XXXVIII. *Experimental Researches on the Transmission of Electric Signals through Submarine Cables.*—Part I. *Laws of Transmission through various lengths of one Cable.* *By* Fleeming Jenkin, *Esq.* *Communicated by* C. Wheatstone, *Esq., F.R.S.*

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In a paper by Professor W. Thomson "On the Theory of the Electric Telegraph," communicated to the Royal Society in 1855 *, the peculiar circumstances affecting submarine wires were especially analysed, and it is probable that all the laws regulating the transmission of signals could, by further development, be deduced from the mathematical theory there stated, if the necessary constants were known.

It is hoped that some account of an experimental research into the same subject may be found interesting, especially as the experiments not only confirmed the conclusions arrived at by Professor W. Thomson, but led also to the discovery of several facts of considerable practical importance.

With the view of elucidating the present subject, many experiments have been made on the charge and discharge observable at the near end of a cable; but although this charge is intimately connected with the retardation of signals, the connexion is complicated, and many false deductions have been drawn from the facts observed.

The author preferred to make his experiments on the signal or current actually received at the far end of the wire, the object being to establish a direct relation between the causes operating at one end and the effects observed at the other. Some experiments of this kind have also been made, but the instruments used have been such as could only indicate some one point of the complete phenomenon, such as the presence or absence of a given current, and the conclusions so arrived at vary with the nature of the instrument employed.

The author used an instrument by which he was able to follow the phenomena throughout, observing the nature and magnitude of every change produced in the received current. An attempt was first made to obtain by experiment, from various lengths of cable, and with various battery power, the curve given by Professor Thomson in the above-named paper, and called by him "the curve representing the gradual rise of the current in the remote instrument when the end operated on is kept permanently in connexion with the battery." This curve will in the present paper be called the arrival-curve.

The effect of continually repeated signals of various kinds was next studied, with various lengths of cable and various arrangements of battery, in order to determine in each case the practicable speed† of signalling.

* *Vide* Proceedings of the Royal Society, May 1855, and Philosophical Magazine, S. 4. vol. xi. p. 146.

† In this paper, where the words "speed of signalling" or "rate of transmission" are used, the author

Certain modifications of the usual signals were by these means discovered which materially increased the rate of legible transmission.

These experiments were all made on one cable, and do not therefore refer to the effects produced by a change of dimensions or materials; they will now be described in detail, and the connexion of the results with the mathematical theory will then be mentioned.

The Red Sea cable only was used in all the experiments; the external diameter of the insulated wire was 0·34 inch; the gutta percha weighed 212 lbs. per knot; the conductor was a copper strand of seven wires, and weighed 180 lbs. per knot. The extreme diameter of the strand was about 0·105 inch, and the ratio of the external to the internal diameter of the gutta percha sheath may be taken as 3·4. The resistance of the conductor per knot was 25×10^7 British absolute units.

The first experiment was made on July 26th, 1859, with 2168 knots disposed in ten coils, each about 26 feet in diameter, and held in a dry iron tank; the cable A C X, the battery B, a Morse key M, a galvanometer G, and the two earth-plates E E were connected as in fig. 1, Plate XLIX.

The effect at the end X produced by connecting the cable at A alternately with the battery and the earth-plate by means of the key was observed on the galvanometer G, being Professor THOMSON'S marine galvanometer.

The suspended magnet m of this galvanometer carried a little mirror n reflecting the image of a flame B on to a scale A about 26 inches off, as shown in fig. 2. The zero of the scale was in the middle, and each division was equal to $\frac{1}{40}$th of an inch. The coil C is shown in section, and the little lens L in its position in front of the mirror. The deviations of the spot of light from the centre measured on the scale were sensibly proportional to the strength of the current causing the deflection, when the deviations did not exceed 200 divisions.

The little magnet was powerfully directed by a fixed external steel magnet N S. The weight of the moveable magnet and mirror was about $1\frac{1}{2}$ grain; the inertia of the moving parts was consequently so small, and the directing force so great, that the variations of a rapidly changing current were accurately represented by the movements of the spot of light along the scale. When the Morse key (fig. 1) was pressed down, the spot of light remained apparently motionless for a short but sensible time, then shot along the scale, moving rapidly at first, but gradually losing speed, until at last it moved very slowly to a maximum deviation, at which it remained quite still: these movements truly showed the gradual change of the received current from nothing to a maximum, a change requiring fifty seconds for its completion. During the latter part of this time the movement of the spot was slow enough to allow the moment at which it passed any given division of the scale to be pretty accurately fixed. Two observers

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refers to the speed with which certain changes in the received current called signals can be made to follow each other, and not to the velocity of propagation of the electric current.

were wanted, one noting by the seconds hand of a watch the interval between the sound of the contact made by the Morse key, and the sound of a little blow struck by the other at the moment when the spot passed the given division.

Only one observation could in general be made each time the current entered the cable. The results of the observations are given in Table I.

The maximum current from a battery of 72 Daniell's cells caused a deviation of 130 divisions. The strength of this permanent current depends simply on the electromotive force of the battery and the resistance of the various parts of the circuit, being quite independent of the inductive phenomena.

The first column shows the number of seconds during which the current had been flowing into the cable when the spot had reached the division of the scale entered immediately beneath in the second column. The third column shows the percentage of the maximum deviation, or strength of current, to which the figures in the second column correspond. Thus, when the Morse key had been pressed down for eight seconds, the spot of light was just passing the 100th division of the scale, showing that the current had attained 77 per cent. of its maximum strength. One part of the arrival-curve might be constructed by using the entries in the first and third columns as coordinates.

The whole curve could not be obtained because the movement of the spot of light during the first four seconds was too rapid to allow of observation.

Table II. contains a similar set of observations made with 36 Daniell's cells instead of 72. By comparing the third lines of the two Tables, it is seen that the same percentage of the maximum strength is reached in the same time with both batteries, or, in other words, that the *electromotive force of the battery has no appreciable effect on the velocity with which the current is transmitted.*

All the variations of the received current are therefore in the Tables reduced to percentages, or to the variations which would have been observed if the permanent current due to the battery used had produced a maximum deviation of 100 divisions in each case. This condition could have been practically fulfilled, but was thought unnecessary, as no change of the battery would have altered the percentage of variation observed in the received current.

Table III. shows some observations for the arrival-curve with 1500 knots of cable in circuit.

Table VII. contains the result of a similar investigation for 1006 knots. The first and second columns of this Table contain similar entries to those in Table I.; the third column shows the division passed by the spot when the current was falling, after the Morse key had been released for the number of seconds entered above in the first column.

Thus, after the end A of the charged cable had been put in connexion with the earth-plate E (fig. 1) for $14\frac{1}{2}$ seconds, the spot was just falling past the 15th division of the scale. As the maximum deviation had been 277 divisions, the spot had, during these

$14\frac{1}{2}$ seconds, traversed 262 divisions of the scale, or the received current had diminished 94·6 per cent. in that time. The fourth and fifth columns give these two numbers. It will be seen from these columns that, measuring from the starting-point, the spot of light traversed the same distance on the scale in the same time when the current was falling as when it was rising. From this we conclude that *the rate of decrease in the current received at* X *after the contact had been made for a given time with earth at* A, *was the same as the rate of increase observed after making contact with the battery at* A *for an equal time.*

Table XII. contains a very perfect set of similar observations with 2192 knots in circuit. The arrival-curves for 1006 knots and 2192 knots constructed from Tables VII. and XII. are shown in fig. 7, Plate L.

The same connexions (fig. 1) were used to test the effect of practical signals, the Morse key being moved up and down in time with a metronome. The signals sent were the dot and dash, or dot and line, singly and combined. These signals are the simplest of all, but the conclusions drawn from them are applicable to all other signals depending on the time during which a given strength of current flows.

The headings of the several columns explain the contents of Table IV., which shows the observations made when various signals were sent at various speeds through 1500 knots of cable. Tables VI., XIII., and XIV. contain similar observations made with other lengths of cable in circuit. It should be observed that the effects recorded are those which occur when the same cycle of operations has been constantly repeated for some time, and are quite distinct, as will presently be shown, from the effects produced when signals of the same kind are for the first time sent through the cable.

The first set of observations recorded in Table IV. may be explained as follows. The metronome was set so as to beat 130 times in the minute. The Morse key alternately connected the cable at A with a battery of 72 Daniell's cells, and with the earth-plate for 0·462 second. The signals sent are called dots, because the sixty-five short contacts with the battery, each followed by an equal contact with the earth, would, through a short cable or air line, have transmitted sixty-five distinct currents, each capable of printing on the common Morse receiving instrument sixty-five equally spaced dots. While the contacts were regularly repeated, the spot of light moved steadily back and forward from the 85th to the 80th division of the scale. By reducing these deviations to a percentage of the maximum deviation (200 divisions), we obtain the numbers 42·5 and 40. The variation of the strength of the received current was therefore $2\frac{1}{2}$ per cent. All these numbers are entered in the several columns of the Table.

The figures annexed to the Tables show by curves the changes of the received current. The abscissæ of the curves correspond to intervals of time, and are taken from the fourth column. The ordinates correspond to the strength of the received current at each moment, reduced to a percentage, and are taken from the eighth column. The ordinates, instead of being measured from a true base-line, are measured from a horizontal dotted line, of which the ordinate is 50.

The dots first entered (Table IV.) appear as an even wavy line; the lowest point of each wave is 10 parts, and the highest point 7½ parts below the dotted line, corresponding to the true ordinates from the base, viz. 40 and 42½. The top and bottom only of the waves are fixed by the observations.

The second kind of signals are called dashes, because if sent through a short cable or air line, they would print a succession of dashes or lines, separated by short spaces equal to those separating dots sent at the same speed. To do this the contact with earth is made the same as for a dot, but the contact with the battery is made twice as long. Examples of the dash will be found in Tables VI. and XIII.

The effect of combining these two primary signals was tried by sending alternate dots and dashes; the results are entered in the Tables. The effect of one complete cycle of operations is shown in the figures annexed to the Tables by that part of the curve drawn with a thicker black line. Thus in the second dot and dash curve of Table IV. the dot curve begins with the ordinate 53·2; the first battery-contact slightly increases the current, till the ordinate of the top of the dot curve becomes 55·5. The first earth-contact diminishes the current, so that the ordinate at the end of the dot or beginning of the dash curve is 48·0; the next battery-contact, being a long contact, raises the dash curve to 61·7. The second earth-contact lowers it to 53·2, when the cycle recommences.

The numbers in the two last columns of the Tables IV., VI., XIII., and XIV., with the figures annexed, are all directly comparable, for they all represent the results reduced to a percentage, and are consequently constant for each length, being independent of any change in the battery.

These observations do not give the retardations properly so called, *i. e.* they do not show the time separating the contact made at A from the effect produced at X, but they establish several conclusions of greater importance than the knowledge of this retardation.

It will be seen (Table VI.) that when 66 dots per minute were sent into 1802 knots of cable at A, a constant current was received at X, in which no oscillation could be seen corresponding to the signals sent*.

The same phenomenon was observed with 2192 knots in circuit, when more than 50 dots per minute were sent. The effect produced at X by these rapidly repeated dots was almost exactly that which would have been observed if the cable at A had been permanently connected with a battery of about 30 cells. In moving the Morse key up and down, a little time elapses between the contact with earth and that with the battery, during which the cable is really insulated at A. This lost time caused the received current to be equal to only 41·6 in one case and 42·9 in the other instead of 50 per cent. of the maximum permanent current, as would certainly have been the case if the sums of the battery and earth contacts had respectively occupied exactly the half of each minute.

* The immobility of the spot could not be accounted for by the inertia of the mirror and magnet, which, when in vibration, moved so rapidly that the oscillations could not be counted. Similar observations made with a galvanometer, the needle of which oscillated slowly, would lead to most erroneous results.

It is certain that in the two cases named the received current did not vary 1 per cent.; here therefore we find one positive *limit to the rate of transmission.* No doubt oscillations of considerably less than 1 per cent. might be observed and recorded by employing a more sensitive instrument and stronger batteries; but we clearly see that the useful effect produced rapidly decreases as the number of signals per minute increases, and therefore that, however sensitive the instrument and powerful the battery, signals sent at more than a certain rate will fail to cause any appreciable useful effect at the receiving end; and we may safely conclude *that in all submarine cables there is a limit to the number of signals which can be sent per minute, a limit which cannot be exceeded by any ingenious contrivance.*

Fifty-six dots per minute were distinctly visible when sent through 1802 knots, and 40 dots when sent through 2192 knots. The mean strength of the currents showing these dots is less than half the maximum permanent current, because of the time lost in moving the Morse key, as already explained. The curves showing these dots appear therefore below the dotted line representing the middle of the scale.

As the speed of sending decreased, the amplitude of oscillation of the spot or variation of the current increased, but the mean strength of the current remained nearly constant.

When dashes were sent (*i. e.* when the length of the battery-contact was made twice as long as the earth-contact), the mean strength of the received current was much higher, being above the middle of the scale.

The effect of dashes could thus, and thus only, be distinguished from that of dots sent at a lower speed. For instance, dashes sent through 1802 knots (Table VI.) when the metronome beat 84 caused a 6 per cent. oscillation, and dots sent when the metronome beat 60 caused very nearly the same oscillation; but the strength of the current due to the dashes varied from $53\frac{1}{2}$ to $59\frac{1}{2}$, whereas that due to the dots varied from 43 to 49. In the corresponding curves the dashes appear above the dotted line and the dots below. This effect will be easily understood when it is remembered that while dots are sent, the end A of the cable is altogether in contact with the earth for nearly half of each minute, but when dashes are sent, it is in contact with the earth for only about one-third of each minute.

When the dot and dash are sent alternately, the effects, differing considerably from those produced when each is sent continuously, can be best studied in the curves annexed to the Tables.

The top of the dot curve is higher, and the bottom does not go so low as when dots only are sent, whereas the top and bottom of the dash curve are both lower than when dashes only are sent; *but the bottom of the dash curve does not go so low as the bottom of the dot curve.* This was seen in every instance, but was most apparent at the higher speeds.

The strength of the received current due to the long battery-contact during the dash is naturally greater than that caused by the shorter contact during the dot; and as the

connexion with earth after the two signals is only of equal duration, it is clear that the received current will not fall so low after the dash as after the dot, and this is precisely the effect shown in the curves. The beginning and end of the dot are at different heights, and similarly the beginning and end of the dash are at different heights, making altogether a very irregular curve, especially at the higher speeds.

This irregularity very seriously interfered with the distinctness of the received signals, although the change of current could be followed throughout by watching the spot. At a high speed the dot appeared as a mere pause followed by a fall, instead of a little rise followed by an equal fall; and if the dots and dashes had been irregularly combined, it would have been impossible to disentangle them, as received, by the eye. If a receiving instrument had been used like the common Morse receiver, simply marking the time during which the received current was above or below a given strength, the signals would have failed to give any intelligible record even at a very low speed: this is shown by the fact that it is impossible to draw a horizontal line intersecting both the curve of repeated dashes and that of repeated dots, even for the very lowest speeds recorded in each Table.

Thus, long before the limit is reached at which signals cease to produce any change at the receiving end, the interference of one signal with another causes so great a confusion in the currents received as to put a fresh limit to the practicable speed of transmission.

This confusion is still further increased by the effect of a pause in the signals between letters, words, or sentences.

During all intervals the cable is left in connexion with the earth at A; and if the pause lasts a little while, the current at X falls to nothing, or nearly nothing, when the effect of the first signals sent is to cause an unintelligible succession of sudden increments in the received current, until, after a certain number of contacts, a permanent mean strength of current is attained, at which regular signals might become intelligible. The higher the speed the greater the number of contacts required for this purpose; for instance when 1802 knots were in circuit, the following Table gives the number of dots required to bring the spot to the mean position in which it was maintained by regular signals.

Beats of metronome.	Dots required to raise current to 42 per cent. of maximum.
92	6
84	6
72	4
60	3
50	
40	2

The curve in fig. 3, Plate XLIX. roughly represents the variations of the received current when the operator begins to send the dots regularly through a cable which has

been fully discharged. Similar but converse effects would be observed if the line were left long in contact with the battery before the signals began.

This irregularity has hitherto put the practical limit to the rate of transmission through long submarine cables. When this rate is exceeded, a dot sent may at one time cause a great rise in the received current, at another time it will barely arrest a fall, and thus similar signals at one end are found to produce utterly dissimilar effects at the other. No change in the battery has the smallest effect on this interference, nor can any delicacy in the receiving instrument disentangle the confusion, which, it should be observed, is totally distinct from the retardation of the signals.

It would matter little that signals should appear in America even a minute or so after they had been made in England, provided the same signal at the sending end always produced the same effect at the receiving end. The experiments show how far this is from being the case.

The usual mode of avoiding this confusion is to signal at so slow a rate that every dot causes a very large percentage of variation in the received current, while the dash causes nearly the maximum current which would be received from a permanent contact with the battery.

In air lines, or in short submarine cables, or in long submarine cables with large conducting wires thickly covered, this plan does not entail too slow a speed for practical work; but to avoid confusion in this manner when working through 2200 knots of the Red Sea cable, it would be necessary to reduce the speed to less than 10 dots per minute, whereas 40 dots or more could be received but for the interference.

Hence we conclude *that there is a wide margin between the limit set to the speed of transmission by the gradual diminution of the received signals and that set by their interference.*

If interference could be prevented by any change in the signals, it was clear that the capabilities of any given cable would be increased at least fourfold.

Reverse currents have been much advocated, on good authority, as a means of greatly increasing the rate of signalling, and their effect was therefore examined, although it was not thought probable that the interference would be diminished by their use. By "reverse currents" the use of alternate positive and negative currents is meant. The negative current substituted for the earth-contact is supposed by its advocates in some way to clear the line and prepare the way for a positive signal.

The connexions used during the experiments on "reverse currents" are shown in fig. 4, Plate XLIX. The first contact sent a positive, and the second contact a negative current through the line.

The effects of single and reverse currents were directly compared on 1165 knots of cable. Tables VIII. and IX. show observations of the arrival-curve and signals when a positive current from 72 cells and an earth-contact were used. Tables X. and XI. show a similar set of observations when a positive current from 42 cells and a negative current from 30 cells were used. By keeping the same total number of cells in each

case, the difference of potentials between the two sources of electricity alternately in connexion with the line was maintained nearly equal. Tables VIII. and IX. are similar to those already described.

The observations in Table X. were made in almost the same manner as those in Tables VIII. and IX., but the following description may make the meaning of the entries more distinct.

The Morse key when untouched left the negative battery connected with the line, and the spot of light then stood at 113 divisions to the left of zero; when the key was permanently pressed down, the spot stood at 157 divisions to the right of zero. All deviations to the right are entered as positive, those to the left as negative. Four seconds after the key was pressed down, the spot passed the 100th division to the right; four seconds after the key was released, it passed to the 60th division on the left. In the first case it had traversed 213 divisions in four seconds, in the second case 217 divisions, or 78·8 and 80·3 per cent. respectively of the sum of the two deflections 157 and 113.

On examining the last columns of Table X. we find that in any given time after moving the key, the spot traversed an equal length of the scale whether the change was from positive to negative or from negative to positive, or, in other words, *the rate of decrease in the current received at* X *after contact had been made with the negative battery at* A *for a given time was the same as the rate of increase observed after making contact at* A *with the positive battery for an equal time*,—a conclusion exactly analogous to that arrived at when single currents were used.

Moreover, comparing the last columns of Tables VIII. and X., we find that the spot traversed the same distance in the same time in each case, and therefore that the rate of increase and rate of decrease, caused by reverse currents, is exactly the same as that observed when single currents are used.

The arrival-curves from the two Tables are shown in figs. 5 & 6, Plate XLIX.

The curves are identical in shape, and differ only in their position relatively to the zero-line.

Thus the ratio between the ordinates of the arrival-curve is the same whatever the two sources of electricity at A, or the potential of the earth at X may be.

Hence we conclude,

1st. That the absolute change in the strength of the received current during a given time after a change in the contact at A, is not influenced by the potential maintained at X, but is simply proportional to the difference of potentials or electromotive force between the two sources of electricity alternately connected with the cable at A.

2nd. That the rate of change is independent of the potentials both at A and X.

It was now clear that the alternation of negative and positive currents could have no effect on the rate of signalling, but to avoid all cavil a few experiments were made with the usual signals.

The results are given in Tables IX. and XI. The signals sent by the reverse currents

were a little above the zero-line, those sent by the single currents were, as usual, near the middle of the range. This was the only difference observed; the amplitudes and relative position of the dot and dash were identical. The use of reverse currents, therefore, *does not alter the limit set by the gradual diminution of the received signals, nor that set by their interference.*

It is just possible that some small effect may be produced by a difference in the insulation when reversals are used, but there is no reason to suppose that this difference would be in their favour.

Abandoning reverse currents, the author was led to seek some other remedy for the confusion observed. One phase of this confusion might be described by saying that the mean strength of the current rose above 50 when dashes were sent, and fell below it when dots were sent, so that the dots and dashes appeared on different parts of the scale. The high position of the dash was due, as has been shown, to the comparatively short contact at A with earth after the long battery-contact. By making the second or earth-contact longer, the dash would be brought down in the scale. If the earth-contact were made equal to the battery-contact, the dash would simply become a dot sent at a slower rate. The mean strength of the current during the slow or long dots would be the same as that during the quick or short dot. The bottom of the long dot curve would be lower than the bottom of the short dot curve, and therefore, when the long and short dot were combined, there would still be considerable confusion. Moreover, if a Morse receiver or analogous instrument were used, the spaces separating the long dots would be twice as long as those separating the short dots, and this unequal spacing would cause fresh confusion.

These effects, consequent on making the second contacts always equal to the first, were well seen when the signals called A^s were sent *. The tendency observed in the original dot and dash was over-corrected. The dash now fell too low, and the dot not low enough, so that the confusion was nearly as bad as before; but the required correction was clearly enough pointed out. If, instead of keeping the *mean* strength of the current constant, the current at the *end* of each signal could be kept the same, the passage from one signal to another would cause no confusion, for the beginning or end of a dot would be exactly like the beginning or end of a dash. It was plain that the current at the end of a dash could be brought to any required point (and therefore to the point at which dots finished) by simply altering the proportion of the second to the first contact. Experiment had shown that the second contact was too short when made only half the length of the first, and too long when made equal to the first; no doubt some intermediate length would fulfil the required condition that the dashes should begin and end at the same division of the scale as the dots. The experiment required to prove this could clearly not be tried by aid of the metronome, and the apparatus shown in fig. 8 was therefore arranged so as to make contacts of any required proportion.

* So called because the dot and dash, followed by a short pause, represent the letter A in the Morse alphabet.

A strip of paper (figs. 8 & 9, Plate L.) was prepared with two parallel rows of alternate holes. This paper was joined so as to form an endless band, and was drawn by the roller R under two little bent wires *b* and *e*, placed abreast, so that each alternately came in contact with the metal plate L through one of the holes in the paper. The plate L was connected with the cable, the wire *b* with the battery, and the wire *e* with earth. As the paper was drawn along under the wires, the alternate battery and earth contacts sent signals through the cable, and the length of the holes in the paper determined the relative length of the contacts.

The first or battery-contact was made through the upper row of holes (fig. 9), the earth-contact through the lower row. Dots were sent by two equal holes, dashes by two longer holes, of which the upper bore to the lower the proportion of 5 to 4, corresponding to the relative length of contacts desired. The length of the two dash contacts was made equal to two pairs of dot contacts.

It was expected that if the right proportion between the first and second dash contacts had been adopted, all confusion from irregular combinations would be avoided; but during any pause, such as is practically required to separate groups of signals, the spot or current would still fall towards zero if the line were left in contact with the earth (or even if insulated at one end), so that the first signals sent after a pause would still cause mere irregular and unintelligible changes in the received current. To avoid this second source of confusion, it was necessary to maintain the received current, during any pause, at the constant final strength to which it returned at the end of each oscillation during a series of signals.

If this were done, the first signal would begin where the last left off, and each signal might be expected in all cases to produce one invariable and intelligible effect.

There were two obvious means of keeping up the current during a pause. The line might be left in contact with a third source of electricity* just sufficiently powerful to maintain the required strength of current, or a very rapid series of contacts might be made alternately with the full battery and with earth. Experiment had shown that such a series of contacts would maintain the current at the receiving end sensibly constant, and the strength of this constant current could be easily adjusted by varying the proportion between the first and second of these very short contacts, increasing the length of the first contact to raise the current, and increasing the length of the second contact to lower the current.

This second plan was easily carried out by the perforated paper. Where a pause was

* When reverse currents are used, if the line is put in contact with earth during a pause, the confusion of the first signals will be much lessened; the earth then acts as the third intermediate source of electricity alluded to in the text. This plan has to some extent been adopted in practice by Messrs. Siemens and Halske, by means of a key invented by Mr. L. Loeffler. This benefit, which may perhaps account for the fancied superiority of reverse currents, might be equally obtained with simple currents by connecting the line during each pause with half the battery. Mr. C. F. Varley informed the author that he also has used a similar key for a considerable time.

required, little holes were cut in the paper to make contacts in pairs, each pair half the length of those used for a dot. In fig. 9 these short openings are shown where the word "space" is written. This arrangement was perfectly successful with 1500 knots in circuit on the very first trial; and although other strips of paper were tried with other proportions between the contacts, none gave better results than those first adopted. When the paper was steadily drawn along, the signals appeared on the galvanometer with all the regularity that could be wished: during the pauses, the light stood trembling at one division on the scale, a dot caused a slight rise followed by an equal fall, and the dashes produced a greater and longer oscillation, at the end of which the spot always returned to the one constant final strength.

A still more decisive test was next made, by substituting a relay and Morse marker for the galvanometer; fig. 10, Plate L. is an exact copy of the signals which were then received, and shows faithfully the slight irregularities which did occur. The only serious flaw in the whole set of signals is shown at the beginning, between A and B, where some dots and a space contact made only unintelligible marks. This flaw invariably occurred at the same place; it was shown equally by the galvanometer and the relay, and for some time the cause could not be discovered. By carefully watching the paper strip, it was at last seen that when the joint of the endless band passed through the rollers R (fig. 8) a little hitch or pause occurred, and that this slight irregularity of speed caused a corresponding confusion in three signals. This accident showed the accuracy of proportion required between the various contacts.

Taking this hitch as the beginning, we next see six well-spaced dashes, three pairs of dots and dashes, one space, one dot, one space, one dash, a long pause, a dot, a long pause, a dash, a short pause, a dot, a dash, and a succession of dots.

In this series every possible difficulty which could arise from interference or confusion was encountered and successfully overcome. The rate was about forty-five dots per minute, and the oscillations for a dot must have been about 5 per cent.*

Signals sent at a much higher rate could have been distinctly received, but the drawing-rollers could only be driven at one speed.

The apparatus was next tried with 1800 knots in circuit: the signals could be read without difficulty on the galvanometer; but to increase the range and to facilitate the adjustment of the relay the battery power was increased, when not only could the regular dots and dashes be received, but even the short space contacts gave distinct legible signals; so that the three sets of signals of three different lengths appeared, without confusion, recorded by the relay. The shortest signals were received at the rate of ninety per minute; and from Table VI. it will be seen that even sixty dots per minute through this length reduced the oscillations to less than 1 per cent. of the permanent maximum strength. Hence we may conclude that, *by the means described, or by*

* When the relay was used the galvanometer could not be observed, for the motion of the soft iron used in the relay induced short currents, causing rapid vibrations of the spot of light.

analogous means, signals can be sent without confusion at any speed which will allow the shortest signals used to cause a sensible variation in the received current.

The cable was available for a few days only, the apparatus used was very imperfect, the paper frequently tore, the openings in it were cut by hand one by one, the speed of the drawing-rollers was far from regular, the relay was difficult to adjust, owing to residual magnetism in the electro-magnets, and the author could give but a small part of each day to the experiments; in spite of these disadvantages, the results obtained were so definite as to leave no doubt of the important conclusion stated above.

No further experiments could be made; but indeed no further improvement appeared possible, except in the mechanism for making the required contacts, and in the choice of signals which should give the greatest number of words with the smallest number of currents. Neither of these points can fitly be treated of in the present paper.

Before proceeding to compare the results obtained with the deduction from mathematical theory, or to apply the conclusions to cables in practical use, it will be well to consider how far the special disposition of the cable may have affected the value of the experiments.

The experiments were made through dry cables, lying in large close coils, whereas the cable when in use lies extended under water. It is found in practice that the insulation and charge of an iron-cased cable is little affected by submersion; but coiling is generally believed to cause an additional impediment to the transmission of signals, and it might certainly be expected that this difference of condition would cause some discrepancy between the experiments described and the results of practice: but since the mathematical theory is framed to meet the case of a submerged and extended cable only, whenever the conclusions experimentally deduced are found to be in accordance with the deductions of theory, it is clear that the experiments and the theory mutually confirm one another, and that the conclusions may be safely applied to the practical case of an extended and submerged cable; for it is impossible to suppose that the dry and coiled state of the cable, not contemplated in the theory, should nevertheless exactly compensate its errors, or that results due only to an accidental arrangement of the cable should by chance coincide with deductions from a defective hypothesis.

When, on the other hand, the results obtained differ from those given by theory, or even when the theory affords no confirmation of the experimental conclusions, we must forbear to extend these conclusions to the practical case of a straight cable.

The arrival-curve obtained by experiment is similar in general appearance to that given by Professor Thomson in "The Theory of the Electric Telegraph*." The identity of the curve obtained from the increase with that obtained from the fall of the received current, follows from equation (3.) in the same paper. The described effects of using alternate currents follow from the principle of superposition, by which also the effects of the increased speed might be shown in diminishing the received signals.

* *Vide* Proceedings of the Royal Society, May 1855, and Philosophical Magazine, S. 4. vol. xi. p. 146.

An example of the confusion arising from interference between successive signals has been given by Professor THOMSON in his evidence before the Committee appointed by the Board of Trade to inquire into the construction of submarine telegraph cables. Professor THOMSON has also informed the author that the compensation derived from experiment, as explained above, is such as theory would demand, but that he has not yet verified the exact proportion required between the first and second contacts*.

Thus every conclusion hitherto stated is in accordance with the mathematical theory, and may therefore without hesitation be applied to submerged and extended cables.

The arrival-curves (fig. 7, Plate L.) do not, however, accurately correspond with that given by Professor THOMSON. The dotted line shows the calculated curve, drawn so as nearly to agree with the experimental curve from 2192 knots, at its origin; the difference between the two curves towards the end is very great. The experimental curve approaches its limiting height much too slowly after the first few seconds ; one part of the curve from 1006 knots is shown on the same figure, and by theory the abscissæ of the two curves corresponding to equal ordinates should be directly as the squares of the lengths. At the origin of the curves this is approximately the case, making a small allowance for the constant resistance of batteries and instruments; but towards the end of the curves this is far from being the case. Some of the causes of the discrepancy may disappear in straight cables, but meanwhile the constants required in the mathematical theory cannot be with confidence derived from these curves or Tables.

It is generally believed that coiling increases the retardation, and the curves obtained might be pointed to as confirming this opinion. It is certain that a mutual electromagnetic induction of considerable importance does occur between the different parts of the coils†, and probably some part of the discrepancy between the observed and calculated curves is due to this cause. But the varying resistance of gutta percha, unknown when the theory was framed, also accounts for a considerable difference between the results of observation and calculation. The allowance to be made for a constant uniform leakage such as would occur if the resistance of the gutta percha were uniform, is described by Professor W. THOMSON in the "Theory of the Electric Telegraph;" but the author of the present paper discovered that the resistance of gutta percha, such as was used for the Red Sea cable, increased more than 60 per cent.‡ during positive or

* Professor THOMSON has also stated that he has long been acquainted with some other modes of producing the required regularity, and one of his methods is alluded to in the evidence before the Board of Trade Committee. *Vide* also Proceedings of the Royal Society, Dec. 1856, and Philosophical Magazine, 1857, where the mathematical principle of the compensation is fully stated.

† *Vide* paper read by Professor THOMSON at the British Association, Aberdeen, 1859, and letter by Professor W. THOMSON and the author, published in the 'Philosophical Magazine,' 1861; also a letter from Mr. F. C. WEBB in 'The Engineer,' August 1859.

‡ These numbers are calculated from data in the paper by the author read before the Royal Society in 1860, and published in abstract in the 'Proceedings' of last year, and in the 'Philosophical Magazine' for 1861; also in full in the Appendix to the Report of the Committee of the Board of Trade on the Construction of Submarine Cables, 1861.

negative electrification, and that a great part of the observed change was completed before the end of the first minute after the cable was connected with the battery. This gradual improvement of insulation would gradually increase the received current long after all inductive phenomena had ceased. For instance, the resistance of the total gutta-percha sheath of 2192 knots at 60°, after negative electrification for about 15″, would be 104×10^{10} absolute British units; after one minute, this resistance would increase to 132×10^{10}. The resistance of the conductor was about 55×10^{10}.

If the insulation had remained constant at the first-named figure, the final maximum arriving current would have been only 78·4 per cent.* of the entering current; and if the insulation-resistance had remained constant at the second figure, the final arriving current would have been 82·4 per cent. of the entering current. It is not therefore surprising that the observed curve, subject to the influence of imperfect and varying insulation, should not more perfectly coincide with the theoretical curve, in which perfect and constant insulation is assumed. When allowance is made for the change in the entering current due to the change in the total resistance of the circuit caused by the change in the insulation-resistance from 104×10^{10} to 132×10^{10}, the final arriving current with the lower insulation would by calculation be about 97 per cent. of the arriving current with the higher insulation, and this proportion very exactly corresponds with the slow increase observed during the last forty seconds of the minute. This increase has therefore no connexion whatever with the retardation properly so called.

The identity of the curve of increase with the curve of decrease seems to show that the apparent increase of the resistance of the gutta percha is rather due to an absorption of electricity which is again given out, than to a real change in the conductivity of the material †.

The effect of varying insulation would be much less felt during the actual transmission of signals, for then the greater part of the cable is constantly electrified in one manner, and the resistance of the gutta percha under such circumstances remains sensibly constant; we might therefore here expect a better agreement between theory and observation.

In order to examine the results of the experiments on repeated signals, the number of dots sent per minute, and the corresponding amplitude of oscillation observed in the received current, might be used respectively as abscissæ and ordinates, to give a curve expressing the rate at which, for each length of cable, the effect of the signals diminished as their speed increased; but, by the mathematical theory, the time required for any electrical operation varies as the square of the length of the cable. The product of the square of the length into the number of dots producing a given amplitude of variation should therefore be constant for all lengths of the same cable; and by using this product as an abscissa, instead of the simple number of dots, one curve should give the

* Appendix, Section I.

† The truth of this conclusion has been established by the results of some experiments on the Malta-Alexandria cable, made by Dr. Esselbach, and received by the author since writing the above.

amplitudes for all speeds through all lengths of cable; and conversely, the observations made on various lengths should, when thus geometrically represented, agree in defining one curve. The agreement between theory and observation may be very readily tested by comparing the observations through various lengths in this manner. But Professor THOMSON has also stated *, as a development of the theory, that if the resistance of the battery and receiving instrument bear but a small proportion to the total resistance of the cable, their effect in retarding and weakening the signals will be sensibly the same as that of adding an equal length of actual cable with its usual electrostatic capacity. (Evidence before Board of Trade Committee.)

It will thus be necessary, in comparing the observations, to add in each case 160 knots, equivalent to the resistance of the battery and galvanometer, to the length of the cable. Table XV. and fig. 11, Plate LI. show the results of the comparison. The first and second columns of the Table give the number of beats and corresponding amplitudes, extracted from Tables IV., VI., and XIII. The third column contains the product of the number of beats into the square of the length of the cable. The fourth column gives the similar product when 160 knots has been added to the length of each cable.

Fig. 11 gives the geometrical representation of the observations made by using the entries in the second and fourth columns of the Table as ordinates and abscissæ respectively.

The star, cross, and circle respectively denote observations with 1500, 1802, and 2192 knots in circuit. All these marks fall sensibly on one curve, affording *a perfect experimental proof that the rate of transmission does vary inversely as the square of the length, whether by rate of transmission be meant that speed at which the repeated signals fail to produce any sensible effect, or the rate producing so great an amplitude that common hand signals can be received without confusion.*

Moreover, it will be found that the curve is more accurately defined by taking the abscissæ from the fourth than from the third column; verifying Professor THOMSON'S conclusion as to the effect of the resistance of the battery and receiving instrument. These points have been much debated, but no doubt should now be felt of the soundness of the theoretical conclusions.

The above is neither the only nor the most remarkable confirmation of the mathematical theory. Professor THOMSON has been so kind as to give the author a Table (XVI.†) of calculated ordinates for the curve in question‡. The full black line (fig. 11) was constructed from this Table, and coincides with the recorded observations in the most striking manner; no more perfect verification of complicated mathematical calculations was probably ever obtained by experiment.

The curve shows at once the relative number of signals per minute which will pro-

* *Vide* Evidence before the Committee of the Board of Trade on the Construction of Submarine Cables, A.D. 1861, p. 125.

† Appendix, Section II.

‡ Proceedings of the Royal Society, 1855 and 1856, and Philosophical Magazine, 1856 and 1857.

duce the various amplitudes in any one length of cable; thus we see that if an amplitude or variation in the received current of 1 per cent. will suffice for distinct signals, twice as many signals can be sent through any given cable as if an amplitude of 7 per cent. is required, or four times as many as if an amplitude of 25 per cent. is required. The latter amplitude is probably necessary for hand signalling, but our experiments have shown that less than 1 per cent. is sufficient when a proper compensation is made. The coincidence between theory and observation places it beyond doubt that the curve truly expresses the relation between the speeds and amplitudes for straight as well as for coiled cables; and if the amplitude at any one speed through any one straight cable were known, the amplitude at any other speed through any other cable of the same materials might be calculated from the curve with certainty; but unfortunately this fact is wanting. There is no proof that the absolute amplitude observed through the coiled cable would remain unaltered if the cable were extended; on the contrary, it is very generally believed that it is easier to signal through a straight than a coiled cable; and if this be so, the amplitude would increase as the cable was laid. Although, therefore, the constants for the mathematical theory might easily be calculated from the values of the coordinates of the curve given by the observations, these constants would probably be inapplicable to straight cables.

Assuming, however, for a moment the identity of a coiled and extended cable, it may be interesting to calculate the amplitudes which would correspond to the rates of signalling recorded for various cables.

For the Red Sea cable the amplitude is found by taking the ordinate corresponding to the abscissa given by the product of the square of the length into twice the number of dots per minute. The speed giving the same amplitude through any other cable of different dimensions, but of equal length, is obtained by a simple proportion.

The author has been informed that ten words per minute have been sent through 640 knots of the Red Sea cable, but that seven words was the more usual speed. The former would correspond to an amplitude of 20 per cent. for the dots*, the latter to about 35 per cent. 1·1 word per minute was sent through the Atlantic cable and received by a relay; this speed would correspond to an amplitude of about 8 per cent.; 2·4 words per minute (the ordinary rate of signalling from Newfoundland having been forty-one dots per minute) were received through the same cable by Professor THOMSON's galvanometer†, corresponding to an amplitude of little more than 1 per cent.

Ninety dots per minute, the speed of the message sent by the perforated paper, would,

* Seventeen dots per word.

† An instrument similar to that used in this research: the observer could therefore follow every change in the received current, and disentangle the meaning of signals which would have produced only hopeless confusion on a relay, or other instrument with a fixed zero.

for 1802 knots, give by the curve an amplitude of 0·3 per cent. only, and there is no reason to doubt this estimate.

In conclusion, the experiments, so far as they went, were successful. They have shown the relative effects of signals transmitted at various speeds through various lengths; they have shown how little the results are affected by changing the power or arrangement of the batteries; they have shown the nature of the ultimate limit set to the rate of signalling by the gradual diminution and disappearance of the signals, preceded by their mutual interference.

The coincidence between theory and observation on these points gives good proof of the soundness of the theory, and permits the extension of the conclusions to the case of a submerged and extended cable. The experiments have also given well-defined curves fully expressing the retardation experienced through the cable as it lay in coils; but owing to this arrangement, the observations cannot be said to fix either the retardation or the absolute effect of signals through a straight cable. A few observations made in the same manner on a sound cable in actual use would be sufficient for this purpose.

Finally, the research has proved that the rate of signalling through a given cable can be very materially increased by removing the confusion or interference of successive signals, and has led to the discovery of one method of effecting this object.

In the present paper, the phenomena depending on the length of the cable, together with the rate and manner of signalling, have alone been considered. The absolute measurement of the effects depending on the materials and dimensions of the insulated conductor will probably form the subject of another research, completing the practical examination of the mathematical theory.

TABLE I.—Arrival-curve for 2168 knots, in 10 coils, with 72 p.p. July 26, 1859.

Maximum deflection caused by permanent current from 72 p.p. . . . 130^d.

Seconds after making contact with battery	4	5	5	6	6	7	8	11	15	21	51
Division of scale passed by spot as the current rises at far end of line	50	60	70	80	80	90	100	110	120	125	130
Reduced distance traversed by spot after contact has been made with battery for each number of seconds	38·5	46·2	53·9	61·6	61·6	69·3	77·0	84·7	92·4	96·2	100

TABLE II.—Arrival-curve for 2168 knots, in 10 coils, with 36 p.p. July 26, 1859.

Maximum deflection caused by permanent current from 36 p.p. . . . $63\frac{1}{2}^d$.

Seconds after making contact with battery	$7\frac{3}{4}$	8	$10\frac{1}{2}$	$16\frac{1}{2}$	18	19
Division of scale passed by the spot as the current rises at far end of line	50	50	55	60	60	60
Reduced distance traversed by spot after contact has been made with battery for each number of seconds	78·5	78·5	86·4	94·2	94·2	94·2

TABLE III.—Arrival-curve for 1500 knots, in 8 coils. July 27, 1859.

Maximum deflection caused by permanent current from 72 p.p. ... 200^d.

Seconds after making contact with battery	6½	6¾	8½	14	33
Division of scale passed by the spot as current rises at far end of line	170	170	180	190	200
Reduced distance traversed by spot after contact has been made with battery	85	85	90	95	100

TABLE IV.—Signals through 1500 knots, in 8 coils. July 27, 1859.

Maximum deflection caused by permanent current from 72 p.p. ... 200^d.

1. Beats of metronome per minute.	2. Signals sent.	3. Source of electricity in contact with line at near end.	4. Duration of contact at near end in seconds.	5. Limit of deflection at far end. First observation.	6. Second observation.	7. Mean limit of deflection caused by contact.	8. Reduced mean limit of deflection caused by contact.	9. Reduced mean amplitude of oscillation caused by two contacts.	Diagrams showing the changes of current caused at the end of the line by the signals. Vertical scale $\frac{1}{100}$th of an inch =1 division (strength of current). Horizontal scale $\frac{1}{10}$th of an inch =1 second (time).
130	Dots.	72 p.p. E.	″0·462 0·462	85 80	— —	85 80	42·5 40	2·5	
100	Dots and dashes.	72 p.p. E. 72 p.p. E.	0·6 0·6 1·2 0·6	112 100 122 110	111 95 125 110	111½ 97½ 123½ 110	55·2 48·4 61·7 55	Reduced amplitude of corresponding dots 4^d.	
92	Dots.	72 p.p. E.	0·652 0·652	85 75	— —	85 75	42·5 37·5	5·0	
	Dots and dashes.	72 p.p. E. 72 p.p. E.	0·652 0·652 1·3 0·652	110 95 122 105	112 97 125 108	111 96 123½ 106½	55·5 48 61·7 53·2		
72	Dots.	72 p.p. E.	0·833 0·833	95 75	— —	95 75	47·5 37·5	10·0	
	Dots and dashes.	72 p.p. E. 72 p.p. E.	0·833 0·833 1·666 0·833	115 90 130 100	112 92 135 105	113½ 91 132½ 102½	56·7 45·5 66·2 51·2		
60	Dots.	72 p.p. E.	1 1	100 75	— —	100 75	50 37·5	12·5	
	Dots and dashes.	72 p.p. E. 72 p.p. E.	1 1 2 1	116 85 140 100	121 90 140 100	118½ 87½ 140 100	59·2 43·7 70 50		

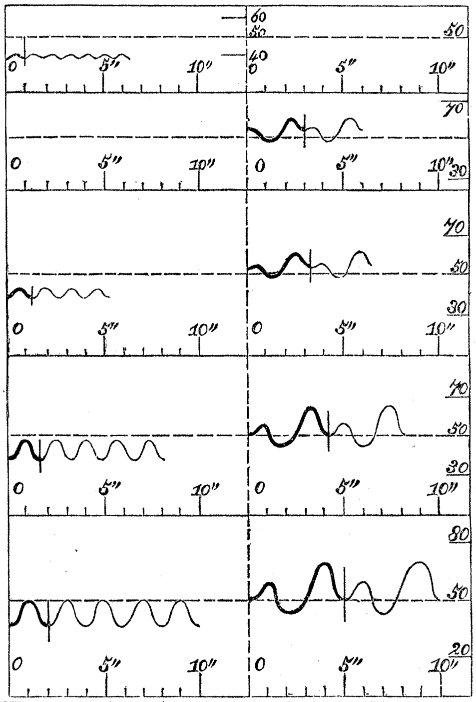


TABLE V.—Arrival-curve for 1802 knots, in 9 coils. July 28, 1859.

Maximum deflection caused by permanent current from 72 p.p. ... 168^d.

Seconds after making contact with battery or with earth	5¾	6¼	7	8	9½	11½	15
Division of scale passed by the spot as the current rises at far end of line	130	135	140	145	150	155	158
Reduced distance traversed by spot after contact has been made with battery	77·3	80·3	83·3	86·3	89·2	92·2	94

TABLE VI.—Signals through 1802 knots, in 9 coils. July 28, 1859.
Maximum deflection with 72 p.p. . . . 168[d].

Beats of metronome per minute.	Signals sent.	Source of electricity in contact with line at near end.	Duration of contact at near end.	Limit of deflection at far end. First observation.	Second observation.	Mean limit of deflection caused by contact.	Reduced mean limit of deflection caused by contact.	Reduced mean amplitude of oscillation caused by two contacts.
132	Dots.	72 p.p.	0·455″	70	—	70	41·6	0 { less than 1[d].
		E.	0·455	70	—	70	41·6	
112	Dots.	72 p.p.	0·536	76	—	76	45·2	1·2
		E.	0·536	74	—	74	44	
100	Dots.	72 p.p.	0 6	73½	—	73½	43·4	1·8
		E.	0·6	70	—	70	41·6	
92	Dots.	72 p.p.	0·652	74½	—	74½	44·3	2·7
		E.	0·652	70	—	70	41·6	
	Dots and dashes.	72 p.p.	0·652	90	85	87½	52	
		E.	0·652	85	80	82½	49	
		72 p.p.	1·3	85	90	92½	55	
		E.	0·652	90	85	87½	52	
84	Dots.	72 p.p.	0·714	75	80	77½	46·1	3·0
		E.	0·714	70	75	72½	43·1	
	Dashes.	72 p.p.	1·427	100	—	100	59·5	6·0
		E.	0·714	90	—	90	53·5	
	Dots and dashes.	72 p.p.	0·714	95	95	95	56·5	
		E.	0·714	85	86	85½	50·9	
		72 p.p.	1·427	100	100	100	59·5	
		E.	0·714	93	94	93½	55·6	
72	Dots.	72 p.p.	0·833	76½	81	79	47	3·9
		E.	0·833	70	75	72½	43·1	
	Dashes.	72 p.p.	1·666	112	—	112	66·6	7·1
		E.	0·833	100	—	100	59·5	
	Dots and dashes.	72 p.p.	0·833	97	—	97	57·7	
		E.	0·833	85	—	85	50·6	
		72 p.p.	1·666	105	—	105	62·5	
		E.	0·833	95	—	95	56·5	
60	Dots.	72 p.p.	1	80	85	82½	49	5·9
		E.	1	70	75	72½	43·1	
	Dashes.	72 p.p.	2	120	—	120	71·4	11·9
		E.	1	100	—	100	59·5	
	Dots and dashes.	72 p.p.	1	99	95	97	57·7	
		E.	1	85	80	82½	49	
		72 p.p.	2	110	112	111	66	
		E.	1	95	90	92½	55	
50	Dots.	72 p.p.	1·2	83	80	81½	48·5	9·2
		E.	1·2	67	65	66	39·3	
	Dashes.	72 p.p.	2·4	120	125	122½	72·9	17·9
		E.	1·2	90	95	92½	55	
	Dots and dasnes.	72 p.p.	1·2	95	100	97½	58	
		E.	1·2	80	85	82½	49	
		72 p.p.	2·4	115	120	117½	69·9	
		E.	1·2	85	90	87½	52	
40	Dots.	72 p.p.	1·5	90	95	92½	55	14·8
		E.	1·5	65	70	67½	40·2	
	Dashes.	72 p.p.	3·0	125	130	127½	75·9	23·9
		E.	1·5	85	90	87½	52	
	Dots and dashes.	72 p.p.	1·5	100	102	101	60·1	
		E.	1·5	72	80	76	45·2	
		72 p.p.	3·0	120	125	122½	72·9	
		E.	1·5	82	85	83½	49·7	

Diagrams showing changes of current at far end of line caused by the signals.

Vertical scale $\frac{1}{100}$th of an inch = 1 division (strength of current).

Horizontal scale $\frac{1}{10}$th of an inch = 1 second (time).

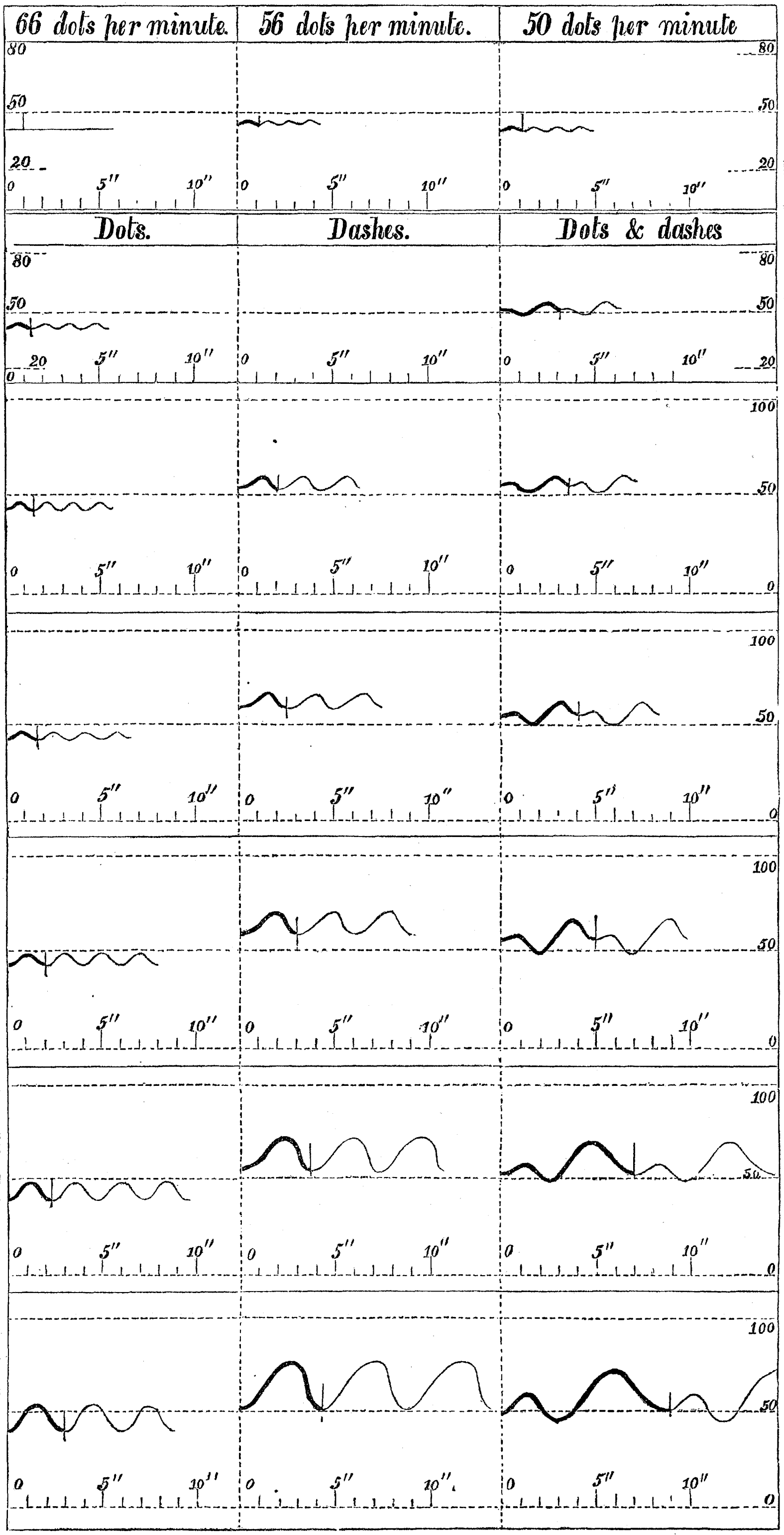


TABLE VII.—Arrival-curve for 1006 knots, in 4 coils. July 29, 1859.

Maximum deflection caused by permanent current from 72 p.p. . . . 277ᵈ.

Seconds after making contact with battery or with earth	1½	1½	2	2½	3	3½	4½	4½	4¾	6	7	9½	14½	19½
Division of scale passed by spot as current rises at far end of line	—	—	—	200	—	210	220	—	230	—	240	250	—	270
Division of scale passed by spot as current falls at far end of line	120	110	100	—	60	—	—	50	—	40	—	—	15	—
Distance on scale traversed by spot after contact has been made with battery or with earth	157	167	177	200	217	210	220	227	230	237	240	250	262	270
Reduced distance traversed by spot after contact has been made with battery or with earth	56·7	60·3	63·9	72·2	78·3	75·8	79·4	81·9	83	85·6	86·6	90·2	94·6	97·5

TABLE VIII.—Arrival-curve for 1165 knots, in 6 coils. July 29, 1859.

Maximum deflection caused by permanent current from 72 p.p. . . . 264ᵈ.

Seconds after making contact with battery or with earth	2¾	3¾	3¾	4¼	7	9	10	17	23
Division of scale passed by spot as the current rises at far end of line	—	200	—	220	—	240	—	—	260
Division of scale passed by spot as the current falls at far end of line	70	—	60	—	30	—	20	10	—
Distance on scale traversed by spot after contact has been made with battery or with earth	194	200	204	220	234	240	244	254	260
Reduced distance traversed by spot after contact has been made with battery or with earth	73·5	75·8	77·3	83·4	88·7	91	92·5	96·3	98·5

TABLE IX.—Signals through 1165 knots, in 6 coils. July 29, 1859.

Maximum deflection caused by permanent current from 72 p.p. . . . 264ᵈ.

Beats of metronome per minute.	Signals sent.	Source of electricity in contact with line at near end.	Duration of contact at near end.	Limit of deflection at far end. First observation.	Second observation.	Mean limit of deflection caused by contact.	Reduced mean limit of deflection caused by contact.	Reduced mean amplitude of oscillation caused by two contacts.
100	Dots.	72 p.p. E.	″ 0·6 0·6	130 100	125 95	127½ 97½	48·3 36·9	11·4
	Dashes.	72 p.p. E.	1·2 0·6	190 130	— —	190 130	72 49·3	22·7
	Dots and dashes.	72 p.p. E. 72 p.p. E.	0·6 0·6 1·2 0·6	150 110 180 120	145 105 180 120	147½ 107½ 180 120	55·9 40·7 68·2 45·5	
	A.	72 p.p. E. 72 p.p. E.	0·6 0·6 1·2 1·2	115 70 170 90	— — — —	115 70 170 90	43·6 26·5 64·4 34·1	

Diagrams showing changes of current caused at far end of line by the signals.

Vertical scale $\frac{1}{100}$th of an inch = 1 division (strength of current).

Horizontal scale $\frac{1}{10}$th of an inch = 1 second (time).

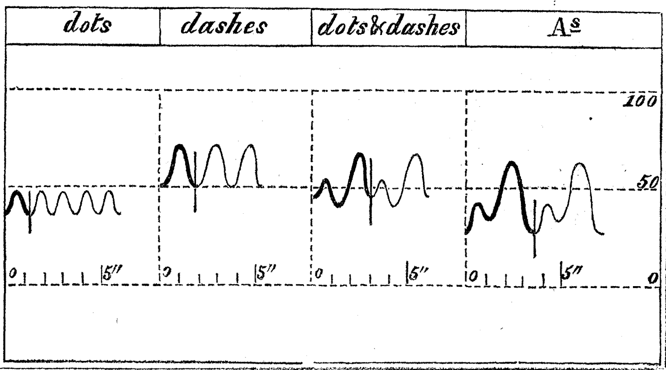


TABLE X.—Arrival-curve for 1165 knots, in 6 coils. July 29, 1859.

Maximum deflection caused by permanent current from +42 p.p. . . 157^{d}
" " " " " −30 p.p. . . 113^{d}
Sum of the two deflections . . . . 270^{d}

Seconds after making contact with positive battery or with negative battery	3	4	4	4½	4½	7	9	9¾	13	14	17	18	25
Division of scale passed by spot as the current arises at far end of line, after contact has been made with positive battery	+90	—	+100	+110	—	—	+130	—	—	+145	—	+150	+155
Division of scale passed by spot as the current falls at far end of line, after contact has been made with negative battery	—	−60	—	—	−70	−80	—	−90	−100	—	−105	—	—
Distance on scale traversed by spot after contact with either battery	203	217	213	223	227	237	243	247	257	258	262	263	268
Reduced distance traversed by spot after contact has been made with either battery	75·1	80·3	78·8	82·5	84	87·7	89·9	91·4	95·1	95·5	96·9	97·3	99·2

TABLE XI.—Signals through 1165 knots, in 6 coils, with alternate positive and negative currents. July 29, 1859.

Maximum deflection caused by permanent current from +42 p.p. . . . 157^{d}
" " " " " " " −30 p.p. . . . 113^{d}
Sum of two deflections . . . . 270^{d}

Beats of metronome per minute.	Signals sent.	Source of electricity in contact with line at near end.	Duration of contact at near end.	Limit of deflection at far end. First observation.	Second observation.	Mean limit of deflection caused by contact.	Reduced mean limit of deflection caused by contact.	Reduced mean amplitude of oscillation caused by two contacts.
100	Dots.	+42	0·6″	+35	+32	+33½	+12·4	13
		−30	0·6	0	− 3	− 1½	− 0·6	
	Dashes.	+42	1·2	+95	+95	+95	+35·1	21·2
		−30	0·6	+40	+35	+37½	+13·9	
	Dots and dashes.	+42	0·6	+40	+55	+47½	+17·6	
		−30	0·6	+10	+20	+15	+ 5·6	
		+42	1·2	+80	+85	+82½	+30·5	
		−30	0·6	+20	+25	+22½	+ 8·3	
	A.	+42	0·6	+10	—	+10	+ 3·7	
		−30	0·6	−20	—	−20	− 7·4	
		+42	1·2	+65	—	+65	+24	
		−30	1·2	−20	—	−20	− 7·4	

Diagrams showing changes of current caused at far end of line by the signals.
Vertical scale $\frac{1}{100}$th of an inch = 1 division (strength of current).
Horizontal scale $\frac{1}{10}$th of an inch = 1 second (time).

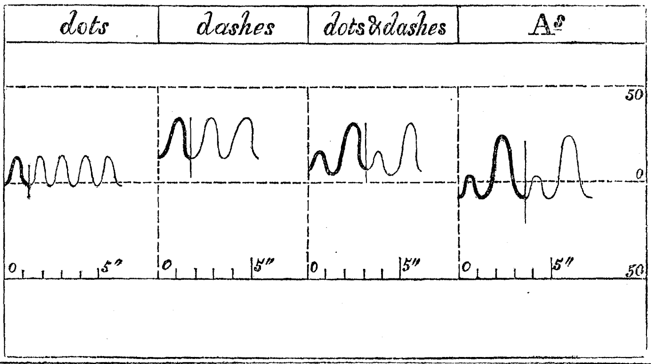


TABLE XII.—Arrival-curve for 2192 knots, in 10 coils. July 30, 1859.
Maximum deflection caused by permanent current from 72 p.p. ... 133[d].

Seconds after making contact with battery or with earth...	2½″	3″	3½″	4″	4½″	5″	5¾″	6″	6½″	7″	7¾″	8½″	8½″	9″	9¼″	10½″	11″	13¼″	16¾″	17″	30″	50″
Division of scale passed by spot as the current rises at far end of line	30	40	50	60	—	—	80	—	90	95	100	105	—	110	110	115	—	120	125	125	130	131
Division of scale passed by spot as the current falls at far end of line	—	—	—	—	70	60	—	50	—	—	—	—	30	—	—	—	20	—	—	—	—	—
Distance on scale traversed by spot after contact has been made with battery or earth..	30	40	50	60	63	73	80	83	90	95	100	105	103	110	110	115	113	120	125	125	130	131
Reduced distance traversed by spot after contact has been made with battery or earth..	22·6	30·1	37·6	45·1	47·4	54·9	60·2	62·4	67·7	71·4	75·2	79	77·5	82·7	82·7	86·5	85	90·2	94	94	97·8	98·5

TABLE XIII.—Signals through 2192 knots, in 10 coils. July 30, 1859.
Maximum deflection caused by permanent current from 72 p.p. ... 133[d].

Beats of metronome per minute.	Signals sent.	Source of electricity in contact with line at near end.	Duration of contact at near end.	Limit of deflection at far end. First observation.	Second observation.	Third observation.	Fourth observation.	Mean limit of deflection caused by contact.	Reduced mean limit of deflection caused by contact.	Reduced mean amplitude of oscillation caused by two contacts.
100	Dots.	72 p.p. E.	0·6″ 0·6	57 57	— —	— —	— —	57 57	42·9 42·9	0
80	Dots.	72 p.p. E.	0·75 0·75	61 59	— —	— —	— —	61 59	45·9 44·4	1·5
60	Dots.	72 p p. E.	1 1	64 60	— —	— —	— —	64 60	48·1 45·1	3
40	Dots.	72 p.p. E.	1·5 1·5	68 58	— —	— —	— —	68 58	51·1 43·6	7·5
36	Dots.	72 p.p. E.	1·666 1·666	68 55	70 58	— —	— —	69 56½	51·9 42·5	9·4
	Dashes.	72 p.p. E.	2·333 1·666	95 74	96 75	— —	— —	95½ 74½	71·8 56·0	15·8
	Dots and dashes.	72 p.p. E. 72 p.p. E.	1·666 1·666 3·333 1·666	76 65 90 70	80 65 90 70	75 60 89 69	80 65 92 71	77 64 90 70	57·9 48·1 67·6 52·6	
	A.s	72 p.p. E. 72 p.p. E.	1·666 1·666 3·333 3·333	60 50 85 45	63 53 85 47	60 51 84 45	60 51 85 46	61 51 85 46	45·9 38·4 63·9 34·6	
30	Dots.	72 p.p. E.	2 2	72 55	— —	— —	— —	72 55	54·1 41·4	12·7
	Dashes.	72 p.p. E.	4 2	100 70	— —	— —	— —	100 70	75·2 52·6	22·6
	Dots and dashes.	72 p.p. E. 72 p.p. E.	2 2 4 2	79 62 95 68	78 60 94 68	80 60 95 67	— — — —	79 61 95 68	59·2 45·9 71·4 51·1	
	A.	72 p.p. E. 72 p.p. E.	2 2 4 4	65 50 91 41	64 50 91 42	63 50 92 42	— — — —	64 50 91 42	48·1 37·6 68·4 31·6	
18	Dots.	72 p.p. E.	3·333 3·333	85 47	— —	— —	— —	85 47	63·9 35·3	28·6

Diagrams showing changes of current at far end of line caused by the signals.
Vertical scale $\frac{1}{100}$th of an inch = 1 division (strength of current).
Horizontal scale $\frac{1}{10}$th of an inch = 1 second (time).

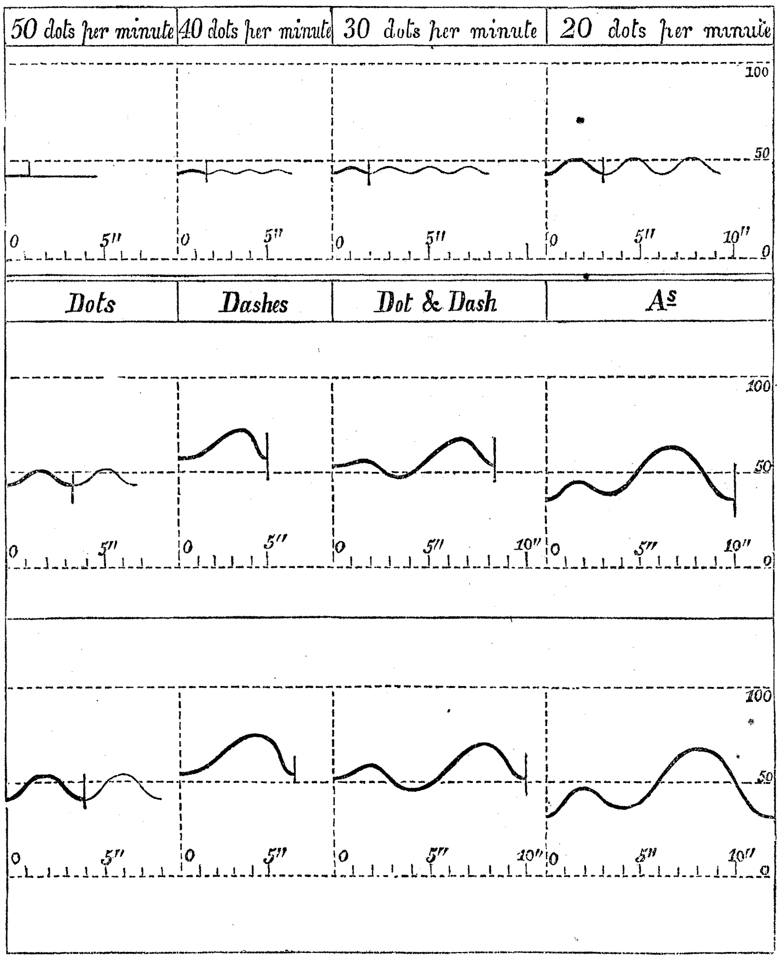


TABLE XIV.—Signals sent through 1812 knots, in 9 coils. July 30, 1859.

Maximum deflection caused by permanent current from 72 p.p. . . . 166[d].

Beats of metronome per minute.	Signals sent.	Source of electricity in contact with line at near end.	Duration of contact at near end.	Limit of deflection at far end. First observation.	Second observation.	Mean limit of deflection caused by contact.	Reduced mean limit of deflection caused by contact.
92	Dots and dashes.	72 p.p.	″0·652	88	90	89	53·6
		E.	0·652	83	83	83	50
		72 p.p.	1·304	95	95	95	57·2
		E.	0·652	88	90	89	53·6
	A.	72 p.p.	0·652	66	—	66	39·7
		E.	0·652	65	—	65	39·1
		72 p.p.	1·304	85	—	85	51·2
		E.	1·304	65	—	65	39·1
84	Dots and dashes.	72 p.p.	0·714	91	—	91	54·8
		E.	0·714	85	—	85	51·2
		72 p.p.	1·429	100	—	100	60·2
		E.	0·714	90	—	90	54·2
	A.	72 p.p.	0·714	72	—	72	43·3
		E.	0·714	70	—	70	42·1
		72 p.p.	1·429	90	—	90	54·2
		E.	1·429	70	—	70	42·1
72	Dots and dashes.	72 p.p.	0·833	92	—	92	55·4
		E.	0·833	80	—	80	48·2
		72 p.p.	1·666	100	—	100	60·2
		E.	0·833	90	—	90	54·2
	A.	72 p.p.	0·833	75	75	75	45·1
		E.	0·833	70	70	70	42·1
		72 p.p.	1·666	95	100	$97\frac{1}{4}$	58·7
		E.	1·666	70	68	69	41·5
60	Dots and dashes.	72 p.p.	1	95	93	94	56·6
		E.	1	80	78	79	47·6
		72 p.p.	2	105	105	105	63·2
		E.	1	90	90	90	54·2
	A.	72 p.p.	1	70	—	70	42·1
		E.	1	65	—	65	39·1
		72 p.p.	2	100	—	100	60·2
		E.	2	60	—	60	36·1
50	Dots and dashes.	72 p.p.	1·2	95	—	95	57·2
		E.	1·2	75	—	75	45·1
		72 p.p.	2·4	110	—	110	66·2
		E.	1·2	85	—	85	51·2
	A.	72 p.p.	1·2	80	72	76	45·8
		E.	1·2	68	60	64	38·6
		72 p.p.	2·4	115	110	$112\frac{1}{2}$	67·7
		E.	2·4	60	55	$57\frac{1}{2}$	34·6
40	Dots and dashes.	72 p.p.	1·5	100	110	105	63·2
		E.	1·5	75	80	$77\frac{1}{2}$	46·7
		72 p.p.	3	120	130	125	75·3
		E.	1·5	85	90	$87\frac{1}{2}$	52·7
	A.	72 p.p.	1·5	80	75	$77\frac{1}{2}$	46·7
		E.	1·5	65	60	$62\frac{1}{2}$	37·6
		72 p.p.	3	115	115	115	69·2
		E.	3	50	45	$47\frac{1}{2}$	28·6

Diagrams showing changes of current caused at far end of line by the signals.

Vertical scale $\frac{1}{100}$th of an inch = 1 division (strength of current).

Horizontal scale $\frac{1}{10}$th of an inch = 1 second (time).

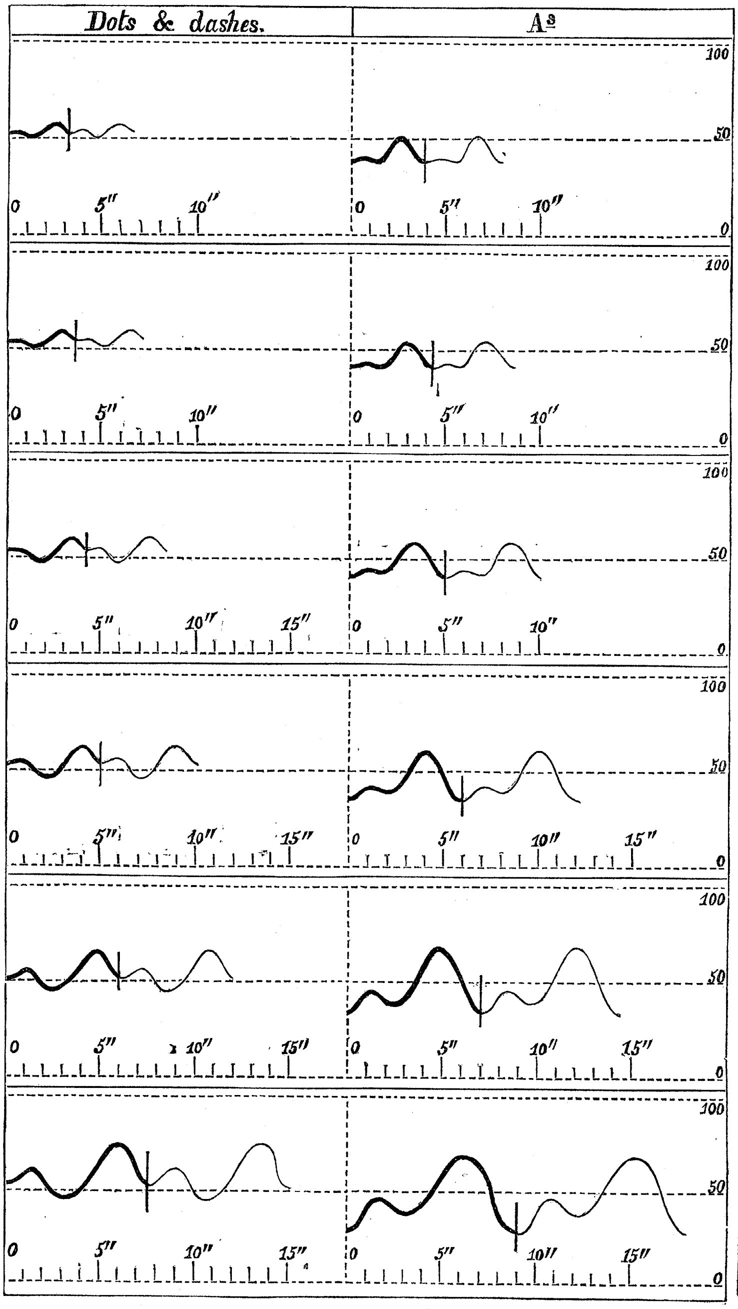


TABLE XV.—Speeds and Amplitudes for various lengths.

	1.	2.	3.	4.
	Number of beats per minute =N.	Observed amplitude reduced to percentage.	Product of number of beats into square of length $=N\times L^2$.	Product of number of beats into square of length corrected for battery and galvanometer $=N\times(L+160)^2$.
L=1500...	130	2·5	297×10^6	364×10^6
	92	5	207 „	254 „
	73	10	162 „	198 „
	60	12·5	135 „	165 „
L=1802...	132	0	429×10^6	508×10^6
	112	1·2	364 „	431 „
	100	1·8	325 „	385 „
	92	2·7	299 „	354 „
	84	3	273 „	323 „
	72	3·9	234 „	277 „
	60	5·9	195 „	231 „
	50	9·2	162 „	192 „
	40	14·8	130 „	154 „
L=2192...	100	0	480×10^6	553×10^6
	80	1·5	384 „	443 „
	60	3	288 „	332 „
	40	7·5	192 „	221 „
	36	9·4	173 „	199 „
	30	12·7	144 „	166 „
	18	28·6	86 „	100 „

APPENDIX.

Received January 14, 1863.

SECTION I.—*Effect of conduction across the sheath of an insulated wire, or of uniformly imperfect insulation on the permanent received current.*

The author is indebted to Professor W. THOMSON for the substance of the following theory.

Consider a cable extending infinitely in one direction from an origin O.

Let the distance of any point P from the origin be called x.

Let i denote the resistance of the unit length of the sheath to conduction across it, *i. e.* the measure of the insulation.

Let m denote the resistance of the unit length of the wire to conduction along it.

Let the potential at O be called V, and the potential at any point P be called V_x.

Let the strength of the current entering at O be called Q, and the strength of the current at P be called Q_x. Then it is not difficult to prove that

$$Q_x=Q\,\varepsilon^{-x\sqrt{\frac{m}{i}}}, \qquad (1.)$$

$$V_x=V\,\varepsilon^{-x\sqrt{\frac{m}{i}}}, \qquad (2.)$$

$$Q=\frac{V}{(im)^{\frac{1}{2}}}. \qquad (3.)$$

We can pass from this case to that of a finite cable of the length l with one end in connexion with the earth by the device of electrical images.

Superimpose two potential curves satisfying equation (2.) with equal but opposite potentials $+V$ and $-V$ at their origins O and O_1. Let these points be situated at a distance $2l$ apart, and let the curves extend from their origin to meet and cross one another. The resultant potential will necessarily be zero halfway between O and O_1, and the resultant curve between this point and each origin will represent the variation of potentials in a cable of the length l with one end in connexion with the earth and the origin at a certain positive or negative potential.

By putting these results into a mathematical form, we obtain from equations (1.) and (2.),

$$V_x=V\left(\varepsilon^{-x\sqrt{\frac{m}{i}}}-\varepsilon^{-(2l-x)\sqrt{\frac{m}{i}}}\right) \quad \text{. . . . . (4.)}$$

$$Q_x=Q\left(\varepsilon^{-x\sqrt{\frac{m}{i}}}+\varepsilon^{-(2l-x)\sqrt{\frac{m}{i}}}\right) \quad \text{. . . . . (5.)}$$

But V and Q do not represent the potential and current at the origin of the finite cable, but the potential and current at the origin of the hypothetical infinite curves superimposed. In order to obtain V_x and Q_x in function of any given potential V_0 at the origin of the finite cable, we must obtain the value of V in function of V_0 by putting $x=0$ in equation (4.), and substitute the value of V in function of V_0 in the general equations (4.) and (5.).

Then we have

$$V_0=V\left(1-\varepsilon^{2l\sqrt{\frac{m}{i}}}\right),$$

and hence

$$V_x=V_0\,\frac{\varepsilon^{-x\sqrt{\frac{m}{i}}}-\varepsilon^{-(2l-x)\sqrt{\frac{m}{i}}}}{1-\varepsilon^{-2l\sqrt{\frac{m}{i}}}}. \quad \text{. . . . . (6.)}$$

and

$$Q_x=\frac{V_0}{(im)^{\frac{1}{2}}}\,\frac{\varepsilon^{-x\sqrt{\frac{m}{i}}}+\varepsilon^{-(2l-x)\sqrt{\frac{m}{i}}}}{1-\varepsilon^{-2l\sqrt{\frac{m}{i}}}}. \quad \text{. . . . . (7.)}$$

To obtain the current flowing into the cable at its origin, make $x=0$; then

$$Q_0=\frac{V_0}{(im)^{\frac{1}{2}}}\,\frac{1+\varepsilon^{-2l\sqrt{\frac{m}{i}}}}{1-\varepsilon^{-2l\sqrt{\frac{m}{i}}}}$$

and

$$Q_x=Q_0\,\frac{\varepsilon^{-x\sqrt{\frac{m}{i}}}-\varepsilon^{-(2l-x)\sqrt{\frac{m}{i}}}}{1+\varepsilon^{-2l\sqrt{\frac{m}{i}}}};$$

or, for brevity, writing $\theta=l\sqrt{\frac{m}{i}}$ and $\theta_{,}=(l-x)\sqrt{\frac{m}{i}}$,

$$Q_0=\frac{V_0}{lm}\,\frac{\theta(\varepsilon^{\theta}+\varepsilon^{-\theta})}{(\varepsilon^{\theta}-\varepsilon^{-\theta})}, \quad \text{. . . . . (8.)}$$

and

$$Q_x=Q_0\,\frac{\varepsilon^{\theta_{,}}+\varepsilon^{-\theta_{,}}}{\varepsilon^{\theta}+\varepsilon^{-\theta}}. \quad \text{. . . . . (9.)}$$

When $x=l$,

$$Q_l=Q_0\frac{2}{\varepsilon^{\theta}+\varepsilon^{-\theta}}. \qquad (10.)$$

The equations (8.) and (10.), applied to the case of the Red Sea cable, give the results in the text,

$$l=2192, \ldots m=250\times10^6 \ldots i=228\times10^{13},$$

$$\varepsilon^{\theta}=\varepsilon^{0\cdot7258}=2\cdot0664 \ldots \varepsilon^{-\theta}=0\cdot48394,$$

$$Q_0=1\cdot1694\frac{V_0}{lm}=\text{the entering current},$$

$$Q_l=0\cdot784Q_0=0\cdot9168\frac{V_0}{lm}.$$

Similarly, when $i=289\times10^{13}$,

$$Q_l=0\cdot824Q_0=0\cdot938\frac{V_0}{lm}.$$

If the cable were perfectly insulated, by OHM'S law,

$$Q_l=\frac{V_0}{lm}.$$

SECTION II.—TABLE XVI.

1.	2.	3.	4.	5.	6.
Period of dot in seconds in function of α.	Factor used in the formula given in the third column.	Reciprocal of amplitude of variation in the received current produced by harmonic variation of potential at the operating end.	Reciprocal of amplitude of variation in the received current produced by the dot signal.	Amplitude produced by dot signals.	Number of dots per minute.
Θ in function of α. $\alpha=\frac{ckl^2}{\pi^2}\times\log_\varepsilon\left(10^{\frac{1}{10}}\right)$.	$i=\sqrt{\frac{\Theta}{\alpha}}\times\sqrt{\frac{\pi^3}{\left(\log_\varepsilon\frac{1}{e}\right)^3}}$ $e=10^{\frac{1}{10}}$.	$\left\{2\sqrt{2}.i\log_\varepsilon\left(\frac{1}{e}\right)e^i\right\}^{-1}$.	Third column multiplied into $\frac{\pi}{4}$.	Reciprocal of fourth column multiplied by 100.	$\frac{60}{\Theta}$.
$0\cdot25\times\alpha$	100·7926	182,840,000	143,600,000	0·000,000,696	240 $\times\frac{1}{\alpha}$
0·5 „	71·2711	288,070	226,250	0·000,442	200 „
0·75 „	58·1926	17,402	13,668	0·007,315	80 „
1·0 „	50·3963	3,337·9	2,631·5	0·038,00	60 „
1·1 „	48·0510	2,040·0	1,602·2	0·062,42	54·5 „
1·2 „	46·0053	1,330·3	1,044·8	0·095,7	50·0 „
1·3 „	44·2005	913·82	717·71	0·139,3	46·2 „
1·4 „	42·5926	654·97	514·41	0·194,5	42·9 „
1·5 „	41·1496	486·24	381·89	0·261,8	40·0 „
1·6 „	39·8418	371·60	291·86	0·342,6	37·5 „
1·7 „	38·6522	291·26	228·76	0·437,1	35·3 „
1·8 „	37·5632	233·24	182·40	0·548,2	33·3 „
1·9 „	36·5617	190·28	149·44	0·669,3	31·6 „
2·0 „	35·6356	157·73	123·88	0·807,1	30·0 „
2·1 „	34·7777	132·65	104·17	0·959,7	28·6 „
2·2 „	33·9782	112·90	88·67	1·127,8	27·3 „
2·3 „	33·2299	97·21	76·35	1·309,8	26·1 „
2·4 „	32·5305	84·52	66·38	1·506,5	25·0 „
2·5 „	31·8742	74·17	58·25	1·716,7	24·0 „
2·6 „	31·2535	65·57	51·50	1·941,7	23·1 „
2·7 „	30·6696	58·41	45·88	2·179,6	22·2 „
2·8 „	30·1180	52·39	41·15	2·430,1	21·4 „

TABLE XVI. (continued).

1.	2.	3.	4.	5.	6.
Period of dot in seconds in function of α.	Factor used in the formula given in the third column.	Reciprocal of amplitude of variation in the received current produced by harmonic variation of potential at the operating end.	Reciprocal of amplitude of variation in the received current produced by the dot signal.	Amplitude produced by dot signals.	Number of dots per minute.
Θ in function of α. $\alpha=\frac{ckl^2}{\pi^2}\times\log_\varepsilon\left(10^{\frac{1}{10}}\right)$.	$i=\sqrt{\frac{\Theta}{\alpha}}\times\sqrt{\frac{\pi^3}{\left(\log_\varepsilon\frac{1}{e}\right)^3}}$ $e=10^{\frac{1}{10}}$.	$\left\{2\sqrt{2}.\,i\log_\varepsilon\left(\frac{1}{e}\right)e^i\right\}^{-1}$.	Third column multiplied into $\frac{\pi}{4}$.	Reciprocal of fourth column multiplied by 100.	$\frac{60}{\Theta}$.
2·9 × α	29·5944	47·26	37·12	2·694,0	20·7 × $\frac{1}{\alpha}$
3·0 „	29·0964	42·86	33·66	2·970,9	20·0 „
3·1 „	28·6232	39·07	30·69	3·195,9	19·4 „
3·2 „	28·1724	35·78	28·10	3·558,7	18·7 „
3·3 „	27·7422	32·91	25·85	3·868,5	18·2 „
3·4 „	27·3312	30·39	23·87	4·189,4	17·6 „
3·5 „	26·9380	28·16	22·12	4·520,8	17·1 „
3·6 „	26·5612	26·19	20·57	4·861,5	16·7 „
3·7 „	26·1998	24·43	19·19	5·211,0	16·2 „
3·8 „	25·8528	22·86	17·53	5·704	15·8 „
3·9 „	25·5192	21·44	16·84	5·938	15·4 „
4·0 „	25·1981	20·17	15·84	6·313	15·0 „
4·1 „	24·8900	19·02	14·94	6·693	14·6 „
4·2 „	24·5909	17·97	14·11	7·087	14·3 „
4·3 „	24·3033	17·02	13·37	7·479	14·0 „
4·4 „	24·0255	16·15	12·68	7·886	13·6 „
4·5 „	23·7570	15·35	12·06	8·292	13·3 „
4·6 „	23·4974	14·62	11·48	8·711	13·0 „
4·7 „	23·2461	13·95	10·96	9·124	12·8 „
4·8 „	23·0021	13·33	10·47	9·551	12·5 „
4·9 „	22·7667	12·75	10·01	9·990	12·2 „
5·0 „	22·5379	12·22	9·60	10·417	12·0 „
5·1 „	22·3158	11·73	9·21	10·858	11·8 „
5·2 „	22·1002	11·27	8·85	11·299	11·5 „
5·3 „	21·8907	10·84	8·51	11·751	11·3 „
5·4 „	21·6871	10·44	8·20	12·195	11·1 „
5·5 „	21·4890	10·07	7·91	12·642	10·9 „
5·6 „	21·2963	9·72	7·634	13·099	10·7 „
5·7 „	21·1087	9·39	7·375	13·559	10·5 „
5·8 „	20·9259	9·08	7·131	14·023	10·4 „
5·9 „	20·7478	8·79	6·904	14·484	10·2 „
6·0 „	20·5742	8·52	6·732	14·854	10·0 „
6·1 „	20·4049	8·260	6·487	15·415	9·8 „
6·2 „	20·2396	8·017	6·296	15·883	9·66 „
6·3 „	20·0784	7·786	6·115	16·353	9·52 „
6·4 „	19·9209	7·569	5·944	16·824	9·37 „
6·5 „	19·7670	7·362	5·782	17·295	9·23 „
6·6 „	19·6167	7·166	5·628	17·590	9·09 „
6·7 „	19·4698	6·980	5·482	18·241	8·96 „
6·8 „	19·3261	6·803	5·443	18·372	8·82 „
6·9 „	19·1855	6·635	5·211	19·190	8·69 „
7·0 „	19·0480	6·474	5·085	19·666	8·57 „
7·1 „	18·9136	6·322	4·965	20·141	8·45 „
7·2 „	18·7817	6·176	4·851	20·614	8·33 „
7·3 „	18·6525	6·036	4·701	21·272	8·22 „
7·4 „	18·5260	5·903	4·636	21·575	8·11 „
7·5 „	18·4021	5·775	4·536	22·046	8·00 „
7·6 „	18·2807	5·652	4·439	22·528	7·90 „
7·7 „	18·1616	5·537	4·349	22·994	7·80 „
7·8 „	18·0448	5·425	4·260	23·474	7·69 „
7·9 „	17·9302	5·317	4·176	23·946	7·60 „
8·0 „	17·8178	5·214	4·095	24·420	7·50 „
9·0 „	16·7988	4·374	3·435	29·112	6·67 „
10·0 „	15·9367	3·780	2·969	33·681	6·00 „

Explanation of TABLE XVI.

Table XVI., given to the author by Professor W. THOMSON, will now be shortly explained. The author will not enter into any detailed explanation of the theory by which the results contained in the Table were obtained, as these results are the direct mathematical consequences of the equations given in the papers already alluded to, and as Professor THOMSON will probably himself publish the full mathematical development of the theory.

The first column headed Θ contains a series of "times" occupied by the full periods of electric operations, each of which, when continually repeated, produces a succession of equal and similar rises and falls in the received current, or of "dots" as they have been hitherto called in this paper. The series begins with the shorter and ends with the longer times, or, in other words, begins with the more rapid and ends with the slower speeds. The numbers in the first column are numbers measuring the times of the periods in terms of a certain quantity α taken as unity. The actual time in seconds occupied by each period or cycle of electric operations corresponding to the series in the first column is equal to the numbers entered there multiplied into α. This quantity α is equal to $\frac{ckl^2}{\pi^2}\cdot\log_\epsilon\left(10^{\frac{1}{10}}\right)$, where

c = the electrostatical capacity of the insulated wire per unit of length in absolute electrostatic measure;

k = the resistance of the conductor per unit of length in absolute electrostatic measure;

l = the length of the conductor.

α varies therefore for every cable and for every length of the same cable. The meaning of this quantity will be best explained by the following extract from a letter of Professor THOMSON'S to the author:—

"α, in definite absolute measure, means the tenth part of the time in seconds in which a simple harmonic electrification established in the wire and left to itself (two ends to earth) would subside to $\frac{1}{10}$th of its amount. Thus in the time α, an harmonic electrification subsides to $\frac{1}{10^{\frac{1}{10}}}$ of its amount. The subsidence here spoken of is the gradual loss of charge by conduction out through the ends to earth."

Now let the electrical operation producing the dot be a simple harmonic variation of the potential at one end while the other is connected to earth $\left(i.\ e.\text{ let } V=A\sin\frac{2\pi t}{\Theta}\right.$, where V= the varying potential, A= a constant, and $\frac{t}{\Theta}$ = any function of the whole period$\left.\right)$. Then, measured as a fraction of the maximum current which would be received if the maximum potential A were constantly maintained at the sending end of the cable, the difference between the maximum and minimum received current will be the reciprocal of the number entered in the third column; or translating this into the language used in

the paper, the reciprocals of the numbers in the third column give the amplitude of the dot measured as a function of the maximum permanent current*. For instance, if each dot occupied a period α, the amplitude of variation in the received current would be $\frac{1}{3338}$th of the maximum permanent current, or would be 0·02956 per cent. of that current.

The fourth column is obtained by multiplying the numbers in the third column into a constant $\frac{\pi}{4}$. The numbers so obtained express the reciprocals of the amplitudes which would result if, instead of being subjected to the harmonic variation previously described, the end operated on had been maintained at the maximum potential for the first half of the periods Θ, and at the minimum during the second half. This was precisely the condition fulfilled when dots were sent in the experiments described. The potential of one pole of the battery was maintained at the sending end of the cable during one half of each dot, and the potential of the earth was maintained during the other half.

The fifth column contains the product of the reciprocals of the numbers in the fourth column multiplied into 100, and gives therefore the amplitudes produced by dots made as in the experiments occupying the various periods in the first column, and these amplitudes are moreover expressed in percentages of the maximum received current, as in the rest of the paper.

The product of the reciprocals of the times entered in the first column, multiplied into 60, will give a series of numbers corresponding to the number of dots per minute in terms of α. This series, expressing "speeds," is entered in the sixth column.

The numbers in the fifth and sixth columns used as coordinates give the curve, shown in fig. 11, Plate LI., corresponding most accurately with the observed speeds and amplitudes.

The scale of amplitudes, shown in full lines, corresponds to the numbers in the fifth-column, and the scale of times, shown by dotted lines, corresponds to the values of $\frac{60}{\Theta}$ when α is taken as unity.

When in any case the amplitude corresponding to a given number of dots is known, the actual value of α can at once be determined from this curve. Thus observation (Table IV.) showed that for a length of 1500 knots of cable +160 knots of resistance, with 92 beats or 46 dots per minute, the amplitude was 5 per cent., and by the curve we find that this amplitude corresponded to a speed of $16{\cdot}4\times\frac{1}{\alpha}$; hence $46=16{\cdot}4\times\frac{1}{\alpha}$, or $\alpha=0''{\cdot}3565$†. From this value the electrostatical capacity per unit of length, and the specific inductive capacity of the dielectric could be determined. These points will, however, be more fully treated of in the second part of this paper.

* The second column only contains the value of a certain quantity i used in the formula by which the third column is calculated.

† It should be observed that inasmuch as this observation does not exactly fall on the curve, so the value of α differs a little from that which would be calculated by the curve alone, as presently to be described.

Quite similarly, if α be known, the number of beats per minute corresponding to any amplitude could be determined; but, practically, α need not enter into the calculation when treating of any given cable. The speed, amplitude, and length are here the three elements of every problem, and when two of these are known the third can be determined; but here it may be observed, that as the speed, multiplied into α, is constant for each amplitude, so will the speed, multiplied into the square of the length, be constant for each amplitude, and the scale of abscissæ may be so chosen as for any one cable to give directly this product by simple inspection.

It is this scale for the Red Sea cable which is drawn at the foot of the curve, fig. 11, and which enables the number of dots corresponding to every amplitude to be ascertained directly, and it is by this scale that the dots, crosses, or circles from Table XV. are put on the figure.

When, as in the present paper, the speed is taken as twice the number of dots, and the unit length is one knot, the ratio of the two scales must clearly be such that if

d = the number of divisions in the upper scale,

D = the corresponding number on the lower scale,

L = the length in knots,

then

$$\alpha = \frac{2dL^2}{D}.$$

Thus, taking a length of 1000 knots and a speed of 100 dots per minute, $D = 2 \times 10^8$, $d = 12 \cdot 6$, and hence $\alpha = 0 \cdot 126$; and the same value would be obtained whatever number of dots had been chosen.

This may be looked on as the mean value of α determined from twenty observations, since this ratio of the scales brought all the various circles, crosses, and stars into the closest approximation with the curve. The values of α for any other length are inversely proportional to the square of the lengths.

The algebraic headings of the different columns will allow them to be still further extended by those who may require to use the Table, as they virtually contain the equation of the curve.

Fig. 1.

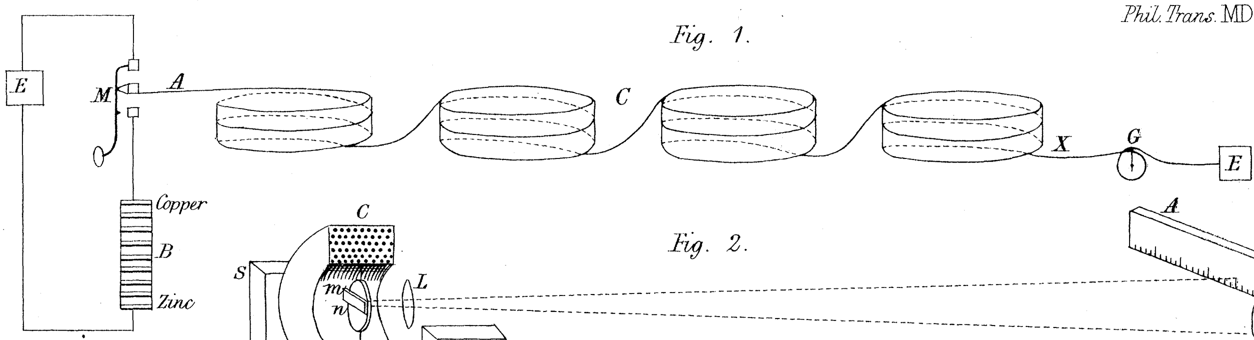
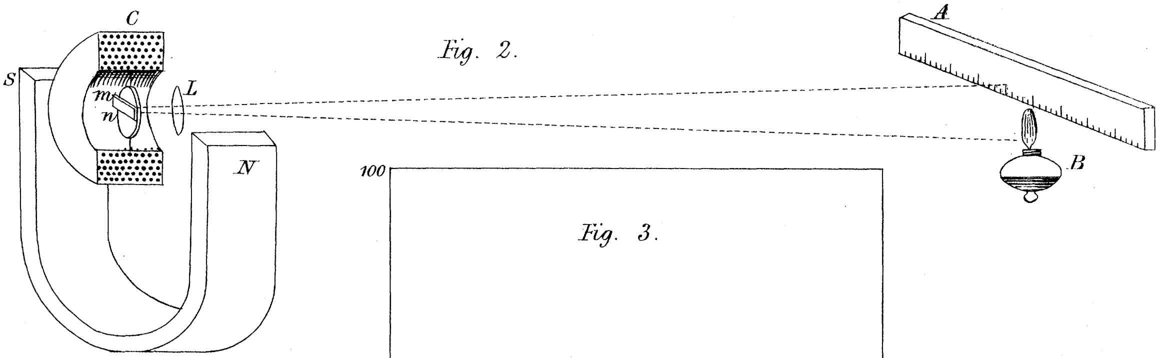


Fig. 2.



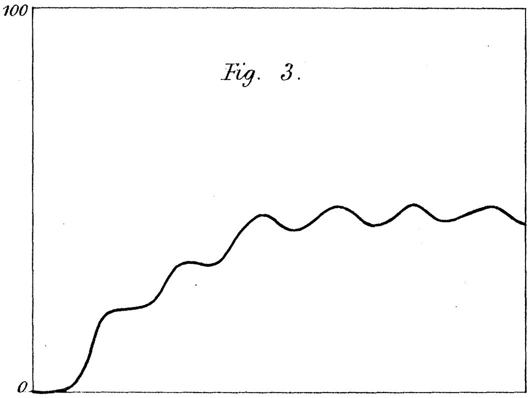


Fig. 4.

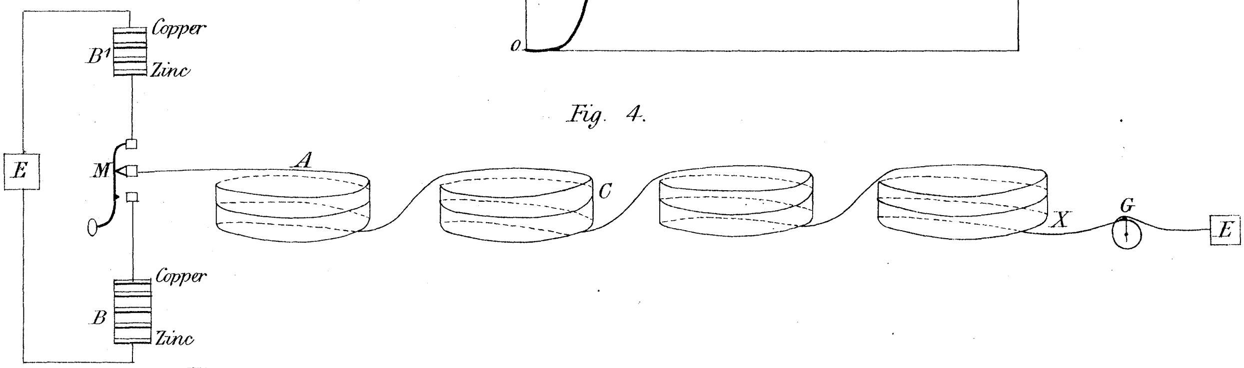


Fig. 5. Arrival-Curve for 1165 knots from Positive currents & Earth contacts.

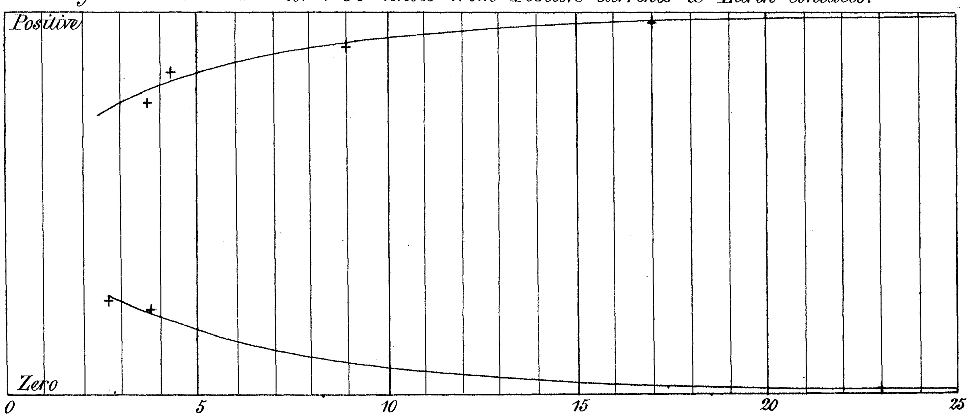


Fig. 6. Arrival Curve for 1165 knots from Positive and Negative Currents.

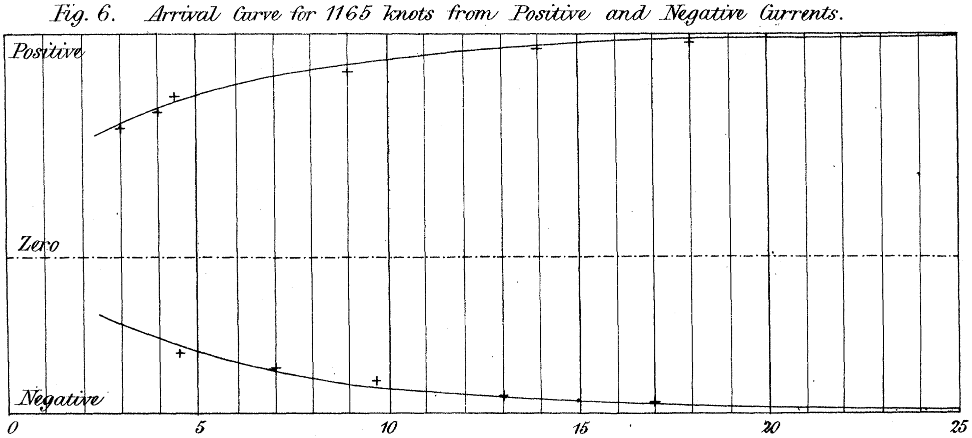


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Fig. 7. Arrival Curve for 1006 knots in 4 Coils and 2192 knots in 10 Coils.

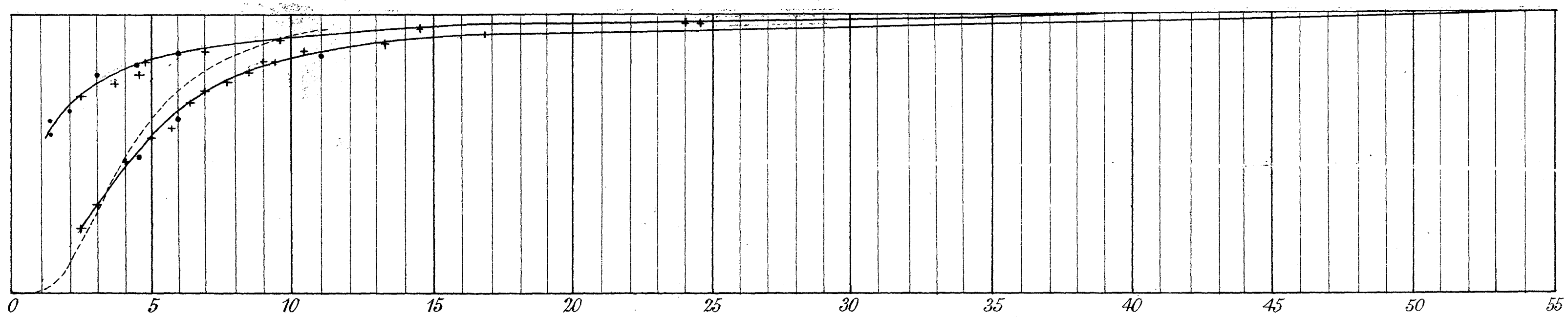

Fig. 8.

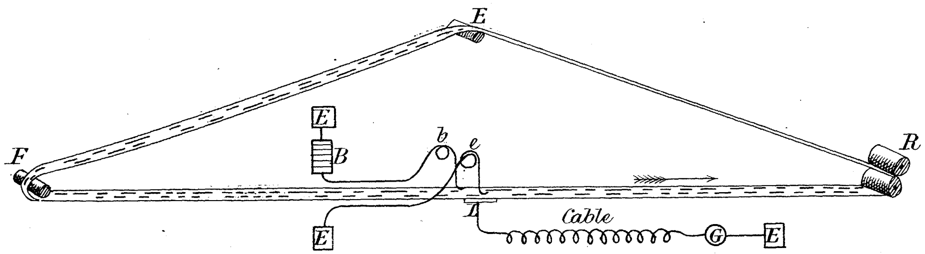

Fig. 9. Paper used to make contacts. ⅕ full size.

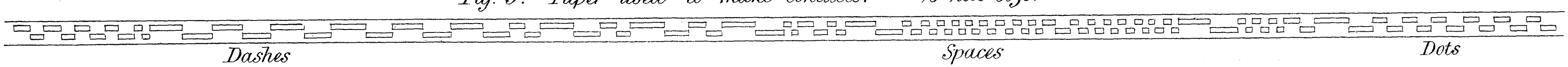

Fig. 10. Signals received from paper in Fig. 9.

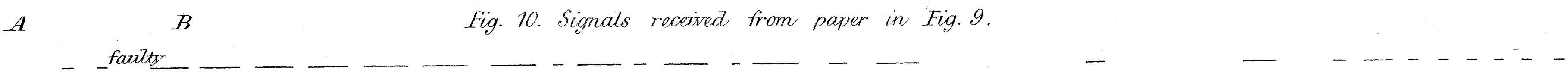

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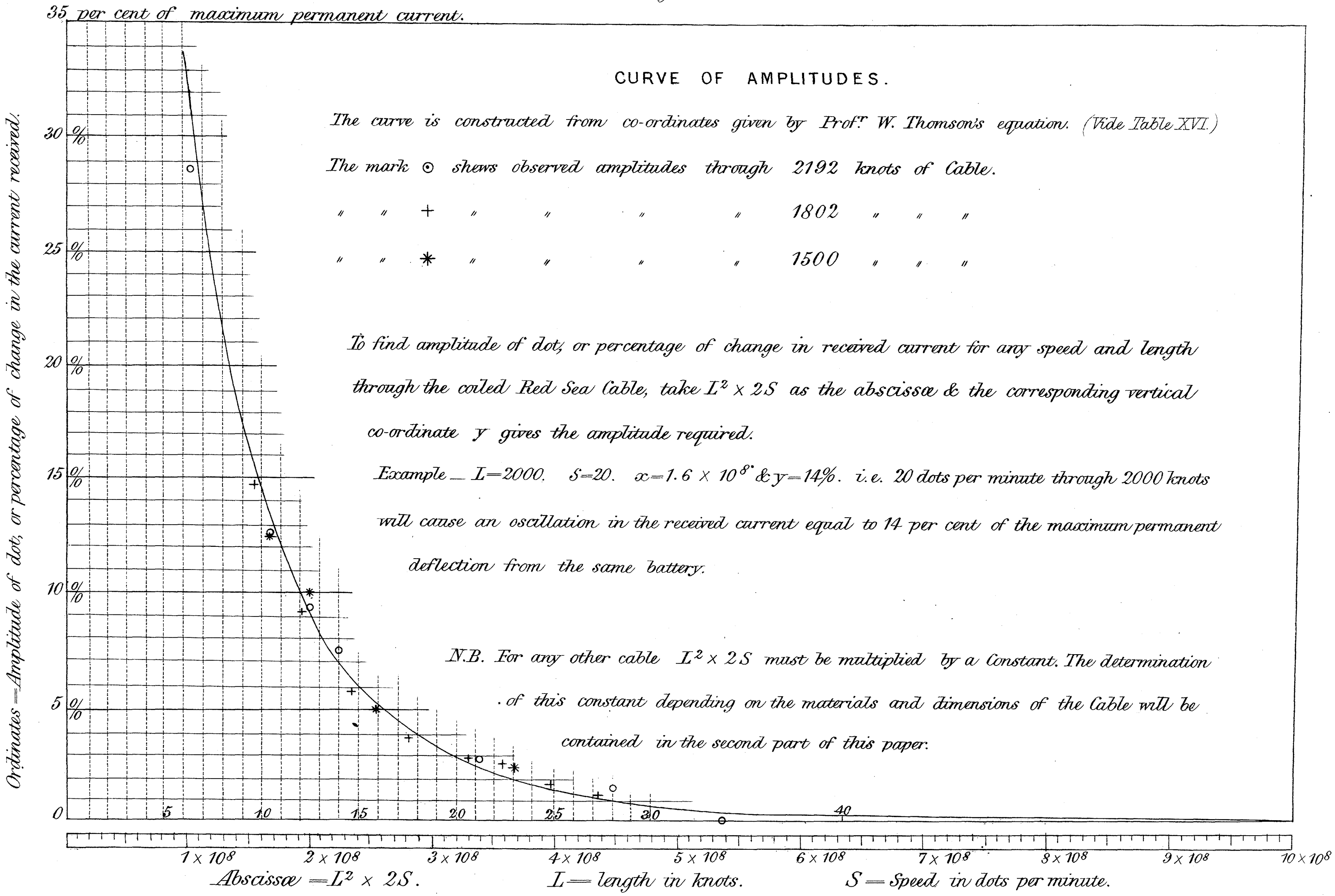
Fig. 11.



The dotted lines give the number of dots per minute in function of x (vide Appendix II.) & Table XVI.

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