be pointed out that the analysis refers only to the contribution of the electrostatic field (E_s) to d_1 and d_2, and thus will only hold for near flashes.

THE RESIDUAL CHARGE RECORD (d_3)

The third stage in the discharge process is the destruction of the residual charge, q_2, at the top of the leader channel, and the resultant field change at the aerial is represented on the oscillograph record by d_3. This process may be expected to be much slower than the main stroke process, and hence d_3 will be unaccompanied by any radiation field. The ionisation processes which established the leader originally are progressively more ancient as we pass upwards from the base of the discharge. The analysis of the Boys' camera records has shown that the rapidity of movement of the return stroke is slower the older the ionised channel it has to traverse, since the luminosity, and consequently the rate of dissipation of energy, is less. With a less rapid rate of movement, the return stroke must carry a smaller current, and hence will produce no radiation effects. All the evidence from the photographic records, as well as from the oscillograph records, seems to suggest that the discharge of q_2 is a slow process, involving a multitude of slow partial discharges of different parts of the cloud region affected.

Now $d_3 = \dfrac{2q_2.h_1}{L^3}$ and $d_1 + d_2 = \dfrac{2q_3.h_1}{L^3}$

Hence
$$\underline{\underline{\frac{d_3}{d_1 + d_2 + d_3} = \frac{q_3}{q_2 + q_3}}}$$

This ratio from the oscillograph records will therefore indicate the ratio of the residual charge remaining in the cloud region affected to the original charge on the cloud region.

FIELD CHANGE MEASUREMENTS FROM OSCILLOGRAPH RECORDS.

EFFECTIVE HEIGHT OF LEADER CHARGE.

Figure 6 is the distribution curve for the ratio d_2/d_1 for first strokes. This ratio ranges from 0.4 to 2.6, with a most probable value not far from unity.

From the previous theoretical discussion of this ratio it may be seen that its value will determine the effective height of the leader charge at the completion of the leader process.

For suppose this height be h_1/n.

Then $d_1 = \dfrac{2q_3h_1(1 - 1/n)}{L^3}$ and $d_2 = \dfrac{2q_3 . h_1/n}{L^3}$

$$\text{Hence} \quad d_2 : d_1 :: 1/(n - 1).$$

If d_2/d_1 be 1, n is 2, and the effective height is $h_1/2$.
" " 0.4 " 3.5, " " " $h_1/3.5$
" " 2.6 " 1.4, " " " $h_1/1.4$

Figure 7 is the distribution curve for the ratio d_2/d_1 for all strokes. The values for this curve have been obtained from all good records of both first and subsequent strokes. It will be seen that, although the range is found to be wider, as may be expected when the records of subsequent strokes are included in the analysis, the most probable value is still not far from unity.

From the results shown in both Figure 6 and Figure 7 it may be concluded that the most probable value of the effective height of the leader charge at the completion of the leader process in both first and consequent strokes is $h_1/2$.

RESIDUAL CHARGE FROM THE OSCILLOGRAPH RECORDS.

Figure 8 is the distribution curve for the ratio $d_3 : d_1 + d_2 + d_3$, for first strokes. It ranges in value from less than 0.1 to about 0.8, and its most probable value lies between 0.3 and 0.4.

Since this ratio measures the ratio of the residual charge remaining on the cloud region to the original charge, these results tend to show that the first stroke of a flash involves the lowering of the greater portion of the charge in the cloud region affected along the leader channel.

Figure 9 is the distribution curve for the same ratio for subsequent strokes. The results included in this curve are only from records which show clearly the transition from d_2 to d_3, i.e. which indicate clearly the end of the main return stroke.

From Figure 9 it may be seen that the value of the ratio ranges from 0.1 to 0.9, and its value is usually higher in the case of subsequent strokes than in the case of first strokes. Hence it may be concluded that the leader to a subsequent stroke lowers a smaller fraction of the cloud charge along the leader channel than does the leader to a first stroke.

TYPE β FIRST STROKES.

As was shown in Table IV, the β type of first stroke occurred in 13 of the 65 flashes examined. An examination of the diagram of the general form of this type shown in Figure 2 indicates that it conforms to the α type as far as the main return stroke and the residual cloud charge destruction are concerned, but differs in the leader process.

From the diagram it may be seen that the leader process in this type of first stroke may be considered as taking place in three stages. The first stage is the normal stepped leader process, lowering a charge into the air beneath the cloud. This occupies a time interval indicated by T_2 in the diagram.

In the second stage the oscillograph trace, instead of rising, bends downwards towards the zero base-line. It will be remembered that, in the construction of the oscillograph unit used in this investigation, a high resistance was inserted across the condenser plates in the aerial circuit, to prevent the accumulation of a charge on the upper plate of this condenser, any such charge leaking to earth through this resistance. It was pointed out that the time constant of this circuit was made very high, so that it should greatly exceed the normal time of duration of any field change under examination by the oscillograph, and thus its effect might normally be neglected. With a field change of long duration, however, the presence of this resistance in the circuit would appreciably affect the nature of the oscillograph trace obtained from such a field change. The trace actually recorded on the film would be the resultant of (a) the curve indicating the field changes occurring at the aerial, and (b) the exponential decay curve due to the inclusion of the resistance. If (b) should exceed (a) at at any stage, then the resultant oscillograph trace, instead of rising, would bend downwards towards the zero base-line. To determine the magnitude of (a) from such a trace it would therefore be necessary to determine the deviation of the oscillograph trace from the exponential curve for the particular aerial circuit employed. From an examination of the oscillograph records of this type of first stroke, it may be concluded that the second stage in the leader process in a β type of first stroke represents a very slow leader propagation.

The third stage is represented by a further rise in the oscillograph trace, just before the main return stroke. This indicates an appreciable increase in the velocity of the leader propagation immediately preceding the main return stroke. The total time of the leader process is indicated by T_1 in the diagram.

It is interesting to note that Schonland, Malan and Collens, in their examination of the Boys' camera photographs, have observed cases of a type of leader of long duration. In this type it is found that the first portion of the leader is fast and powerfully stepped, and the second portion very slow, the steps being faint and weak. This type of leader has been the subject of a special investigation by them, the results of which have not as yet been published.

TIMES ASSOCIATED WITH LEADER TO β FIRST STROKES.

The distribution curves for T_1 and T_2 for the Type β records in the present investigation are given in Figures 10 and 11.

It will be noted that the complete time interval occupied by the leader process varies from 13.6×10^{-3} second to 63.6×10^{-3} second, with a mean value of 38.2×10^{-3} second. On the other hand the time interval occupied by the first part of the leader process (T_2) varies from 1.9×10^{-3} second to 10.3×10^{-3} second, with a mean value of 5.8×10^{-3} second. A comparison between these values and those for the normal Type α first stroke leader are of interest. It was shown from Figure 4 that these latter lie between 2.86×10^{-3} second and 38.37×10^{-3} second, with a most probable value of about 18×10^{-3} second. Thus it may be seen that the first part of the leader process in a Type β first stroke occupies a shorter time interval on the average than the normal stepped leader process for a first stroke, while the whole leader process is on the average much longer. It therefore appears as though the leader process commences in the same manner in both cases, and that, in the case of the Type β, there is a marked decrease in the velocity of propagation before the final stage to earth.

It is interesting to note that the first portion of the leader process, during the time interval T_2, is invariably stepped, since all the records of this type examined have been found to exhibit leader ripple on the first portion of the oscillograph record. On the other hand, no trace has been found of this leader ripple on the other portions of the leader trace. The quantitative records associated with the leader ripple in this type of first stroke are included in the results tabulated in Table VI.

TYPE γ AND δ FIRST STROKES.

It will be observed from Table IV that, of all the first strokes examined in the present investigation, only two were of Type γ, and five were of Type δ. Of these latter, three were records which consisted of a single stroke.

The small number of these recorded precludes any detailed analysis of the types, and it is only possible to indicate certain possible explanations of their presence. An examination of the diagrams of these types in Figure 2 shows that both types are characterised by possessing a leader with a pronounced ripple, but no main return stroke record. The leader ripple frequency, as may be seen from Table VI, is in agreement with that for stepped leaders. Thus they may be either cloud discharges which have been incorrectly reported as ground flashes by the external observer, or discharges which do not reach the ground. Schonland, Malan and Collens, in their publication Progressive Lightning II, Section 10, discuss discharges of this type as observed on the Boys' camera photographs, and point out that they are of two types, stepped and dart respectively. In neither type is there evidence of a return main stroke.

VARIATION IN MAGNITUDE OF FIELD CHANGES WITH DISTANCE.

In the present investigation the only method that was available for the estimation of the distance of the flash from the oscillograph unit was to determine the time interval between observing the flash and first hearing the resultant thunder due to the flash. This determination was made in every case by the external observer, and his result was subsequently noted in the log book against the flash with the other relevant information.

It is clear that such a method precludes accurate information, even if each flash and its attendant thunder could be isolated. In addition, however, it must be remembered that, in an active storm, flashes are sufficiently frequent to make it often impossible to differentiate between them. Further, as has been previously mentioned, there may be two or more active storms at different distances flashing more or less simultaneously, all within thunder distance of the observer. It therefore becomes clear that the estimation of the distance between flash and oscillograph can only be relied on to furnish an order of magnitude, and may often be totally incorrect. In the following analysis the estimated distance of the flash from the oscillograph, as supplied by the observer, has been used, but the limitations of this estimate must be borne in mind in considering the results of the analysis.

It has been pointed out previously that the relationship between the change of moment in the cloud (M) and the corresponding field change at the aerial of the oscillograph (E) is given by

$$E = \frac{1}{r^3} \cdot M + \frac{1}{c r^2} \cdot \frac{dM}{dt} + \frac{1}{c^2 r} \cdot \frac{d^2M}{dt^2}.$$

Further, it was shown that in general,

E_s is proportional to M

E_i is proportional to dM/dt.

E_r is proportional to d^2M/dt^2

The relative values of these three terms depend on the value of the distance of the flash from the oscillograph unit. Hence it follows that, in general,

E_s will vary as L^{-3}

E_i will vary as L^{-2}

E_r will vary as L^{-1}

For a flash near the oscillograph, where the value of L is small, the film trace may be considered as a measure of the Electrostatic field change alone, and, when allowance is made for the relationship between the actual field change taking place in the neighbourhood of the aerial and the resultant voltage across the condenser in the aerial circuit, which in turn is applied through the amplifier to the working plates of the oscillograph, the reduced value of $(d_1 + d_2 + d_3)$ from the film will give a measure of E_s. This latter relationship, as has been previously shown, is given by

$$E = \frac{1}{h}\left\{\frac{C + C_o}{C_o}\right\} V$$

where C_o is the capacity of the aerial

C is the capacity of the condenser in the circuit

V is the voltage applied through the amplifier

h is the effective height of the aerial.

It follows that, if it were possible to obtain oscillograph records from the same flash for various values of L, provided all these values were small, E_s should vary as L^{-3} or $E_s.L^3$ should be a constant.

In the present analysis it is only possible to compare the records from different flashes at different distances. For the product $E_s.L^3$ to be constant, therefore, each flash should proceed from a cloud at a constant height above the ground, and moreover each flash should result in the destruction of an equal charge. Any variation in either of these factors will result in a corresponding variation in the value of the product $E_s.L^3$. The results of the previous analyses of the films previously given indicate that both the height of the cloud and the total charge destroyed by a flash vary from case to case, and, when the uncertainty of the value of L is taken into account, the various values of $E_s.L^3$ may be expected to differ considerably.

Figure 12 is a diagram showing the value of the logarithm of the product $E_s.L^3$ for first strokes of a flash plotted against the corresponding value of L as supplied by the external observer. The results are shown in this form because of the considerable variation in the value of this product for different flashes.

When allowance is made for all the variable factors previously mentioned, the diagram seems to indicate a tendency for the field changes from near storms to have abnormally low values. This result, however, may be due to any of the factors mentioned above, and further investigation of this point is necessary.

VARIATION OF E_r WITH DISTANCE.

The present investigation is concerned with the field changes in the near neighbourhood of the lightning flash, and, as was pointed out in the previous section, the oscillograph records provide, in the main, a measure of the variation in E_s with time due to the flash. Whenever an abrupt change in the slope of the oscillograph record occurs, however, the radiation term, E_r, becomes prominent on the oscillograph trace. Such a change always occurs at the end of the leader process, when the main return stroke process commences, and this may be seen in the diagram of the typical record of an α type of first stroke shown in Figure 2. For comparative purposes use may be made of the values of the distance marked R on this diagram to determine the value of E_r for any particular stroke, and such values have been used in an attempt to analyse the variation in the value of E_r with the distance of the flash from the oscillograph unit.

In the previous section it was shown that, when the reduced value of E_r has been determined from the film trace, E_r should vary as L^{-1} for the same flash at various distances, and hence the product $E_r.L$ should be constant under these circumstances. As in the case of E_s discussed in the previous section, however, it is only possible to compare the records from different flashes at different distances, and all the variable quantities discussed in connection with E_s apply equally to E_r. Hence a large variation in the values of the product $E_r.L$ obtained from the records may be expected.

The results of the determination of the values of this product from the records are shown in Figure 13, which has been compiled in the same form as Figure 12. This diagram, too, seems to indicate a tendency for abnormally low values for field changes from near storms.

VARIATION OF THE RATIO E_s/E_r WITH DISTANCE.

In the two previous sections it has been shown that, if it were possible to obtain records of the field change due to the same flash for different values of L, then both the product $E_s.L^3$ and the product $E_r.L$ should be constant. It follows that the value of the product $\frac{E_s.L^2}{E_r}$ should be constant under these conditions.

This quantity, which involves the ratio E_s/E_r, has distinct merits when compared with the quantities previously considered, which involved either E_s or E_r alone. Any factor associated with the oscillograph unit itself, and which affects the magnitude of the trace obtained on the film due to any field change, will affect E_s and E_r to the same degree. It is therefore clear that the ratio of these two quantities will not be affected by any variation in one or more of these factors. If this quantity be used in any analysis of the variation of field strength with distance, the results obtained from the oscillograph records will be independent of any variation in site factor, aerial capacity, amplification factor of the amplifier, condenser potentiometer effective height of the aerial, etc.

Figure 14 is a diagram showing the value of the logarithm of this quantity for first strokes plotted against the corresponding values of L as supplied by the external observer. It must be remembered that the results still involve all the variations due to differences in the quantities associated with the flash itself, and the inaccuracies in the determination of the value of L, and thus a large variation in the value of $\frac{E_s.L^2}{E_r}$ is to be expected.

RADIATION ASSOCIATED WITH SUBSEQUENT STROKES.

In a previous portion of this thesis some indication was given of the processes involved in the development of the charge on a thundercloud, and the subsequent destruction of a portion of that charge by a lightning flash. It was shown that the generative processes result in a separation of charge within the cloud, and that these proceed until some critical potential be reached, when the leader process commences, ionising a conducting path to earth, to be followed immediately by the intense main return stroke. The complete stroke results in the destruction of a certain portion of the cloud charge, this being drawn from the particular region of the cloud which is tapped by the stroke.

Immediately the first stroke is completed, there will be, within the cloud, a movement of charge towards this region to replenish it, and, owing to the nature of the particles composing the cloud, this flow of charge will not be uniform, but will resemble in some measure the stepped process associated with a first leader. The generative process within the cloud is continuous, and thus it may be expected that the time interval occupied by this flow of c charge to the affected region will be short.

When a first stroke is followed by several subsequent strokes, it may be expected that the charge to replenish the affected region will be progressively drawn from more and more remote regions of the cloud, and thus, after each stroke, the time interval occupied by the subsequent movements of charge within the cloud will increase progressively.

The actual change in the moment of the cloud due to such movements of charge within the cloud will be too small to appear on the oscillograph records. Since this flow of charge is not continuous, however, the sudden changes in movement will give rise to radiation effects, and these may be sufficiently large to affect the record. For this reason the oscillograph record of a flash may be expected to show evidence of such radiation effects on the portion of the film trace immediately following the record of the stroke itself.

An examination of the oscillograph records forming the subject of the present investigation reveals indications of the presence of these radiation effects on practically all records of ground flashes. An attempt has been made in Figure 15 to indicate the manner in which the time interval over which these radiation effects following the main field change extend varies over the several strokes composing a complete flash. A separate graph has been constructed for each complete flash , using the classification employed in the previous analysis of the flashes. The separate strokes composing the flash have been equally spaced along the x-axis, since there appears to be no direct relationship between the time interval between strokes and the duration of this radiation effect (T_r) The ordinates in the diagram indicate the relative values of T_r for the various strokes composing each complete flash taken in order. The first stroke of the flash is indicated by a dot in red, and subsequent strokes by small circles. Each flash is drawn to scale, although the scale used is not the same for different flashes.

RADIATION TIMES (T_r) FOR SUBSEQUENT STROKES.

An analysis of the diagrams shown in Figure 15 indicates that 79% of subsequent strokes have a value for T_r which is greater than the value of this quantity for the corresponding first stroke of the flash.

It will be noticed that the diagrams often show a progressive increase in the value for T_r after the first stroke, and then a sudden decrease , often followed by another progressive increase. Illustrations of such a change may be seen at the 5th. stroke of the diagram marked F_1, the 5th. stroke of the diagram marked O_1, etc. This seems to suggest the possibility of a record of this type not being that of a single flash, but of two or more flashes, either from the same or different clouds, which have occurred almost simultaneously, and have thus been classified on the oscillograph records as a single flash. Reference has been made previously to the possibility of the occurrence of such an error in classification, when consideration was given to the results shown in Table I, and it was shown that the total number of strokes per flash from the oscillograph records provided figures which were in general higher than the corresponding results from the analysis of the Boys' camera photographs.

If the suggestion made in the preceding paragraph were correct, and if the diagrams of the various flashes in Figure 15 were to be arranged so that each stroke such as those mentioned above formed the starting point of a new series, so that each series showed a progressive increase in T_r, the first stroke of each series should indicate, on the oscillograph record, the characteristics of a first stroke record. Thus for such records it should be found:-

(a) a long value for the leader duration (t_1)

(b) indications of leader ripple

The oscillograph records have been submitted to a careful examination in this connection, and on some of the records there appears to be evidence pointing to the probability of incorrect classification. The following Table indicates some of the results obtained.

Flash.	Stroke	Leader Duration in 10^{-4} sec.	Ripple.
F.1.	5	94.6	Slight
0.1	5	33.8	Distinct
A.Q.1	3	88.5	Nil
A.Q.2	3	95.3	Nil
A.Q.3	11	98.3	Nil
A.R.2	6	108.8	Distinct.

From the results shown in the table it may be seen that in certain cases there is every probability that two ~~[illegible]~~ flashes have been combined in the original classification as a single flash. In other cases, however, where the results from Figure 15 would suggest incorrect classification of this nature, the films show no evidence to support it.

IONOSPHERIC REFLECTION.

It has been previously shown that the lightning flash gives rise to an electromagnetic wave, which proceeds outwards from the region in which the flash occurs, and that the equation representing the field changes due to this wave at any point consists of three terms, known as the electrostatic (E_s), induction (E_i) and radiation (E_r) terms respectively. It was pointed out that for small values of L the E_s term predominates, whereas for large values of L the E_r term is the important one. It therefore followed from this that the field changes recorded on the oscillograph trace due to the lightning flashes in the present investigation were due mainly to the E_s term, but that the rapid change that occurred in the field at the commencement of the main return stroke would be indicated on the record by a radiation term, and this was shown on the diagram of a typical first stroke record in Figure 2, the magnitude of the field change being indicated by R.

When the electromagnetic wave, originating at the lightning flash, reaches the ionosphere, it will suffer reflection, and when it again reaches the earth it will have traversed a sufficient space for the radiation term in the equation to predominate. Thus any such wave reaching the oscillograph unit after reflection at the ionosphere may be expected to make its presence evident on the oscillograph trace by a record of this main return stroke radiation field alone. If the magnitude of the reflected wave be sufficient to affect the record, its position on the record will be such that the time interval represented by the record of the field change due to the main return stroke of the flash and that due to the reflected wave will provide a measure of the effective height of the reflecting layer of the ionosphere.

If reference be made to the diagrams of typical first stroke records shown in Figure 2, it will be seen that a depression or "bump" is found to occur on the oscillograph trace shortly after the record of the field changes due to the three stages of the stroke itself. This bump is found to occur on a large number of records, and it is thought that a possible explanation of its presence may be, as indicated above, that it is the record of the arrival of the reflected wave at the oscillograph unit.

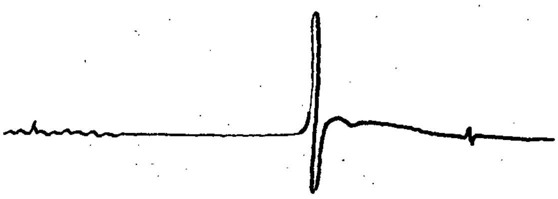
If this suggested explanation be correct, then the time interval marked t_b on the diagram in Figure 2 may be utilised to calculate the equivalent height of the reflecting layer, provided the value of L, the distance between flash and oscillograph unit, be known. It must be remembered, however, that such a calculation would be based on two quantities, both of which, due to the limitations of the apparatus and methods of the present investigation, can only be determined very approximately. Thus a calculation of this type cannot be expected to do more than furnish an order of magnitude for the equivalent height of the reflecting layer.

Some 20 values of t_b have been obtained from measurements on the oscillograph records, and the corresponding equivalent height of the reflecting layer calculated. The values thus found range from 95 Kilometres to 119 Kilometres, with a most probable value in the neighbourhood of 100 Kilometres. When the limitations of the method are taken into account, this result seems to point to the possibility of the explanation of the presence of/the bump given above being correct.

RECORDS OF (a) DISTANT FLASHES (b) CLOUD FLASHES.

The primary object of the present investigation was to investigate the field changes occurring in the neighbourhood of a near lightning flash, and to correlate the oscillograph records of such changes with Boys' camera records of the flashes. Since these latter were in the main records of ground flashes, the oscillograph records of the field changes due to this type of flash have been the principal subject of discussion. It is felt, however, that some mention should be made of two other types of record which frequently appear on the films, and some indication given of their general form.

During the summer season the whole of the Witwatersrand area is subject to thunderstorms, and the position often arises when several separate storms occur more or less simultaneously over this area. When the oscillograph unit is put into operation to record some particular storm, it is often affected by lightning flashes taking place in some other storm at a much greater distance, and the films are found to contain numerous records of field changes due to such disturbances. It has been pointed out previously that the field changes due to a distant lightning flash are characterised by the predominance of the radiation term, E_r, and records from distant flashes may be readily identified from this fact. The electrostatic field changes previously discussed are barely determinable, and the records consist mainly of radiation ripple, with the radiation due to the main return stroke more pronounced. The following sketch illustrates the general form of these records.



It was stated previously that, in spite of the fact that the oscillograph unit was seldom put into operation except in the neighbourhood of a storm actively flashing to ground, numerous records from flashes which did not strike to ground appear on the oscillograph films. Bearing in mind the primary object of the present investigation, and the absence of detailed analysis of Boys' camera records of such flashes, these oscillograph records have not, as yet, been submitted to analysis. The examination and classification of records from such cloud flashes have been postponed for a separate investigation. At the present stage it is only possible to mention certain of their characteristics.

Cloud flashes are found to give records of field changes which differ considerably from those from ground flashes, and often which differ considerably from one another. Certain of them are characterised by extensive radiation ripple, whilst others show slow changes of comparatively long duration, and of relatively small amplitude. Unlike the records from ground flashes, cases of reversal of field sometimes occur, and, although series of strokes may be suspected, the regularity of form which was observed in the case of ground flash records seems absent.

DIRECT CORRELATION OF CAMERA AND OSCILLOGRAPH RECORDS.

It was indicated previously that the problem of obtaining a Boys' camera photograph of a lightning flash, and at the same time obtaining an oscillograph record of the field changes due to the same flash, proved a difficult undertaking. This was due to several factors, including the limited period of run of the recording drum camera, the necessity for having the Boys' camera trained directly on the flash, the fact that the latter instrument could only be operated at night, as well as the general difficulties associated with obtaining both types of record singly. On only one occasion, during the course of the field work now under review, was it found possible to obtain such simultaneous records, and these records were not of the best.

With so little data available in this connection, it is clear that, at this stage, it is not possible to do more than indicate very briefly some of the results revealed by the records obtained on this one occasion. It may be mentioned that it is intended in the future to endeavour to obtain sufficient of such directly correlated records to permit of a complete analysis.

In the first place it was found that an examination of the records made it possible to identify the strokes of a flash on the camera record with the corresponding oscillograph records of field changes, and the time intervals separating strokes as obtained from the two types of record were found to agree within the limits of accuracy of the measurements. It was thus possible to identify a particular camera record of a single stroke with a particular record of field changes on the oscillograph film.

One possible point of comparison between the two types of record was furnished by the times of duration of the leader process. For two of the records of particular strokes the leader times as determined from the Boys' camera photographs were found to be 1900 micro-seconds and 170 micro-seconds respectively. The values for the leader time (t_1) as obtained from the corresponding oscillograph records were found to be 3000 micro-seconds and 240 micro-seconds respectively. These results not only indicate agreement in the order of value obtained by the two methods, but show that in general the value from the oscillograph record is higher than that from the camera record. This result is to be expected when it is remembered that the camera is limited to a record of visible phenomena.

It may be mentioned that certain anomalies were observed in the records, but it was not possible to investigate them fully with so little data available. The analysis of the Boys' camera records was kindly undertaken by Dr. Schonland.

CONCLUSION.

The investigation forming the subject of the first portion of this thesis, in which the Cathode Ray Oscillograph Direction Finder was employed to investigate the direction of arrival of atmospherics, was undertaken with the assistance of a grant from the Research Grant Board towards the cost of the necessary apparatus. The investigation of the field changes in the neighbourhood of a lightning flash formed part of the work of the Lightning Research Committee of the S.A.Institute of Electrical Engineers.

The author wishes to tender his grateful thanks to the many individuals who, by their assistance and advice, greatly facilitated the progress of the work. In particular he is greatly indebted to

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Finally, the author wishes to place on record his deep gratitude to Professor B.F.J.Schonland, the Director of this research. His advice and assistance were always freely given at all stages in the investigation, his wise guidance pointed the path to surmount many an obstacle, his enthusiasm was an inspiration, and the team spirit which he inspired and fostered made the whole work a pleasure.

DERIVATION OF THE EQUATION.

Suppose a cloud carries a charge q at an effective height h above the ground, so that the electrical moment of the cloud charge is M (2qh).

It is necessary to determine the relation existing between the moment M and the vertical electrical field (E) at a point on the earth distant r from the cloud, where r is very much greater than h.

Maxwell's Equations of the electromagnetic field in air in a region where there are no magnetic or electrical charges are:-

$$\frac{1}{c}\frac{dE_x}{dt} = \frac{dH_z}{dy} - \frac{dH_y}{dz} \quad \ldots\ldots\ldots\ldots\ldots(1)$$

$$\frac{1}{c}\frac{dE_y}{dt} = \frac{dH_x}{dz} - \frac{dH_z}{dx} \quad \ldots\ldots\ldots\ldots\ldots(2)$$

$$\frac{1}{c}\frac{dE_z}{dt} = \frac{dH_y}{dx} - \frac{dH_x}{dy} \quad \ldots\ldots\ldots\ldots\ldots(3)$$

$$-\frac{1}{c}\frac{dH_x}{dt} = \frac{dE_z}{dy} - \frac{dE_y}{dz} \quad \ldots\ldots\ldots\ldots\ldots(4)$$

$$-\frac{1}{c}\frac{dH_y}{dt} = \frac{dE_x}{dz} - \frac{dE_z}{dx} \quad \ldots\ldots\ldots\ldots\ldots(5)$$

$$-\frac{1}{c}\frac{dH_z}{dt} = \frac{dE_y}{dx} - \frac{dE_x}{dy} \quad \ldots\ldots\ldots\ldots\ldots(6)$$

$$\frac{dE_x}{dx} + \frac{dE_y}{dy} + \frac{dE_z}{dz} = 0 \quad \ldots\ldots\ldots\ldots(7)$$

$$\frac{dH_x}{dx} + \frac{dH_y}{dy} + \frac{dH_z}{dz} = 0 \quad \ldots\ldots\ldots\ldots(8)$$

By elimination of the other quantities it is possible to show that, if F represent any one of the quantities dE_x, dE_y, dE_z, dH_x, dH_y, dH_z, then:-

$$\frac{d^2F}{dx^2} + \frac{d^2F}{dy^2} + \frac{d^2F}{dz^2} = \frac{1}{c^2}\frac{d^2F}{dt^2}$$

This is the well known equation of wave motion.

Since the required solution in the problem is to depend on r alone, using the transformation for spherical polar co-ordinates $(r, \theta, \phi,)$ the equation for F becomes:-

$$\frac{1}{r^2}\,\frac{d}{dr}\left(r^2\,\frac{dF}{dr}\right) + \frac{1}{r^2}\cdot\frac{1}{\mathrm{Sin}^2\theta}\cdot\frac{d^2F}{d\phi^2} + \frac{1}{r^2}\cdot\frac{1}{\mathrm{Sin}\,\theta}\cdot\frac{d}{d\theta}\left(\mathrm{Sin}\,\theta\cdot\frac{dF}{d\,\theta}\right)$$

$$= \frac{1}{c^2}\cdot\frac{d^2F}{dt^2}\,.$$

Since F is a function of r alone, this gives:-

$$\frac{1}{r^2}\cdot\frac{d}{dr}\left(r^2\,\frac{dF}{dr}\right) = \frac{1}{c^2}\cdot\frac{d^2F}{dt^2}$$

$$\frac{2}{r}\cdot\frac{dF}{dr} + \frac{d^2F}{dr^2} = \frac{1}{c^2}\cdot\frac{d^2F}{dt^2}$$

If we put X equal to r.F, we have

$$\frac{1}{r}\cdot\frac{d^2X}{dr^2} = \frac{1}{c^2}\cdot\frac{1}{r}\cdot\frac{d^2X}{dt^2}$$

$$\text{or}\quad \frac{d^2X}{dr^2} = \frac{1}{c^2}\cdot\frac{d^2X}{dt^2}$$

Since this is the simple equation of wave motion, the expanding wave is given by:-

$$X = f(t - r/c)$$

$$\text{or}\quad F = 1/r.f(t - r/c)$$

Consider the wave equation, $F = 1/r.f(t - r/c)$, so that

$$\frac{d^2F}{dx^2} + \frac{d^2F}{dy^2} + \frac{d^2F}{dz^2} = \frac{1}{c^2}\cdot\frac{d^2F}{dt^2}$$

Since this equation is linear, any form such as dF/dx, $d^2F/dx.dt.$, etc. will satisfy the wave equation, since F does. It will be necessary, however, in giving various values to E_x, etc., to see that all the Maxwell simultaneous equations are satisfied.

From the nature of the problem, let H_z be zero.

Then from (6) $dE_y/dx = dE_x/dy$.

Suppose Y be some function of x and y.

Then
$$\frac{d^2Y}{dx.dy} = \frac{d^2Y}{dy.dx}$$

or
$$\frac{d}{dx}\left(\frac{dY}{dy}\right) = \frac{d}{dy}\left(\frac{dY}{dx}\right)$$

Hence $E_y = dY/dy$ and $E_x = dY/dx$.

From (1) we then have

$$\frac{1}{c}.\frac{dE_x}{dt} = 0 - \frac{dH_y}{dz}$$

or
$$\frac{1}{c}.\frac{d^2Y}{dx.dt} = - \frac{dH_y}{dz}$$

It follows that Y must be a partial differential coefficient of a function with respect to z. Suppose Y is dF/dz.

Then
$$E_x = dY/dx = d^2F/dx.dz.$$
$$E_y = dY/dy = d^2F/dy.dz.$$

From (1) $H_y = - 1/c.d^2F/dx.dt.$

From (2) $H_x = 1/c.d^2F/dy.dt.$

From (3) $E_z = -\left(d^2F/dx^2 + d^2F/dy^2\right).$

or, making use of the general wave equation,

$$E_z = d^2F/dz^2 - 1/c^2.d^2F/dt^2.$$

The general solution is therefore:-

$E_x = d^2F/dx.dz.$ $E_y = d^2F/dy.dz.$ $E_z = d^2F/dz^2 - 1/c^2.d^2F/dt$

$H_x = 1/c.d^2F/dy.dt$ $H_y = - 1/c.d^2F/dx.dt$ $H_z = 0.$

where $F = 1/r.f(t - r/c)$

Substituting for F in the general solution gives the following results:-

$E_x = 3xz/r^5.f + 3xz/cr^4.f' + xz/c^2r^3.f''$
$E_y = 3yz/r^5.f + 3yz/cr^4.f' + yz/c^2r^3.f''$
$E_z = 3z^2/r^5.f + 3z^2/cr^4.f' + z^2/c^2r^3.f'' - (1/r^3.f + 1/cr^2.f' + 1/c^2r.f'')$

$H_x = - y/cr^3.f' - y/c^2r^3.f''$
$H_y = x/cr^3.f' + x/c^2r^3.f''$
$H_z = 0$

where f, f', f^2 represent the function and its first and second differential coefficients.

In the present problem, suppose that any lowering of the cloud charge causes a conduction current i.

Then a length dl of the channel carrying this current will create at the point under consideration a magnetic field such that:-

$H_z = 0 \quad H_y = x/cr^3.idl \quad H_x = - y/cr^3.idl$

if r be large in comparison with h.

Now from the general solution it is clear that the solutions must be of the form:-

$$H_x = - y/cr^3.f' - y/c^2r^3.f''$$
$$H_y = x/cr^3.f' + x/c^2r^3.f''$$

Now $idl = - dM/dt$, and the solution is then

$$H_x = y/cr^3.\ d/dt\ M(t-r/c)$$

We can thus identify f with $- M$.

Hence, from the general solution for E_z, putting $z = 0$, we have:-

$$E_z = - (1/r^3.f + 1/cr^2.f' + 1/c^2r.f'')$$

or $$E_z = 1/r^3.M + 1/cr^2.dM/dt + 1/c^2r.d^2M/dt^2$$

where the values of the quantities involving M are the retarded values at a time $(t - r/c)$.

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APPENDIX. I

Reprinted from the
SOUTH AFRICAN JOURNAL OF SCIENCE, *Vol. XXXII, pp. 113-117, November, 1935.*

RADIO DIRECTION-FINDING WITH THE CATHODE RAY OSCILLOGRAPH.

BY

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Read 2 July, 1935.

It is well known that certain types of aerial, whether used for the transmission or the reception of signals, have directional properties, varying in degree with a number of different factors. Various means have been devised to utilise this principle to determine the direction of an incoming signal, and these are exemplified in the direction finders which have been, and are at present, in use in navigation by air or at sea, such as the Bellini-Tosi and the Adcock direction-finders.

The application of the cathode ray oscillograph to the visual recording of the direction of incoming signals has been developed during the last ten years by Watson-Watt and his co-workers at the Radio Research Station at Slough. This was primarily undertaken for the determination of the azimuth of arrival of atmospherics. But the ease with which the movement of the fluorescent spot on the oscillograph screen can be recorded photographically, thus making the apparatus self-recording, largely eliminates the human factor, and has led to the development of a relatively high precision instrument.

Further, the fact that the source of atmospherics on the earth's surface is always found at a region where there is a state of maximum meteorological discontinuity (e.g. storm centre) makes the apparatus an important, if not practically an essential part of the equipment of every meteorological department. Any one instrument has a range of three to four thousand miles, and with two, or preferably three, stations making simultaneous records, centres of disturbance can be located accurately, and their movements traced and recorded. It seems unnecessary to stress the importance of all meteorological data in South Africa, this country of alternating drought and flood, and an avenue of information such as this offers seems well worth exploration.

PRINCIPLE OF THE APPARATUS.

The apparatus here described will be demonstrated before the Association. It has been constructed in the Physics Department of the University of Capetown on the lines described by Watson-Watt, Herd and Bainbridge-Bell in their publication "The Cathode Ray Oscillograph in Radio Research."

The principle of the instrument is briefly as follows:—Two identical frame aerials are taken and placed with their planes vertical, the one oriented along the North-South geographical meridian, the other East-West, so that their planes are mutually at right angles. If a vertically polarised electromagnetic wave, travelling in a direction making some angle A with the geographical meridian, passes the aerials, it will produce in the North-South frame a voltage equal to k Cos. A, and in the other frame a voltage equal to k Sin. A, where k is some constant.

If these two voltages, either directly or after suitable and *equal* amplification, are applied respectively to the two pairs of deflecting plates of the cathode ray oscillograph, they will produce deflecting fields on the electron beam equal to K Cos. A and K Sin. A respectively at right angles to one another. The resultant of these will cause the beam to be deflected in a direction making an angle A with the direction of deflection of the beam when oscillating under a voltage on the pair of plates connected to the North-South frame alone, and hence the angle which the incident wave makes with the geographical meridian is directly indicated.

The length of excursion of the fluorescent spot on the screen of the oscillograph depends on the final voltage applied to the oscillograph plates. The attenuation of an electromagnetic wave with distance is well known, and hence, even with frames of large area and number of turns, when signals from a source at any distance are to be received and recorded, it becomes necessary to amplify the voltages from the aerial before application to the oscillograph plates. The amplifiers used for the two limbs require to be closely matched, not only in the gain, but also in the phase displacement which they impose on the deflecting voltages applied to the plates. If equality of gain were absent, the angle of deflection on the oscillograph would not be the same as that of the incoming wave on the frames. On the other hand, if the two original signal components, co-phasal as they leave the frames, suffer phase-displacement in the two amplifiers, the pattern on the oscillograph screen is no longer a line, but an ellipse, whose dimensions depend on the phase difference introduced by the amplifiers.

THE FRAME AERIALS.

The aerials in use at present are such as can be comfortably housed indoors. They are rectangular, and carry 100 turns of wire of side 1 metre, the spacing between turns being 0·5 cms. The inductance of the frame, measured by the usual bridge method, is 13·6 m.H. The frames are made of iron water piping $\frac{3}{4}$ inch internal diameter. Since there are two such frames set close together and at right angles, the closed metallic loops of one frame are parallel to the windings on the other frame, and comparatively closely coupled to it. Hence eddy currents in the frames must be avoided, and this is achieved by inserting insulators of ebonite in the frames so that all closed metallic loops are avoided.

The work of Appleton and Watson-Watt on the wave form of atmospherics has shown that in general they are aperiodic disturbances. Further, the signal strength of an atmospheric is greater on a system tuned for longer than for shorter waves, hence for the direction-finder the aerials are tuned approximately to a frequency of 10 kilocycles/sec., representing a wave length of 30,000 metres.

THE AMPLIFIERS.

The amplifiers used are resistance-capacity coupled, and each contain three stages, with a fourth stage which can be added if necessary. Anode-circuit de-coupling is introduced to reduce retroaction and series resistances are placed in the grid circuits to prevent self-oscillation. The amplifier units are carefully screened and the wiring kept as short as possible and brought close to the metal case, so that the wire-to-metal capacity may act as a shunt for unwanted high frequency currents.

A potentiometric input is inserted to the grid of the third valve in each amplifier. This serves as a means of adjusting the overall gain in the amplifier unit, and also serves to adjust the two amplifiers to approximate similarity of gain. The bias to the grid of the first valve in each amplifier can also be varied by a potentiometer in the input grid circuit, and this provides a means of exactly matching the two amplifiers for gain.

If care be taken during construction to match the two amplifiers as far as valves, components, lay out and wiring are concerned it will be found that very little, if any, phase-displacement takes place—any that may occur may be adjusted by a variable condenser inserted between the output from one of the amplifiers and earth.

THE OSCILLOGRAPH.

The Oscillograph used is that put on the market by Messrs. A. C. Cossor, Ltd., London. Although at the present time these are manufactured with a high degree of accuracy, yet they may have certain inherent faults e.g. the vertically and horizontally deflecting plates may not give exactly the same amplitude of excursion when the same voltage is applied separately to each pair of plates or the two sets of plates may not be oriented so that the axes of deflection are strictly orthogonal to each other. For this reason it is not sufficient to inscribe on the screen face of the oscillograph a geometrical protractor. The protractor has to be inscribed "electrically." This is done by taking two potentiometers in series, the resistance steps in each potentiometer varying respectively as the sines and cosines of angles increasing say in steps of 10°. By this means a voltage 2E applied to the input terminals of the potentiometers will result in a voltage E Cos. A being applied to the vertically deflecting plates, and E Sin. A to the horizontally deflecting plates, and the spot will indicate the correct position of A on the screen face. Any errors in the construction of the oscillograph will be indicated by the departure of such an electrical protractor from the geometric, but it will clearly give the correct direction of the incoming signal.

LINE UP.

It has been emphasised that, for the correct functioning of the direction-finder, close matching of the two limbs, in both gain and phase, is essential, and this process of matching stage by stage is known technically as " lining up." To facilitate this matching process, use is made of a " test oscillator." This is an oscillator at approximately the frequency to which the frames will be tuned, and which must be very carefully screened to prevent undesired pick up in any parts of the circuit. This is coupled equally into the two frame circuits, either by means of a mutual inductance or, preferably, by earthing the centre points of each loop through two accurately matched resistances, and connecting the test oscillator to these points through buffer resistances to reduce the consequent coupling between the frames.

The first stage in the line up is to common the two sets of plates of the oscillograph. Any voltage applied to this point affects both sets of plates equally, producing a deflection of the spot at 45°. This line is the effective reference line for all matching, and is carefully marked on the screen face. The amplifiers may now be matched stage by stage by commoning their respective grid inputs. Thus if the final grid input circuits of the two amplifiers are commoned, any voltage is applied to both amplifiers in equal magnitude and phase, and both amplifiers can be carefully matched. If the commoning connection be then removed, any variation from the 45° line or any ellipse will indicate discrepencies in the matching of the aerials themselves.

SENSE DEVICE.

Any recorded signal on the cathode ray oscillograph direction-finder so far described gives an ambiguity of 180°. That is to say, a signal from the North-East gives a line across the whole face of the oscillograph, and thus gives no indication as to whether the direction of arrival is from the North-East or the South-West. This is a fault found in all radio direction-finders, and is overcome in the case of aural instruments by a second determination to fix the direction absolutely. In the case of the cathode ray instrument the direction of arrival may be fixed absolutely by a device which leaves the beam in focus on the screen in the required quadrant, and defocusses it completely in the opposite or unwanted quadrant, thus fixing the direction of arrival absolutely in a single operation, a necessity where intermittent phenomena such as atmospherics are concerned.

The focussing of the spot on the screen depends on the voltage applied to the Wehnelt cylinder of the oscillograph. In addition to the two frame aerials, a non-directional aerial is erected, tuned to the same frequency, and, after passing through a similar amplifier, its voltage is applied through a negatively biassed valve, the change in the anode-circuit resistance current of this valve altering the potential of the focussing cylinder of the oscillograph. This circuit is so arranged that signals reaching the oscillograph from it and the loop amplifiers are co-phasal. Thus the aerial signal will affect the cylinder over the half-cycles while the jet is moving between the origin and its further or unwanted quadrant, leaving it focussed in the required quadrant. When a signal comes from the opposite direction the phase of the aerial current is unchanged, while that in the loops is changed 180°. Hence the defocussing is transferred to the opposite quadrant, and the direction sense is again absolutely determined.

PHOTOGRAPHIC RECORDING.

As previously indicated, the ease with which the movements of the fluorescent spot may be recorded photographically makes the instrument one of high precision. The camera used is an ordinary drum camera carrying a roll of film, which moves vertically at constant speed. The speed must be sufficiently slow for no broadening of a trace to take place due to film motion. In practice a film speed of 2 cm./sec. is found sufficient to avoid opening of an individual trace, yet allowing the recording of numerically high rates of incidence of signals. To obviate the registration of the undeflected spot as a continuous line, masking all North-South deflections, the centre of the screen is covered by a small piece of ruby paper.

When simultaneous observations are being made at two or more stations, synchronisation of the records is of the greatest importance. This is done by the transmission to the stations from some common source, either by telegraph line or by radio signals, of periodic time signals, which are impressed on the oscillograph. After development, the films can then be placed side by side, and the results simultaneously reduced to give the exact location of the particular atmospheric source.

In conclusion may I again point out that experience has shown that, where these methods have been adopted, data of the first importance has been made available. I trust that, in the near future, these methods may be put into use in South Africa, and provide data equally useful, not only to this country alone, but to the wider field of world meteorology.

APPENDIX II.

REPRINT FROM THE

TRANSACTIONS

OF THE

ROYAL SOCIETY OF SOUTH AFRICA.

VOL. XXIV. PART II.

The Relation between Thunderstorms and Atmospherics in Southern Africa.

By B. F. J. Schonland, M.A., Ph.D., and
D. B. Hodges, M.Sc.

CAPE TOWN
PUBLISHED BY THE SOCIETY
—
1936.

THE RELATION BETWEEN THUNDERSTORMS AND ATMOSPHERICS IN SOUTHERN AFRICA.

By B. F. J. Schonland, M.A., Ph.D., The University of Capetown, and D. B. Hodges, M.Sc., Natal University College, Durban.

(With Plate VI and two Text-figures.)

(Read October 16, 1935.)

The application of the Cathode Ray Oscillograph to the determination of the direction of arrival of atmospherics at a station has been developed by Watson Watt and his co-workers at the Radio Research Station at Slough.* The device they have evolved employs the well-known principles of radio direction finding to obtain, on the oscillograph screen, an instantaneous and direct reading of the true bearing of the source giving rise to any single atmospheric reaching the station with sufficient energy to operate the instrument.

It is clear that, if two such bearings of the same source are obtained at different stations, a fairly accurate location of the position of the source may be made, whereas a single bearing from one station merely gives the direction of the source. The amplitude of the disturbance recorded on the instrument from a source will depend, however, amongst other things, on the distance between source and station. It is therefore possible, even with a single station, to obtain an approximate estimate of the distance of the source from a consideration of the average amplitude of the records on the instrument.

Considerable evidence has been advanced by Watson Watt to show that the great majority of atmospherics, if not all, originate in regions of disturbed weather, and are associated with electrical disturbances of the nature of lightning. A similar conclusion has been reached by Munro and Huxley † as the result of extensive investigations carried out by them in Australia. The Cathode Ray Direction Finder thus makes it possible to

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* "The Cathode Ray Oscillograph in Radio Research," by Watson Watt, Herd, and Bainbridge Bell (H.M. Stationery Office).

† "Atmospherics in Australia," Report No. 5, Radio Research Board, Australia. A further valuable report, No. 8, 1935, has reached us too late for consideration in this paper.

determine the location of disturbed weather conditions within a radius of 2000 miles or more of any station. For this reason the method is likely to be of value in meteorological forecasting, and it has already been successfully employed in this way in Australia.

At the present time the Government Meteorological departments in Southern Africa depend for their information of local weather conditions on reports from observers at various points scattered over the sub-continent. With such a large and thinly populated area to be covered this method has obvious disadvantages, and it is impossible for the departments concerned to obtain complete records. They are further handicapped by an absence of reports on weather conditions over the oceans in their neighbourhood, which would greatly facilitate weather forecasting. The proposed establishment of a meteorological station at Tristan d'Acunha, which would supply information of depressions in the Atlantic Ocean, would have its value greatly enhanced, as far as South Africa is concerned, if means were available for following their direction of movement. The report system has a further disadvantage in the delay which occurs in reports of disturbed weather conditions reaching the meteorological offices. This is of special importance in the case of air-routes, and a rapid and practically instantaneous means of locating thunderstorms and heavy rainstorms along such routes would be of great value.

It thus appeared desirable to explore the possibilities of the use of the Cathode Ray Direction Finder in South Africa, and the present paper contains an account of a preliminary investigation on these lines using a single station located at Cape Town.

DESCRIPTION OF APPARATUS.

The principle of the apparatus has been fully described elsewhere,*† and only a brief description will be given here.

Two identical frame aerials are set up close together, their planes vertical and at right angles to each other, the one along the North-South, the other along the East-West geographical meridian. If an incoming electro-magnetic wave is such that the horizontal component of its magnetic vector makes an angle A with the plane of the N-S loop, it will induce in this coil an alternating E.M.F. proportional to cos A, and in the other coil an E.M.F. proportional to sin A. If these two E.M.F.'s, after equal amplification in both gain and phase, be applied respectively to the y and x deflecting plates of the oscillograph, the resultant trace on the screen

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* Watson Watt, *et alia, loc. cit.*, p. 162.

† Watson Watt, *et alia, loc. cit.*, p. 162; "Radio Direction Finding with the Cathode Ray Oscillograph," by D. B. Hodges, Journ. S.A. Assoc. for Adv. of Science, 1935.

produced by their combined effect will be a straight line making an angle A with the y axis of the oscillograph, thus giving a direct reading of the direction of the incoming wave.

The frame aerials used by us were 1 metre square, and consisted of 100 turns of wire with a spacing of 0·5 cm. between the turns. Each coil had a resistance of 12 ohms, and its self-inductance was found to be 14·3 mH. Each coil was tuned by a fixed condenser of capacity 0·015 mfd., so that signals were received at a frequency of 10·86 kc./sec., corresponding to a wavelength of 27·61 kilometres. The signals were then directly amplified at this signal frequency by means of two carefully matched amplifiers. Each of these had four stages of resistance-capacity coupled amplification, using L.S.5.B. valves. A gain control on the third stage in each amplifier provided a means of adjusting the amplitude of the final signal on the oscillograph. Actually full gain was never employed in this work.

The oscillograph tube used was a Type A Cossor Cathode Ray Oscillograph. The compass dial was inscribed on the fluorescent screen of the tube by an electrical method.* Three concentric circles were then inscribed on the face with the stationary spot as centre, of radii 0·5 cm., 1 cm., and 2 cm. respectively. These were used to provide a rapid means of estimating the amplitude of any given signal. A general view of the experimental arrangement, showing the frame aerials, amplifiers, and cathode ray oscillograph with compass dial, is shown in Plate VI.

The methods used for the matching of the frames and amplifiers both for gain and phase, were those laid down by Watson Watt † under the head of "lining up." In this process a sealed oscillator was used to inject into one or both of the aerials a known E.M.F. This oscillator was of the usual Hartley type, tuned to the required frequency, and enclosed in a welded iron box with a mercury seal, as perfect screening of the oscillator is essential.

The various stages in this "lining up" process are, briefly, as follows:—

(*a*) A strong signal from the oscillator is injected into one aerial, while the other aerial is connected through its amplifier, set at maximum gain, to the plates of the oscillograph. If any signal is indicated, it shows that coupling exists between the two coils. The second coil is then moved in its own plane until no signal is indicated on the oscillograph.

(*b*) The two sets of oscillograph plates are connected, thus throwing the signal from the test oscillator equally on to both sets. The resultant signal on the oscillograph disc will be a straight line at 45° to the axes, known as the reference line. The amplifiers are then matched, stage by stage, by commoning their respective

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* Watson Watt, *et alia*, *loc. cit.*, p. 162.

† Watson Watt, *loc. cit.*

inputs. Any departure from equality of gain is shown by a deviation from the reference line, and can be adjusted by the gain controls. (If careful matching of components has been adopted in construction, this is usually found to be inappreciable.) If inequality of phase exists, it is indicated by the signal becoming an ellipse instead of a straight line. This is adjusted by means of a phasing condenser in the one amplifier.

(*c*) With the amplifiers matched, any deviation from the reference straight line in the signal from the oscillator injected equally into both frames must be due to faults in the frames themselves. These are finally adjusted by means of a variable condenser in parallel with the fixed tuning condenser on one of the frames.

METHODS OF OBSERVATION.

After the process of "lining up" is completed, the gain controls are adjusted so that the signal from the test oscillator has a given amplitude (usually 1 cm.). This is done so that use may be made of the amplitudes of the signals from various sources and on various days for comparison purposes. The oscillator is then switched off, and readings taken over a stated period. One observer watches the dial, and, as each signal is observed, calls out its direction and amplitude. These are taken down and tabulated by an assistant. It was found that greater accuracy could be obtained by allowing the observer to concentrate on observing alone, instead of tabulating his own observations. Directions could be estimated with an accuracy of ±3°, and amplitudes were obtained by means of the concentric circles on the dial. In this preliminary work no arrangements were provided for obtaining the sense of the direction of the signal. With the apparatus as so far described, signals both from the North-West and from the South-East, for example, would give the same straight line on the dial at 45° to the axes. Continuous observations were made for a period of about ten minutes each day the instrument was in operation, usually in the afternoon between 2 p.m. and 5 p.m. local time. In a few cases morning and night observations were made, mainly to test whether any general variation in amplitude was noticeable.

We are greatly indebted to the Chief Meteorologist, Irrigation Department, Pretoria, and to the Chief Meteorologist of Southern Rhodesia, who kindly supplied us with the meteorological maps compiled by their respective offices covering the period of our investigation. It was thus possible to compile maps on which were plotted the bearings given by the direction finder together with the meteorological information from the departmental maps. From this information we were able to ascertain the range of the instrument, which was found to be about 2000 miles from Cape Town in the afternoon. Sources correlated with actual thunderstorms ranged in distance from 350 miles to 1000 miles from Cape Town.

Table I is an extract from the log book showing a typical set of observations on one afternoon. Observations were made on 26 days between 3rd September 1935 and 18th October 1935.

TABLE I.

Date:	October 9th, 1935.	Oscillator Calibration	1 cm.
Time:	13¼ hours.		
Run:	10 minutes.	Observer	D. B. H.

W.	←N→		E.	
30°	1°	15°	45°	70°
10	10		6	8
10	7	Continuous	8	20
8	5	Amp. 5.	10	10
	8			8
	10			10
	8			10
	8			10
	8			10
				8
				10
				10

GENERAL SURVEY OF RESULTS.

The series of maps shown in figs. 1 and 2 cover the period of the investigation, and we have included a map for each day on which readings were made with the instrument, with no omissions. The straight lines indicate the bearings of sources of atmospherics as given by the Cathode Ray Direction Finder. Against each bearing there are three symbols.

1. M. A. or E. indicated that observations were made in the morning, afternoon, or evening.
2. The second symbol indicates the *average* amplitude of the signals on the compass dial from that particular bearing in millimetres reduced to a common level for comparative purposes. This standard setting for amplitude is that which gives a deflection of 1 cm. from the standard oscillator, and represents an input field strength of 1020 micro-volts/metre.
3. The third symbol indicates the average frequency of the signals from

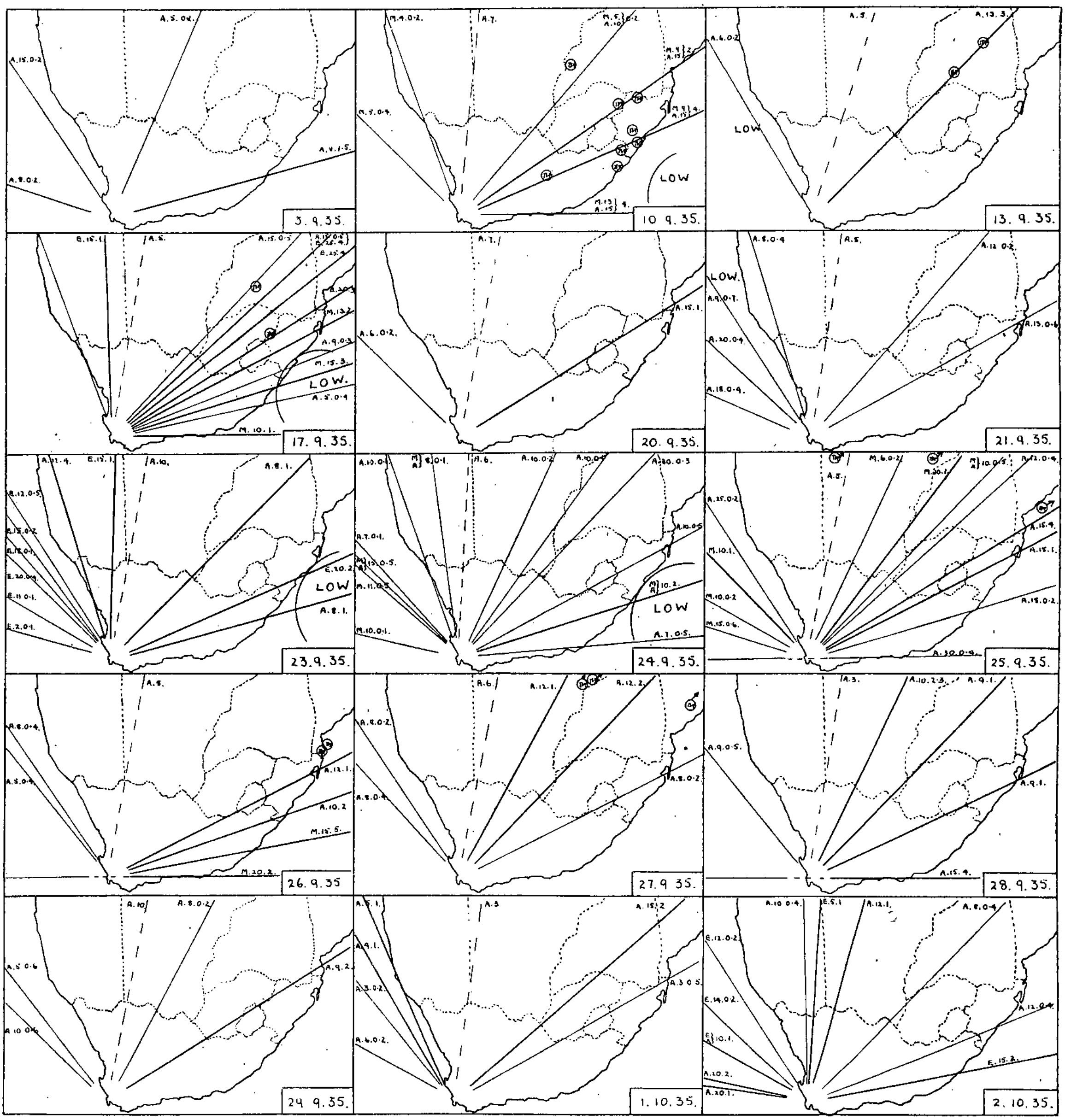
3. 9. 35.
10 9. 35.
LOW
13. 9. 35.
17. 9. 35.
LOW.
20. 9. 35.
21. 9. 35.
LOW.
LOW
23.9. 35.
LOW
24.9. 35.
LOW
25. 9. 35.
26. 9. 35
27. 9 35.
28. 9. 35.
24 9. 35.
1. 10. 35.
2. 10. 35.

FIG. 1.

a particular source, the figures giving the average number per minute during the period of observation. Where this average frequency exceeds 1 per minute, a heavier straight line has been used to indicate the bearing.

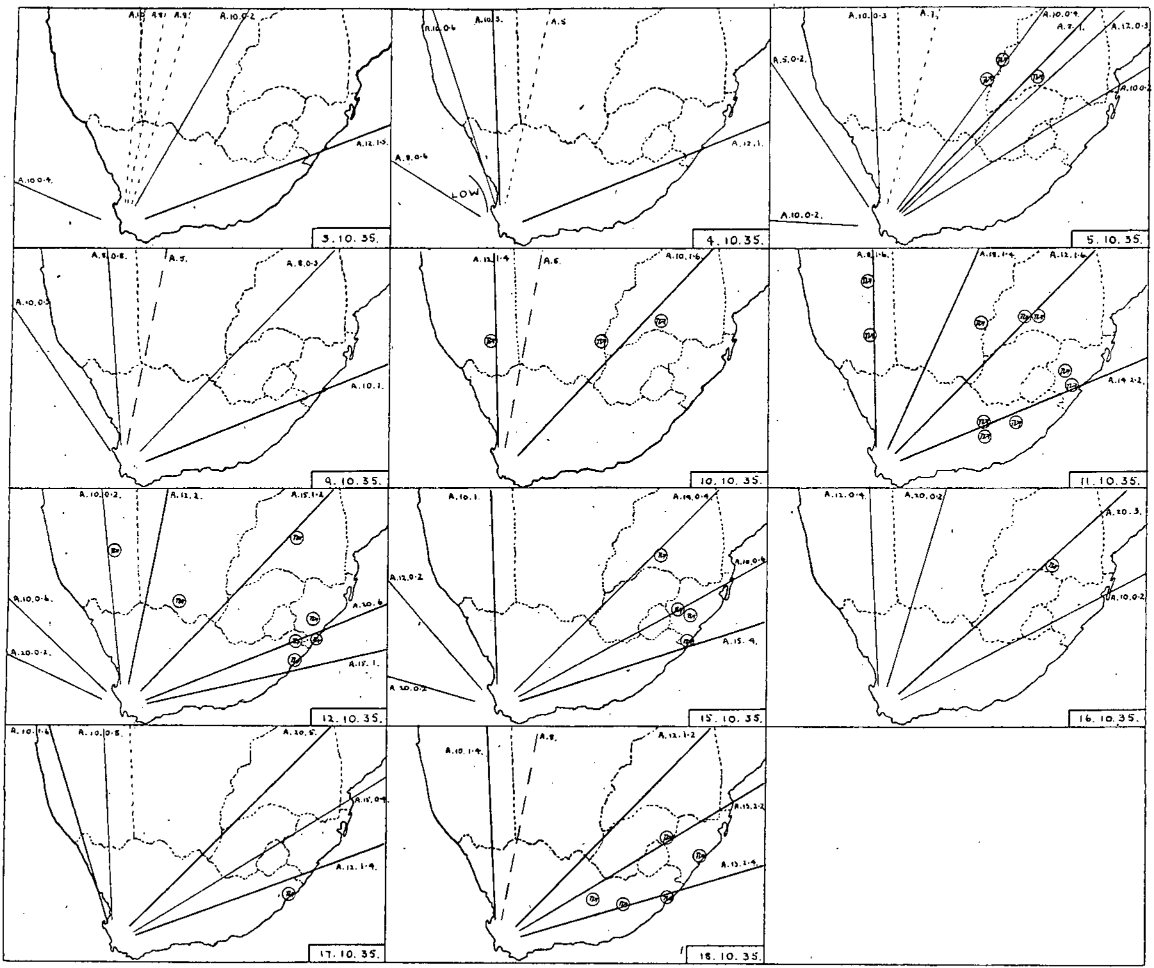

FIG. 2.

In general it was found that afternoon signals came in continuously with an amplitude of about 0·5 cm. from the well-known active area of the Congo watershed. This source, actually extending in bearing from 5° to 15° E. of N., is shown on the maps by a dotted line, and in our observations we usually neglected it for the closer study of nearer sources.

RELATION BETWEEN THE BEARINGS OF ATMOSPHERICS AND REPORTED THUNDERSTORMS.

During the period under review the meteorological maps indicated that thunderstorms were reported as having occurred in fifty-four different places. In 35 (65 per cent.) of these cases atmospherics were detected, during the running of the instrument, with bearings lying within 3° of that of the reported thunderstorm, and in 48 (89 per cent.) of these cases the bearing lay within 5° of the reported thunderstorm. When it is remembered that the usual time devoted to the making of observations with the direction finder was ten minutes per day, while the meteorological reports cover the whole twenty-four hours, the agreement is striking.

In all a total of 174 bearings on sources of atmospherics was obtained during the experimental period, 57 being from sources located in the Atlantic and Indian Oceans, and 117 from sources over the land. Of these latter land sources, 27 (23 per cent.) gave bearings within 3° of those of thunderstorms actually reported on meteorological maps, and 15 (13 per cent.) were associated with the active region of the Congo watershed previously mentioned. Of the remainder, 37 (31·5 per cent.) were from directions indicating sources in S.W. Africa, the Kalahari, or Bechuanaland, all regions where the meteorological report system is practically non-existent, and 38 (32·5 per cent.) were from other land sources. If those directions which the report system is known not to cover be neglected, then of the 80 recorded bearings 42 (52·5 per cent.) are found to be definitely associated with thunderstorms. When it is remembered that the report system, even in the more populous areas, cannot be expected to report every thunderstorm which occurs, and, further, that a certain number of the uncorrelated signals were of small average amplitude, and thus might very well be associated with depressions in the Indian Ocean, it is reasonable to conclude that the lightning flash is the chief, if not the only, source of the atmospherics received. In the course of this work our observations have given us no indication of any other source of atmospherics.

OCEAN ATMOSPHERICS AND COAST PRESSURE RECORDS.

In South Africa there are practically no meteorological data available with regard to weather conditions at any appreciable distance from the coast on the Atlantic side of the sub-continent. On the Indian Ocean side a certain amount of information can be deduced as to the existence of "highs" or "lows" at sea from meteorological reports and occasional reports from ships from India and Madagascar. An analysis of the bearings obtained with the Cathode Ray Direction Finder of sources located at sea is therefore of interest.

ATLANTIC OCEAN SOURCES.

Sources of atmospherics were located in the Atlantic Ocean on 20 different days. On 4 of these days (13th and 21st September, 4th and 9th October) there were definite "lows" shown on the meteorological maps off the west coast in the region of Port Nolloth. The bearings and amplitudes on these 4 days are shown in Table II. These indicate sources about 1000 miles away from Cape Town.

TABLE II.

Bearings of Atlantic Sources on Days of West Coast "Lows."

3 at 30° of amplitude (average)	8 mm.[*]
1 ,, 45° ,, ,,	20 ,,
1 ,, 60° ,, ,,	8 ,,
1 ,, 65° ,, ,,	19 ,,
	Average—12 mm.

On 9 of these days (10th, 20th, 25th, 26th, 29th September; 2nd, 3rd, 12th, 15th October) there was a general decrease in pressure on moving north along the coast from Cape Town, suggesting the presence of a "low" at sea approximately 1000 miles away. The bearings and amplitudes of the signals received on these days are shown in Table III.

TABLE III.

Bearings of Atlantic Sources on Days of probable near Atlantic "Lows."

2 at 30° of amplitude (average)	16 mm.[†]
1 ,, 35° ,, ,,	5 ,,
2 ,, 40° ,, ,, ,,	8 ,,
5 ,, 45° ,, ,, ,,	10 ,,
3 ,, 60° ,, ,, ,,	13 ,,
4 ,, 75° ,, ,, ,,	7 ,,
	Average—13 mm.

On the remaining 7 days (3rd, 23rd, 24th, 27th, 28th September, 1st, 5th October) definite "highs" were recorded off the coast at or beyond Port Nolloth.[‡] The bearings and amplitudes of the signals received on these days are shown in Table IV.

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[*] 1 mm. = 102 μ volts/metre.

[†] 1 mm. = 102 μ volts/metre.

[‡] We are indebted to Mr. N. Sellick, Meteorologist to the Government of Southern Rhodesia, for the information that on all except one of these days (5th October), known

TABLE IV.

Bearings of Atlantic Sources on Days when no near "Lows" were present.

1 at	20°	of amplitude		5 mm.[*]
4 ,,	30° ,,	,,	(average)	5 ,,
1 ,,	35° ,,	,,		4 ,,
5 ,,	40° ,,	,,	,,	6 ,,
2 ,,	45° ,,	,,	,,	13 ,,
2 ,,	60° ,,	,,	,,	5 ,,
2 ,,	75° ,,	,,	,,	12 ,,

Average—7 mm.

It will be noticed that the amplitudes recorded in Table IV are about half those recorded on the two preceding tables, and indicate that the sources from which the signals were received were at distances appreciably greater than those of the previous sources, perhaps twice as great. It is reasonable to conclude that these signals came from sources in no way related to the conditions existing along the coast. On 5 days (17th September, 10th, 11th, 16th, 18th October) the coastal situation was such that definite "highs" were indicated off the coast, and on one day (17th October) there was no coastal variation in pressure, and on none of these days were signals received from the Atlantic Ocean.

INDIAN OCEAN SOURCES.

Depressions off the East Coast of South Africa are less easy to observe from Cape Town, since their effects are often masked by land storms. On 4 days (10th, 17th, 23rd, 24th September) definite "lows" were recorded on the meteorological maps off the coast of Natal and Pondoland. On all these occasions signals which could not be attributed to land sources were received on the Cathode Ray Direction Finder from these directions.

REDUCTION OF AMPLITUDES TO INPUT FIELD STRENGTH.

A land thunderstorm at a distance of 800 miles gave, on the average, an oscillograph deflection of amplitude 1 cm. In order to reduce this to the equivalent intensity in the same sense as that used by Munro and Huxley,[†] *i.e.* the field intensity of the continuous wave which will produce on the screen the same deflection as does the atmospheric, we proceeded as follows.

---

disturbances were passing along the S. and S.E. coasts. The same may apply to 1 of the 5 days in Table I (21st September) and to 4 of the 13 days in Table II (20th and 25th September and 12th and 15th October).

[*] 1 mm. = 102 μ volts/metre.

[†] Munro and Huxley, *loc. cit.*

The amplifier gain was determined with an A.C. 50 cycle input, and found to be $1 \cdot 0 \times 10^4$ or 80 decibels. Calculation from the frame constants previously given then yields an equivalent field intensity of 1020 micro-volts/metre for unit deflection. The corresponding figure obtained by the Australian writers is 1000 micro-volts/metre. As the above method of reduction is only approximate, the close agreement is fortuitous.

THE RANGE IN THE AMPLITUDE OF ATMOSPHERICS FROM A PARTICULAR SOURCE.

The question of the actual range in the amplitude of atmospherics from a particular thunderstorm is of some practical importance. In analysing the observations for this purpose we have found it desirable to omit consideration of all storms which gave maximum amplitudes on the screen less than 20 mm., in view of the possibility that very small deflections might have escaped notice. For 27 storms giving maximum deflections greater than this, the ratio of maximum to minimum amplitude has been determined, and a distribution table is given below.

TABLE V.

Range of Amplitude of Atmospherics from a Particular Source.

Ratio max./min. lying between .	0–1	1–2	2–3	3–4	4–5
Number of cases	0	3	10	5	9

It will be seen that the most frequent value for this ratio lies between 2 and 3. The few observations made at night indicate clearly a rise in the average amplitude of atmospherics from a particular source after dark by a factor of the order of two, but are insufficient in number for further discussion at this stage.

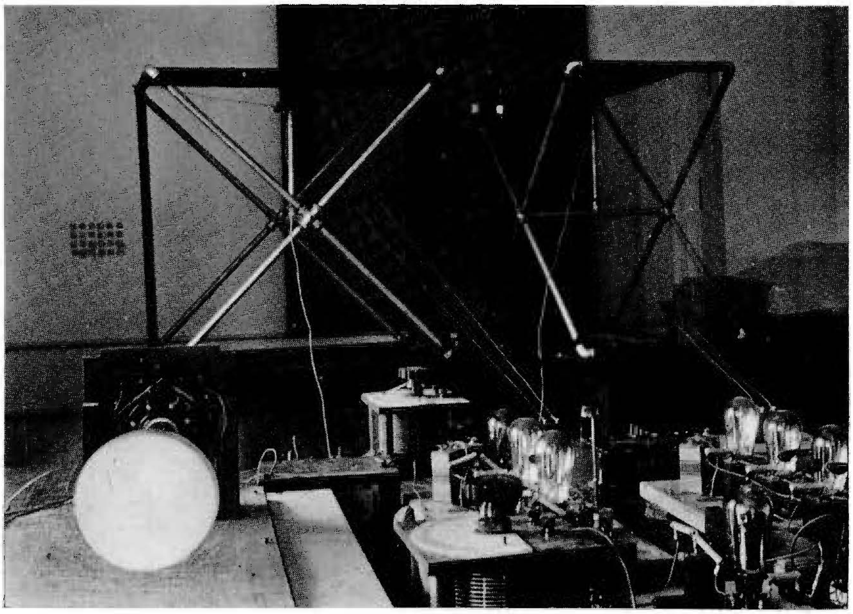
The investigations described in this paper were greatly assisted by the advice and co-operation of the staff of the British Radio Research Station, Slough, and, in particular, of the late Mr. J. F. Herd. We wish to thank Mr. Linton, of the University of Cape Town, for much valuable assistance, and the Government Meteorologists of the Union of South Africa and Southern Rhodesia for their interest and co-operation.

SUMMARY.

Directional location of sources of atmospherics on a wavelength of 27·6 kilometres from a station in Cape Town has been carried out over a

period of 26 days in September and October 1935. Eighty-nine per cent. of the thunderstorms reported by the meteorological report network were correctly located in bearing. Fifty-three per cent. of the bearings over regions covered fairly satisfactorily by the meteorological network were definitely associated with thunderstorms. The results thus support the conclusion of Watson Watt and others that the lightning flash is the chief source of atmospherics.

Sources of atmospherics over the Indian and Atlantic Oceans are shown to be related to the presence of ocean depressions. The ratio of the extreme amplitudes of atmospherics from a particular source has a range of between 2 and 5. The sources observed ranged in distance from 350 miles to 1000 miles.



Schonland and Hodges. *Neill & Co., Ltd.*

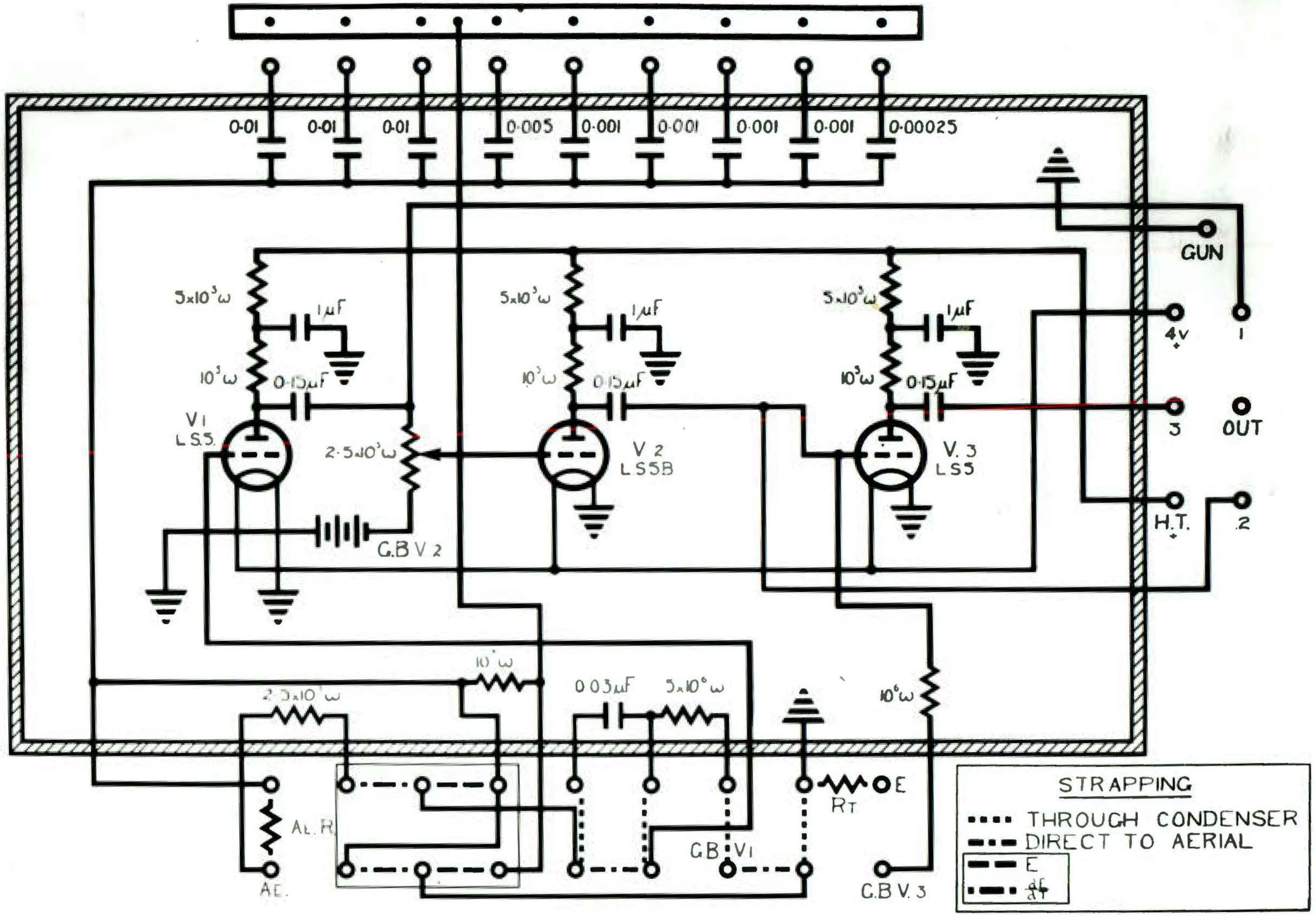
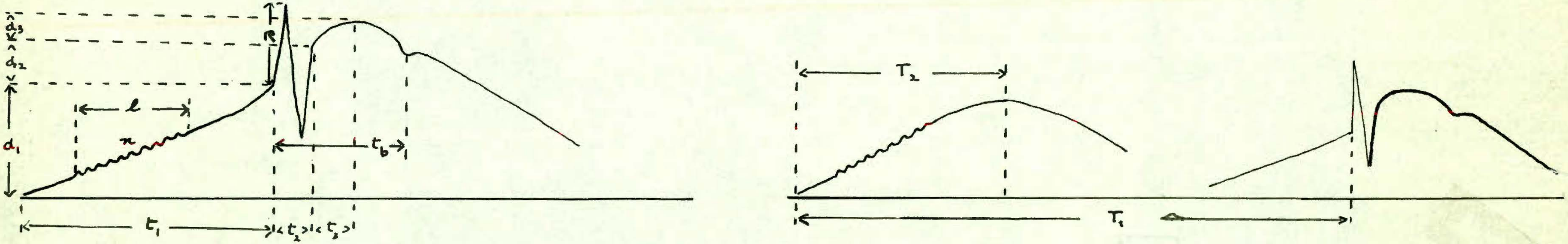

0·01
0·01
0·01
0·005
0·001
0·001
0·001
0·001
0·00025
GUN
5×10³ω
1μF
10³ω
0·15μF
V1
L.S.5.
2·5×10³ω
G.B V 2
5×10³ω
1μF
10³ω
0·15μF
V 2
L S 5B
5×10³ω
1μF
10³ω
0·15μF
V. 3
L S 5
4v +
1
3
OUT
H.T. +
2
10⁶ω
2·5×10⁶ω
0·03μF
5×10⁶ω
10⁶ω
Rт
E
AL.R.
AE.
G.B V1
G.B V. 3
STRAPPING
THROUGH CONDENSER
DIRECT TO AERIAL
E
df/dt

FIGURE I.

FIGURE 2.

TYPES OF FIRST STROKE.



TYPE α.

TYPE β.

TYPE γ

TYPE δ.

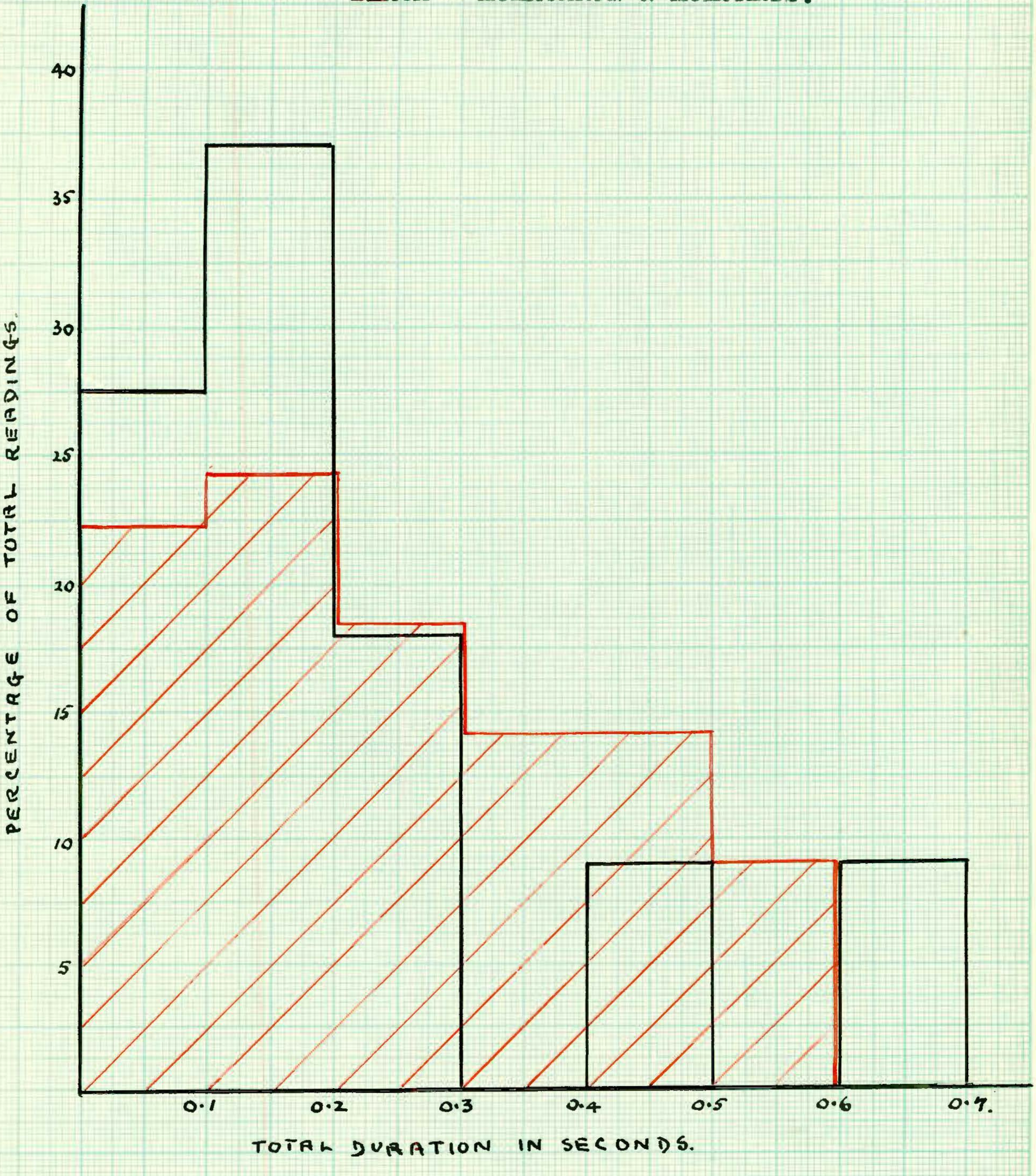
TYPE D (NO LEADER)

TYPE Dα.

FIGURE 3 - TOTAL DURATION OF FLASH.

RED - OSCILLOGRAPH RECORD.

BLACK - McEACHRON & McMORRIS.



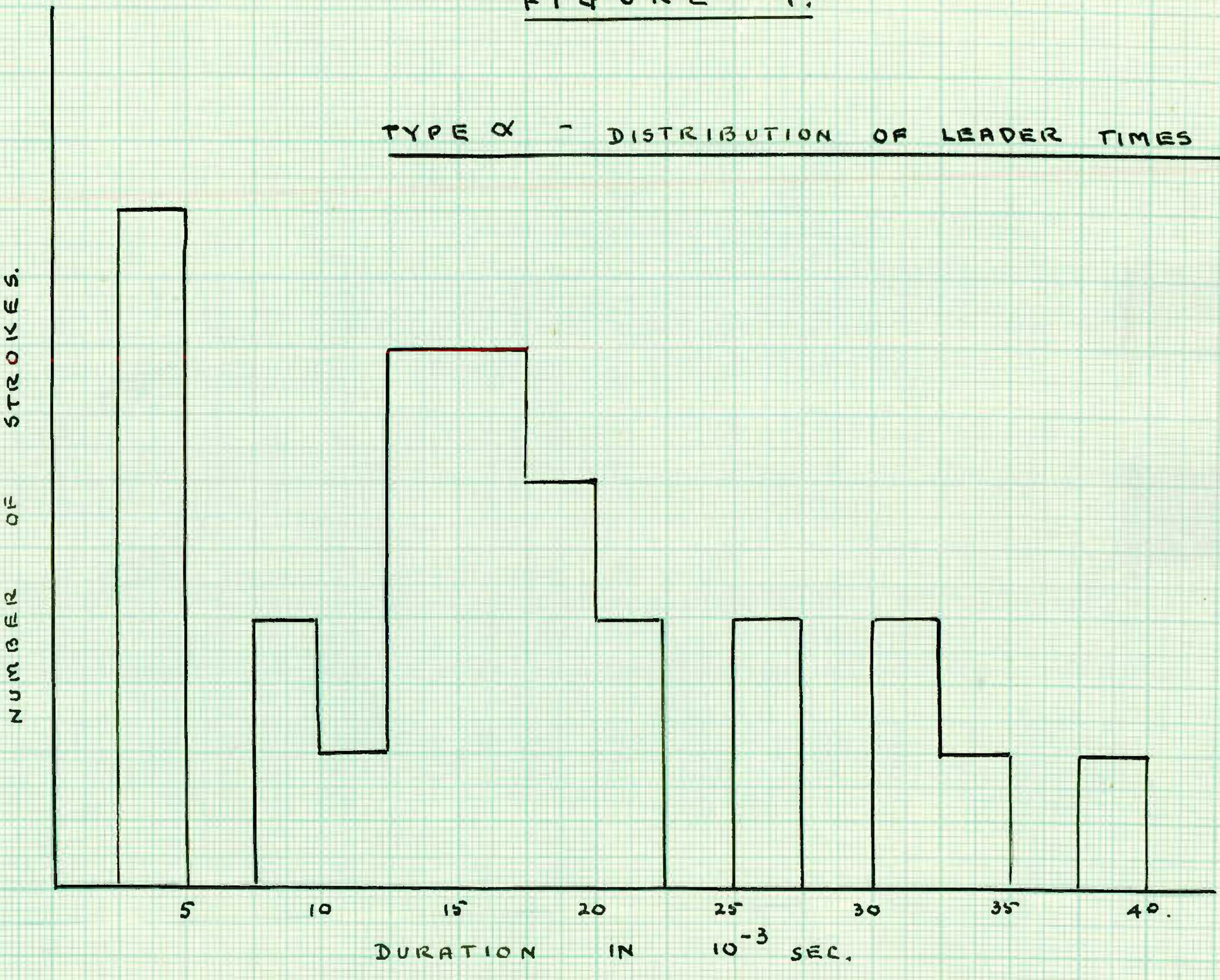


FIGURE 4.

TYPE α - DISTRIBUTION OF LEADER TIMES (t_1).

FIGURE 5.

DISTRIBUTION OF MAIN STROKE TIMES (t_2).

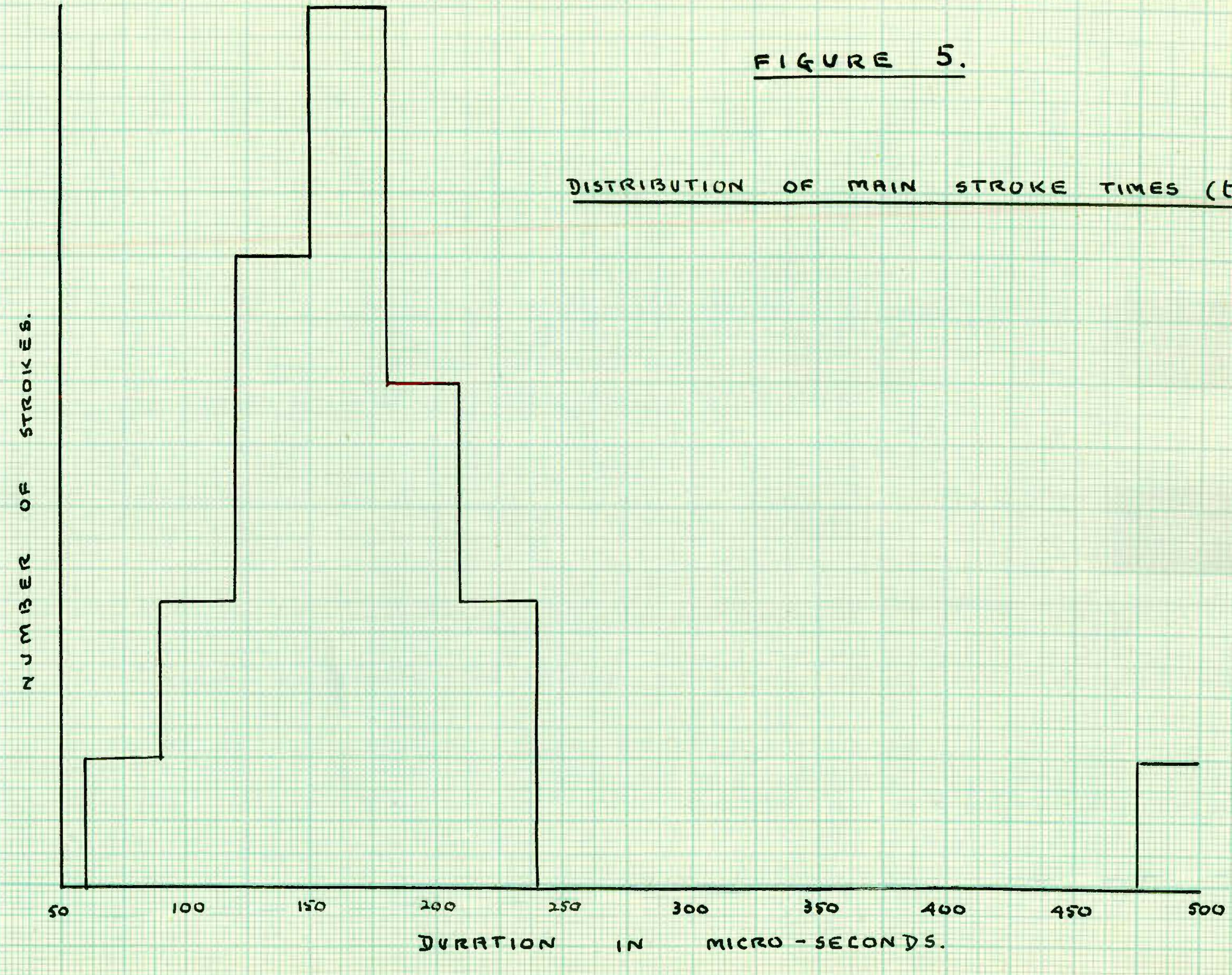


FIGURE 6.

DISTRIBUTION OF RATIO d_2/d_1 FOR FIRST STROKES.

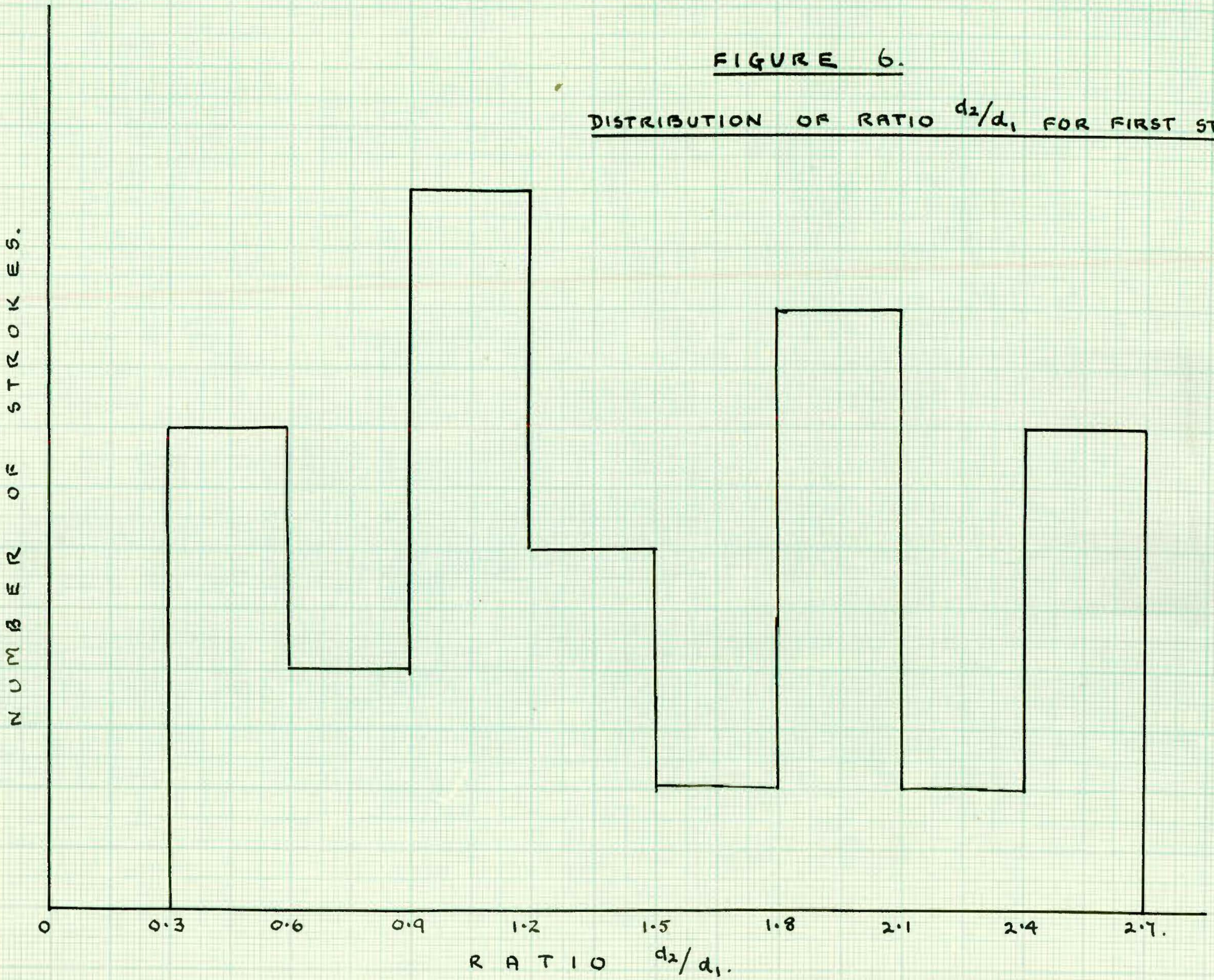


FIGURE 7.

DISTRIBUTION OF RATIO d_2/d_1 FOR ALL STROKES.

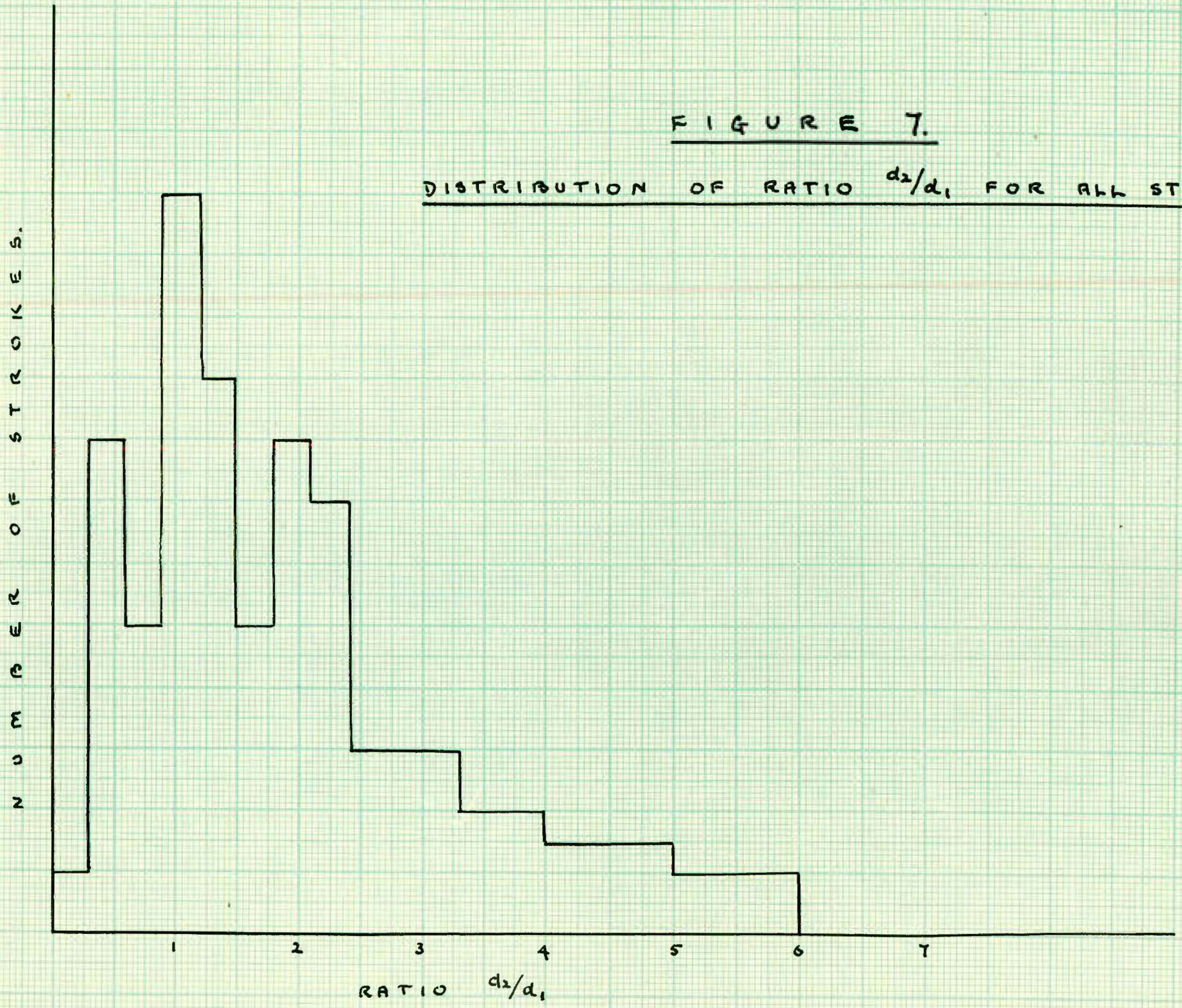


FIGURE 8.

DISTRIBUTION OF RATIO $\frac{d_3}{d_1+d_2+d_3}$.

FOR FIRST STROKES.

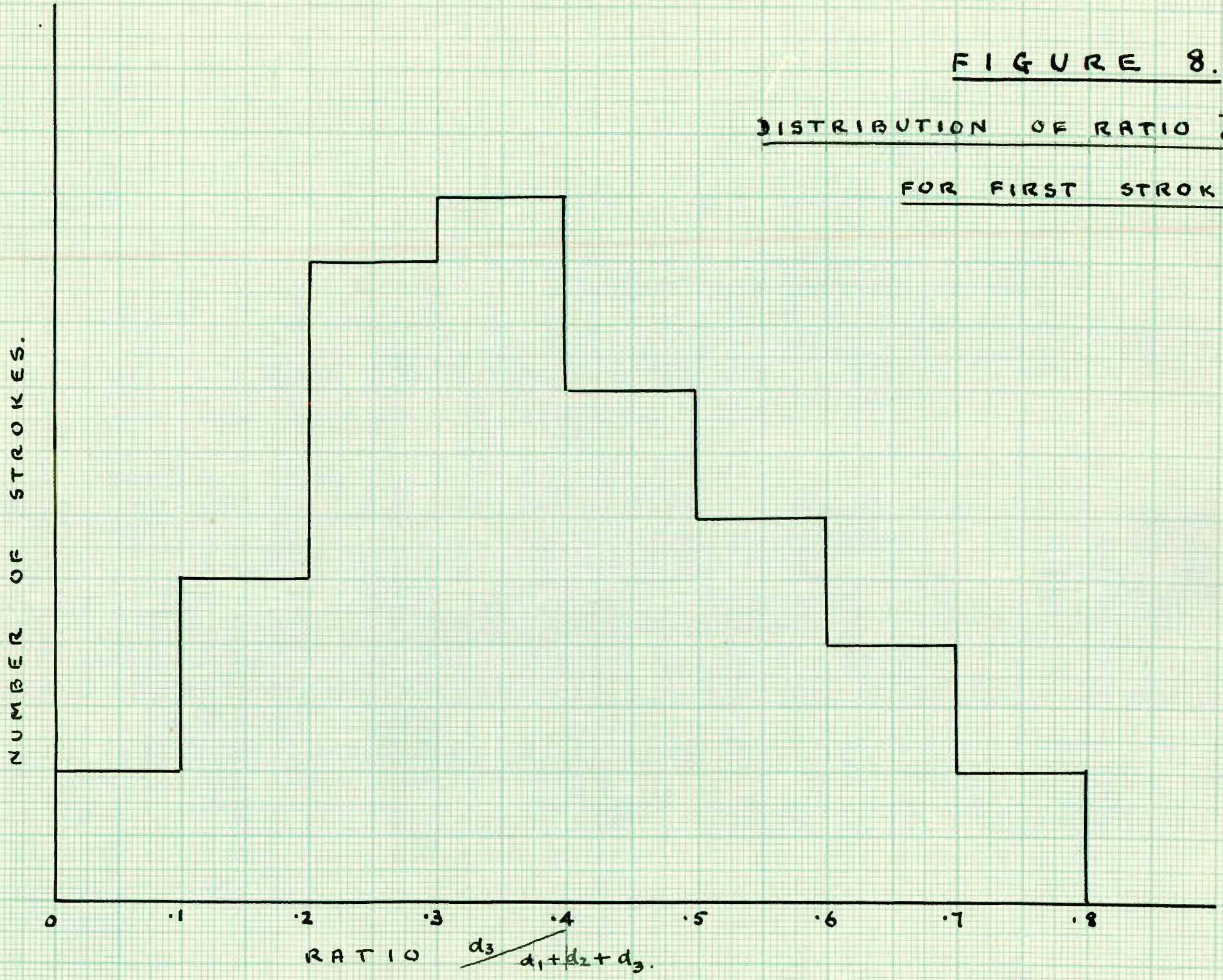


FIGURE 9.

DISTRIBUTION OF RATIO $\frac{d_3}{d_1+d_2+d_3}$ FOR SUBSEQUENT STROKES.

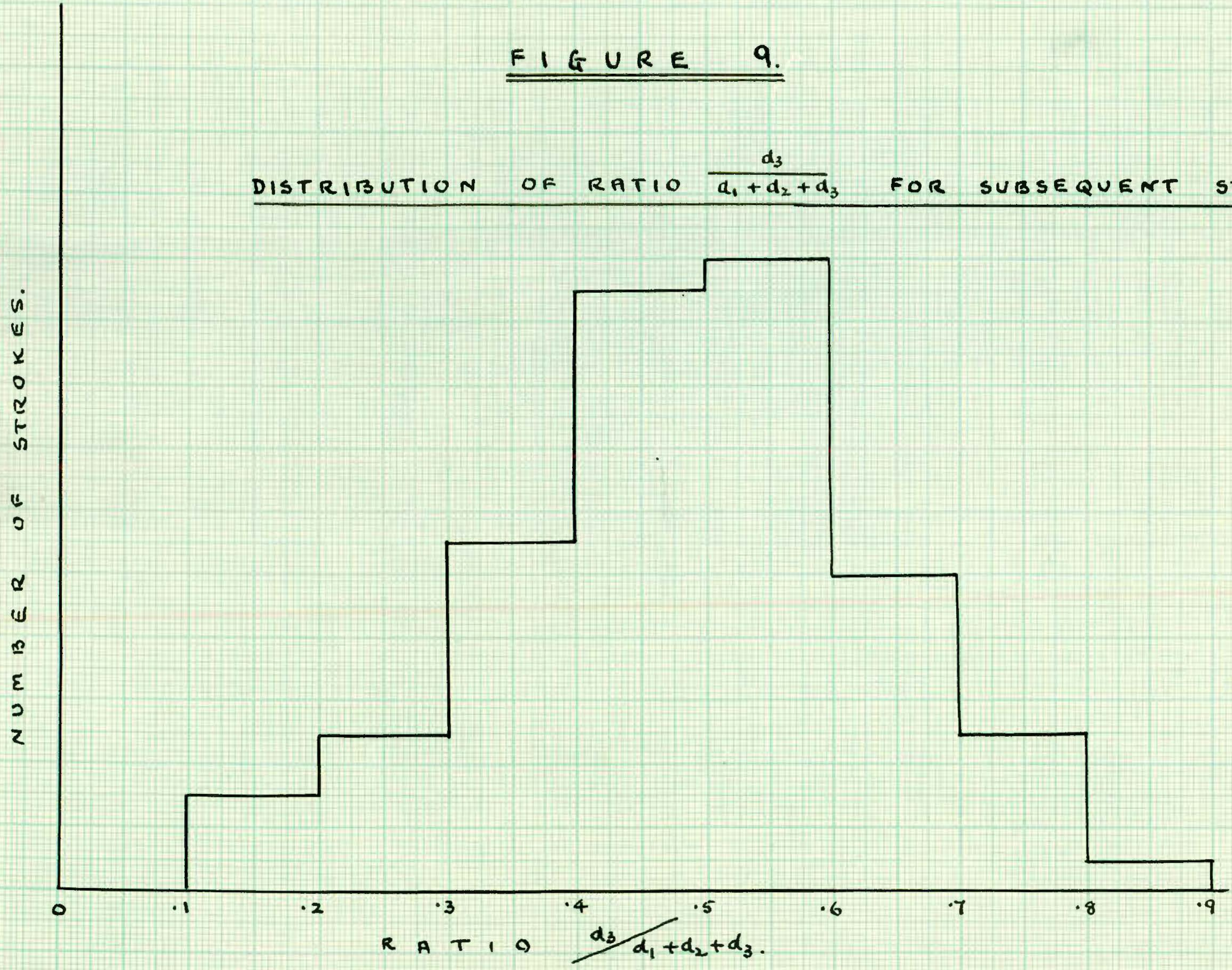


FIGURE 10.

TYPE β - DISTRIBUTION OF TOTAL LEADER TIMES. (T_1)

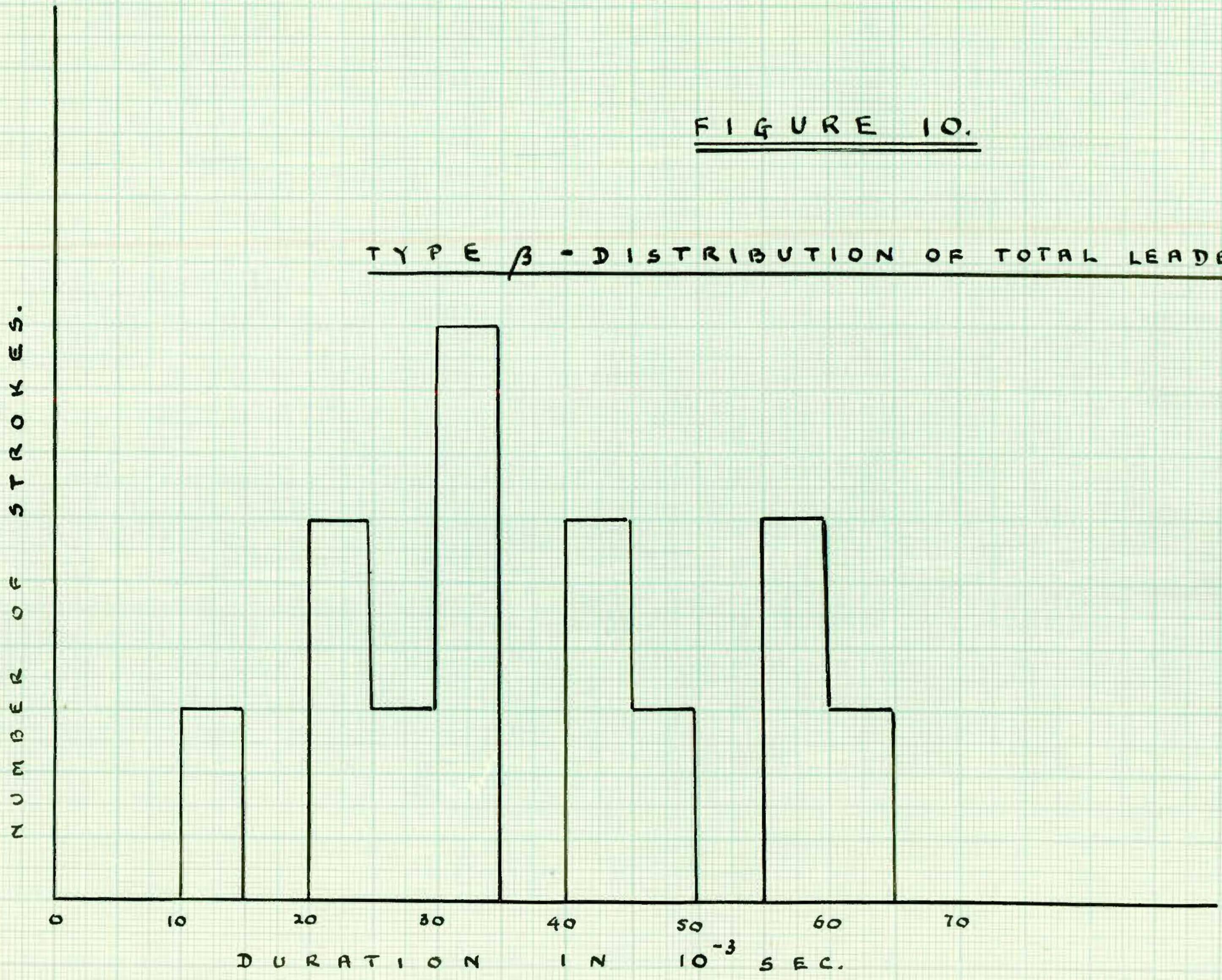


FIGURE 11

DISTRIBUTION OF TIMES OF FIRST PORTION OF TYPE β LEADER (T_2).

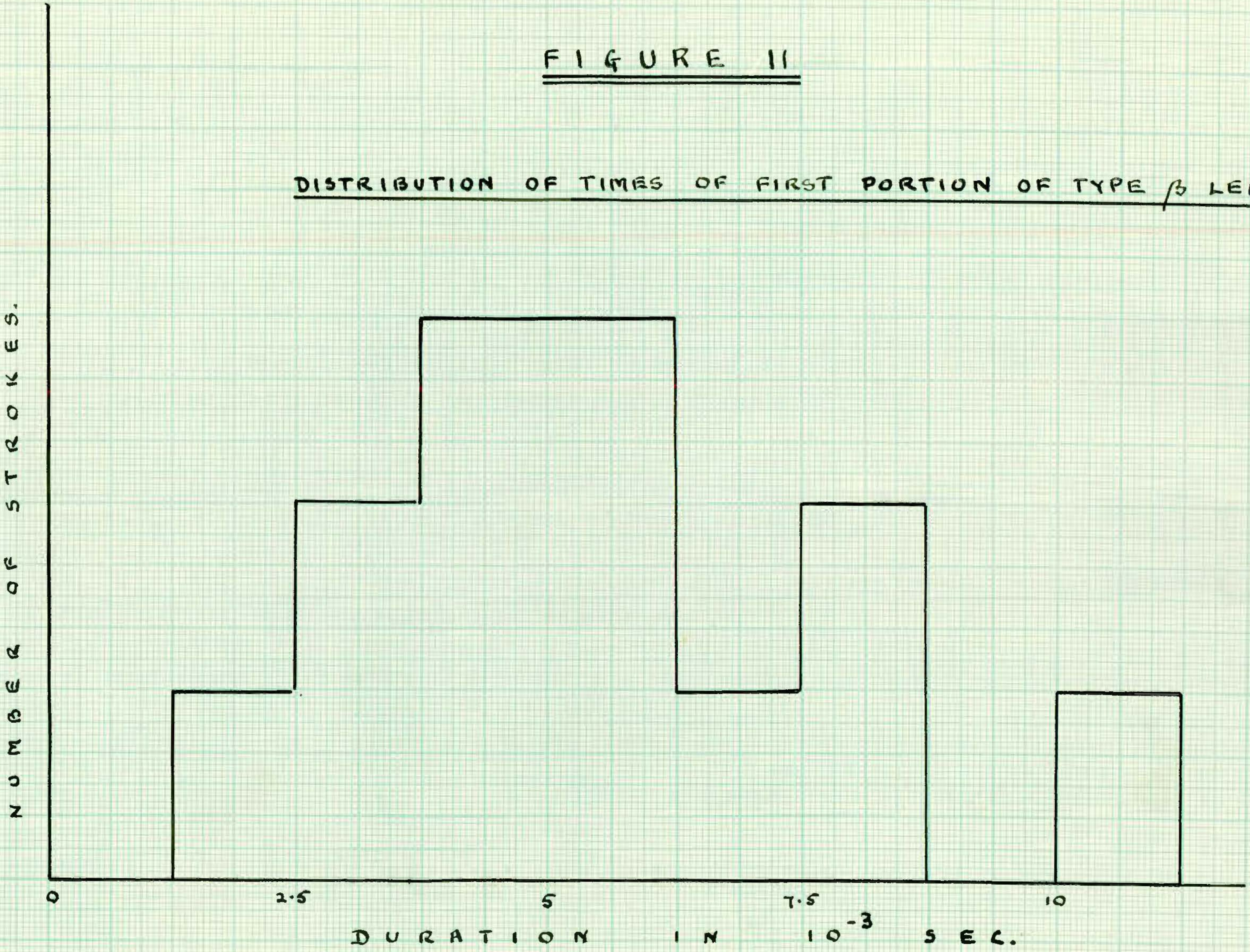


FIGURE 12.

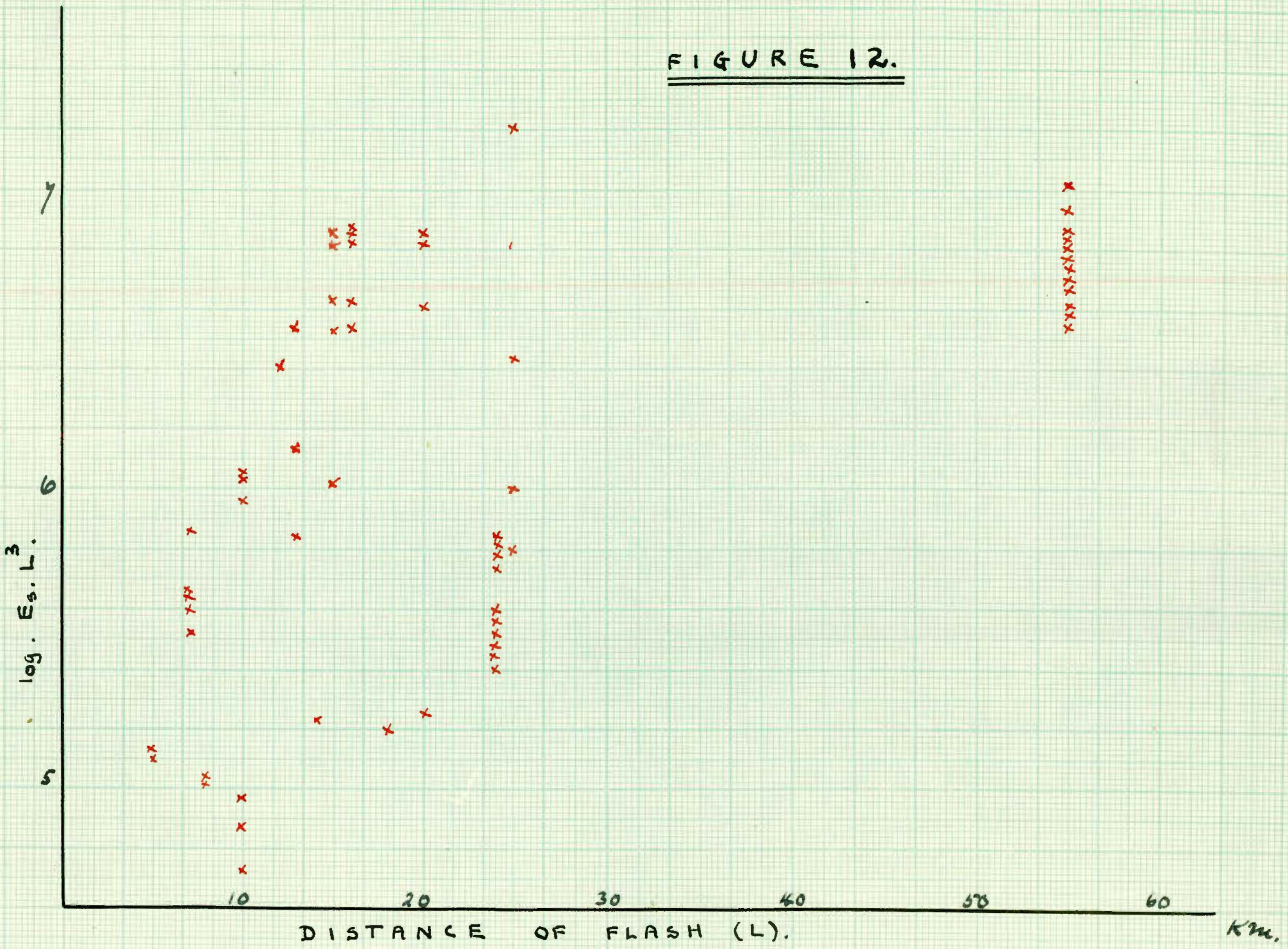


FIGURE 13.

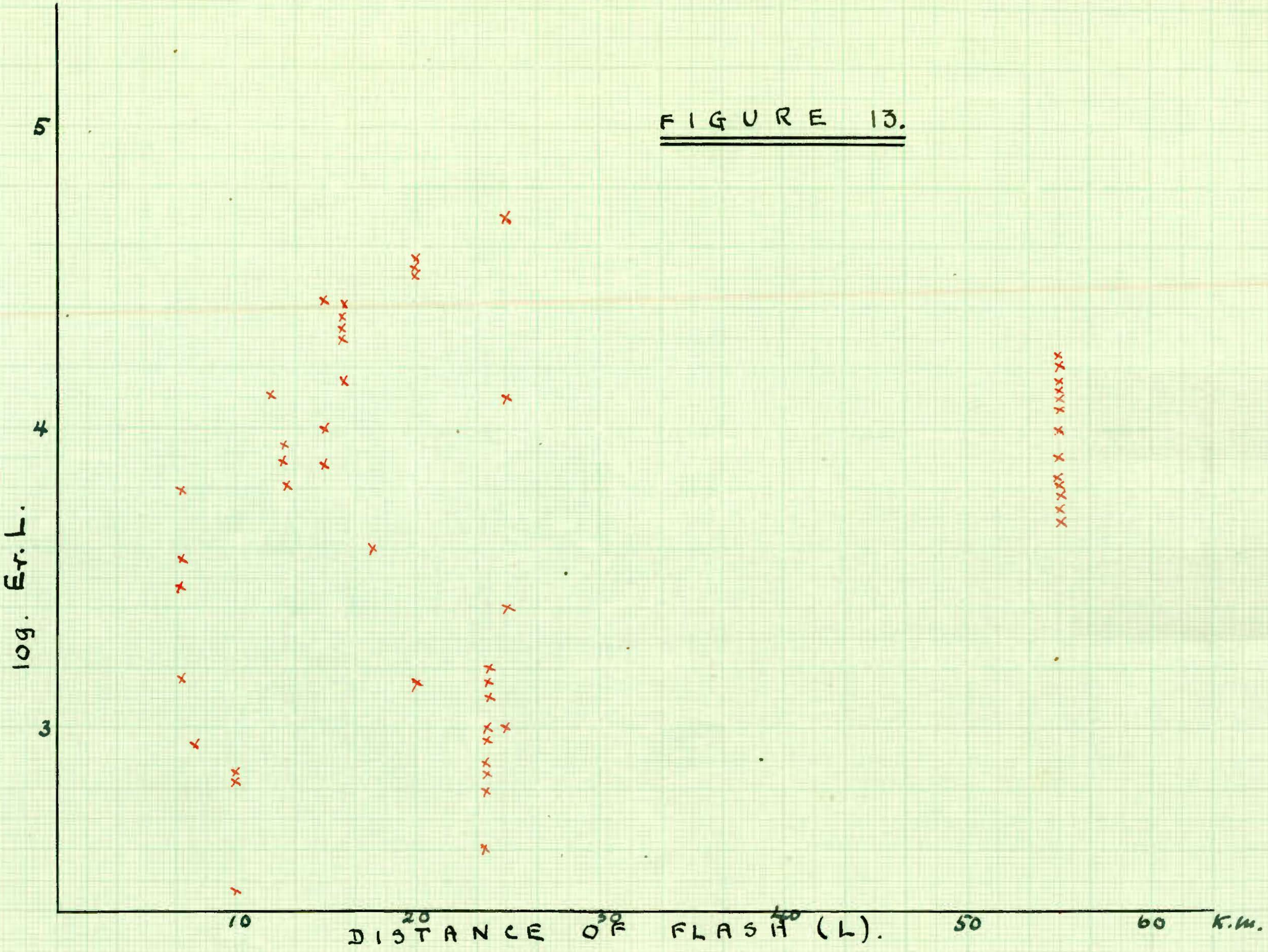


FIGURE 14.

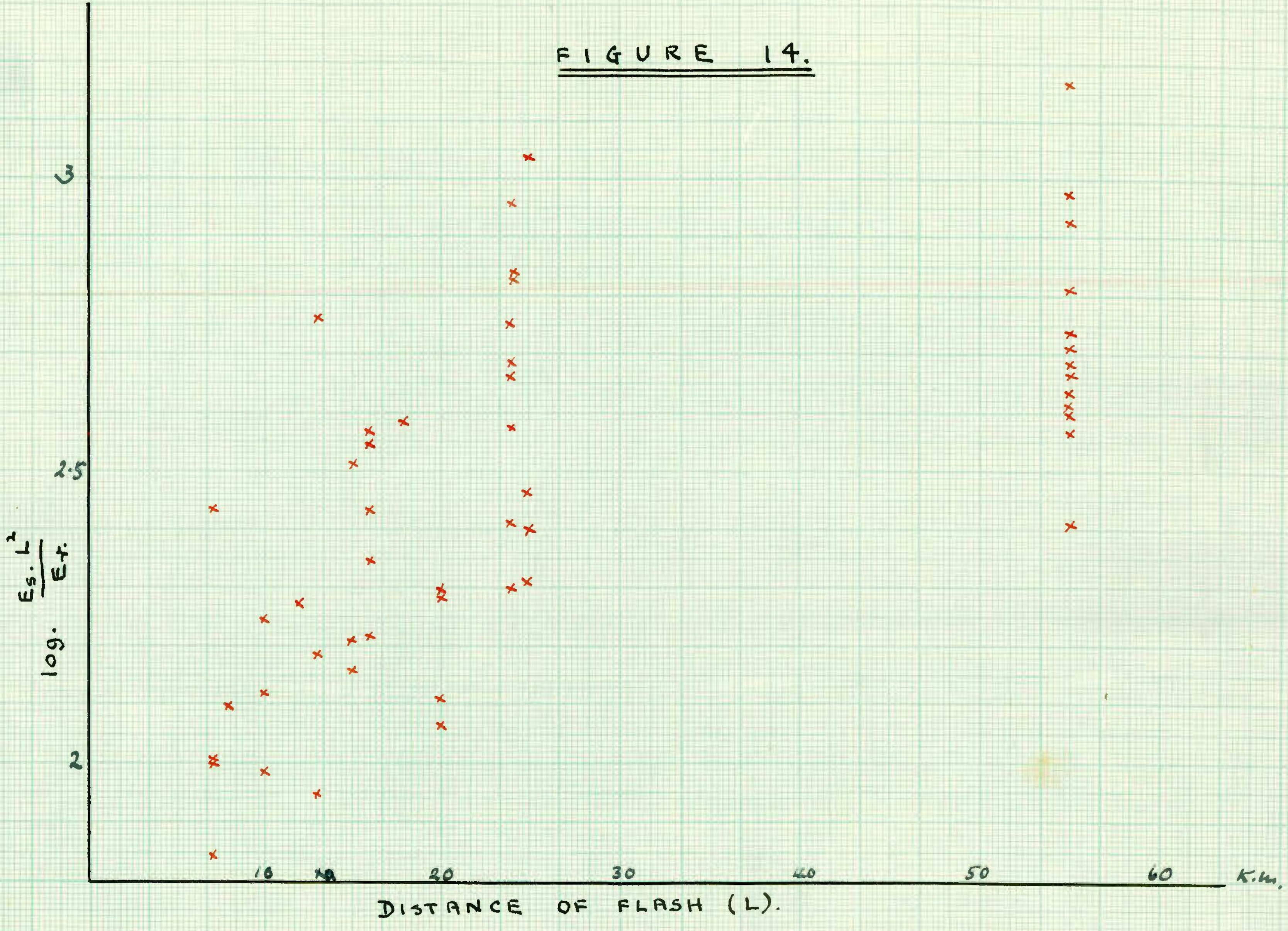
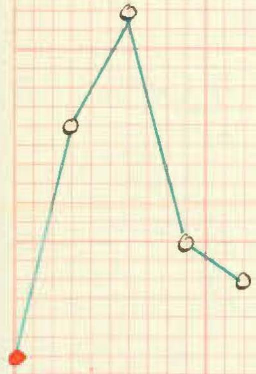
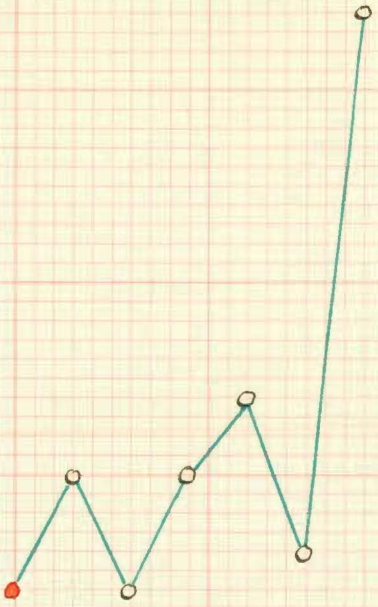


FIGURE 15

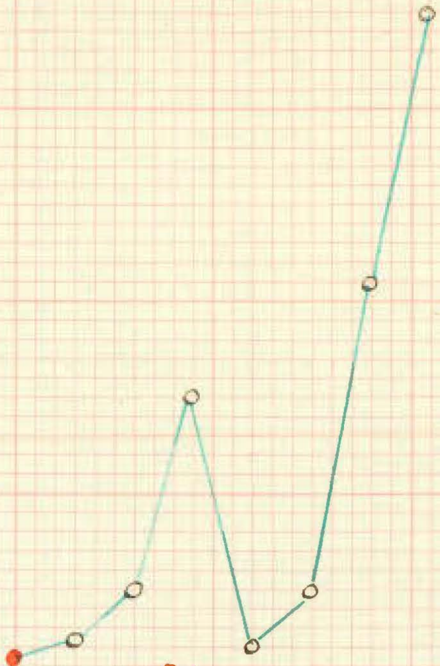


J. 2.



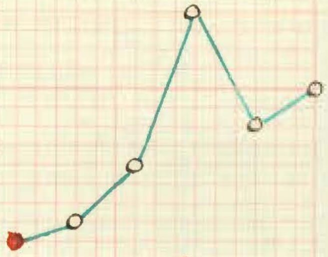
J. 3.

J. 4

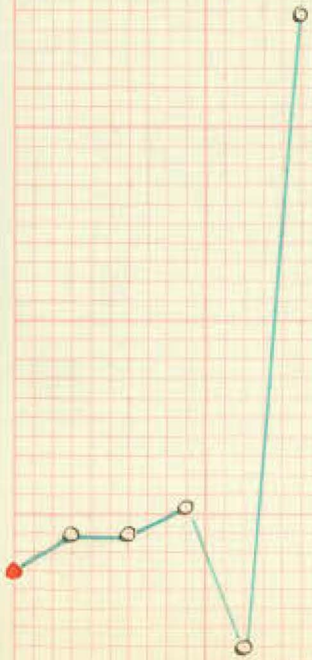


O. 1.

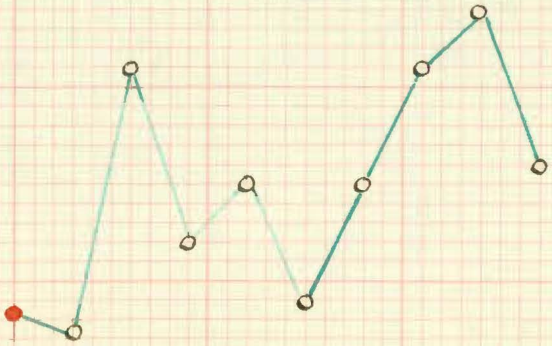
O. 2.



R. 1.



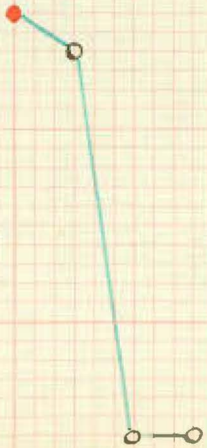
X. 1.



X. 2.

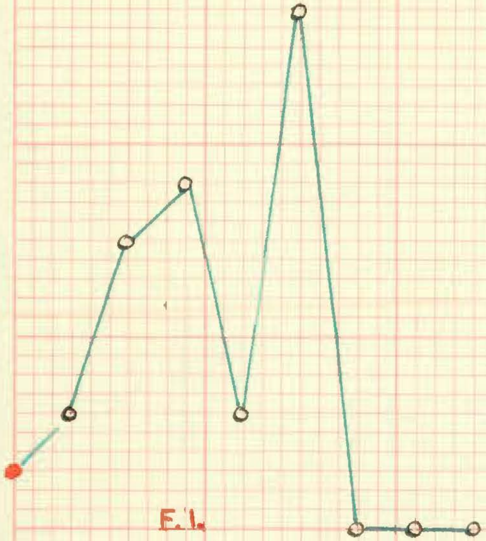
X. 3.

Y. 1.

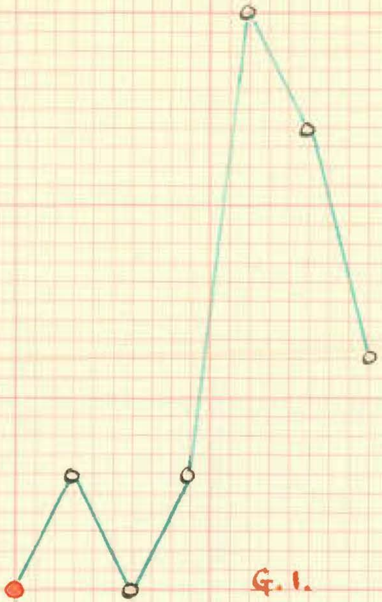


Y. 4.

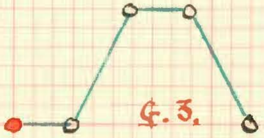
Z. 1.



E.1.

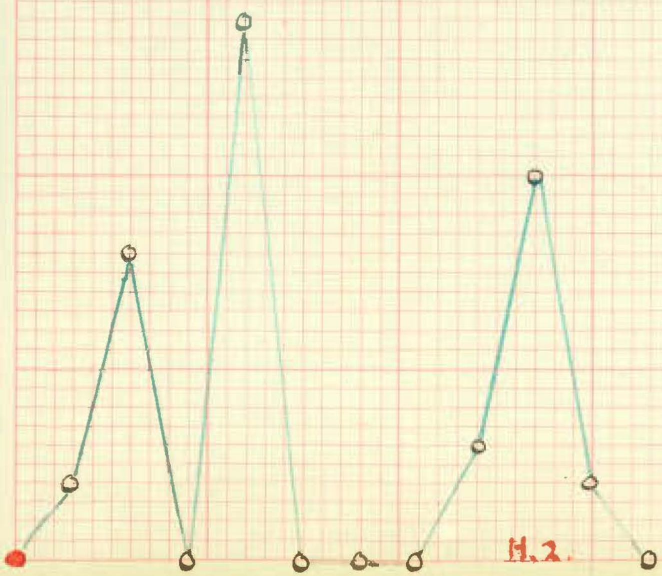


G.1.



G.3.

H.1.

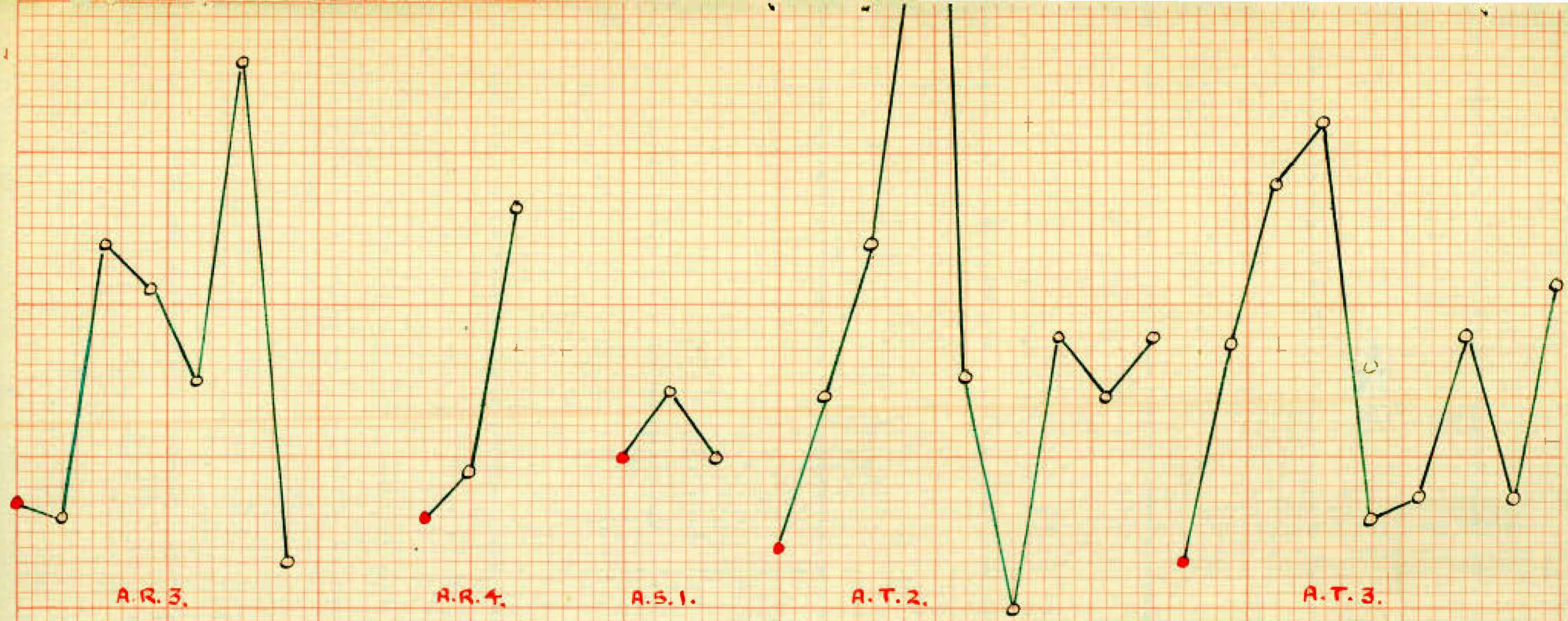


H.2.

I.1.

I.2

I. 3.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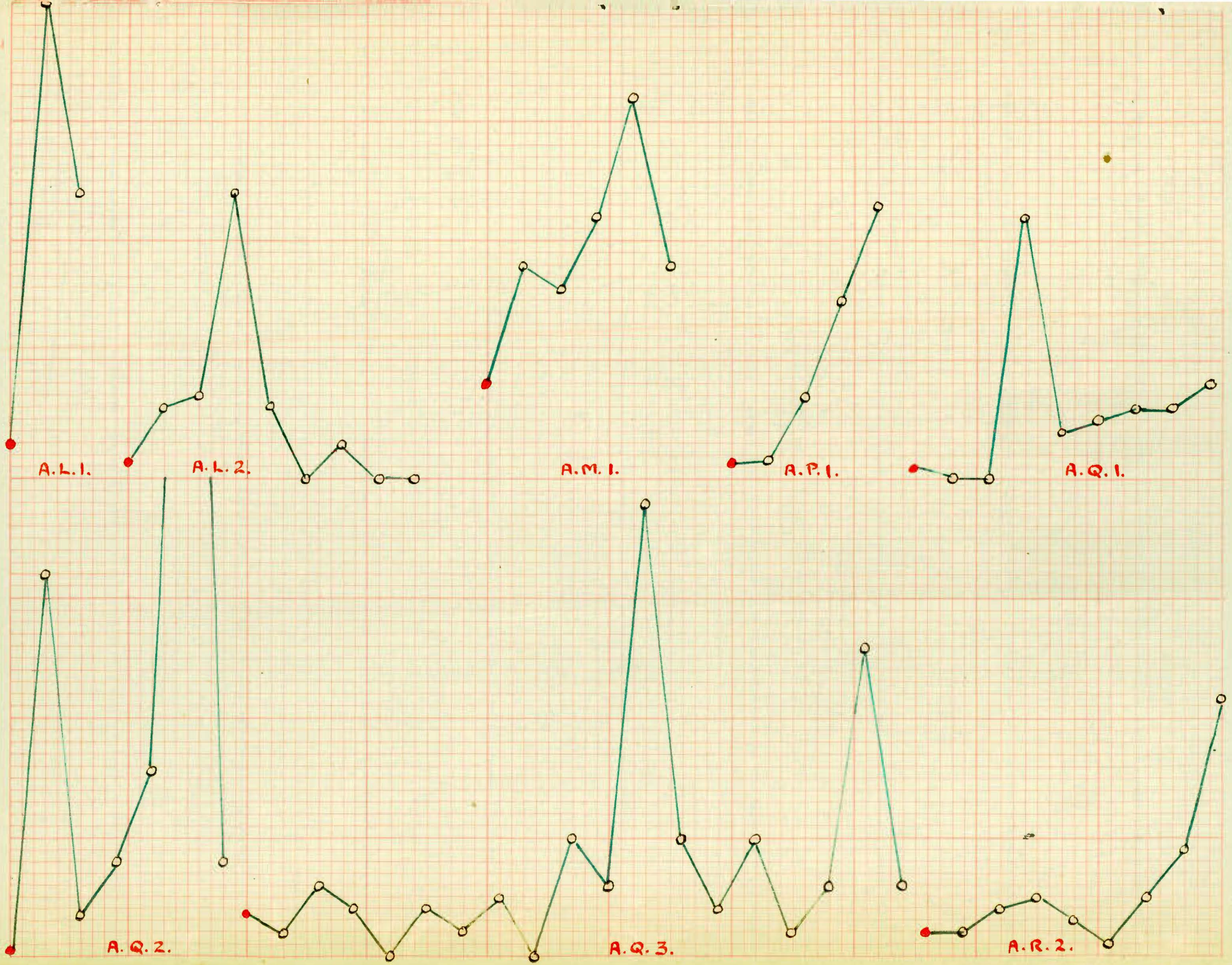
A.R.4.
A.S.1.
A.T.2.
A.T.3.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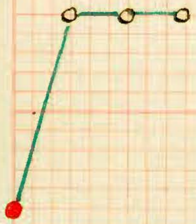
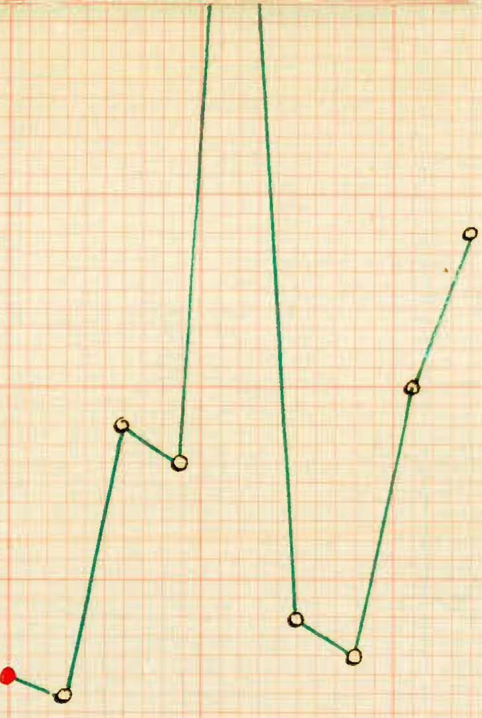
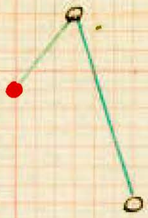
A.R.2.


Z.2.


Z.3.


A.B.1.


A.B.2

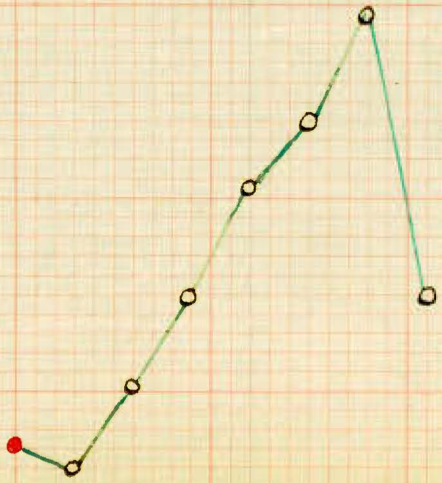

A.E.2


A.E.3


A.E.8.


A.F.1.


A.F.2.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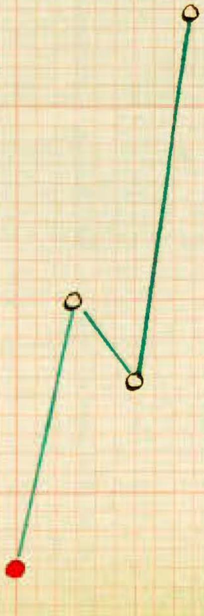
A.H.1.


A.K.1.


A.K.2.