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Appendix C

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HY-WIRE AND FAST ELECTRIC FIELD CHANGE MEASUREMENTS NEAR AN ISOLATED THUNDERSTORM

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National Aeronautics and
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ABSTRACT

Electric field measurements near an isolated thunderstorm at 6 4 km distance are presented from both a tethered balloon experiment called Hy-wire and also from ground based fast and slow electric field change systems Simultaneous measurements were made of the electric fields during several lightning flashes at the beginning of the storm which the data clearly indicate were cloud-to-ground flashes In addition to providing a comparison between the Hy-wire technique for measuring electric fields and more traditional methods, these data are interesting because the lightning flashes occurred prior to changes in the dc electric field, although Hy-wire measured changes in the dc field of up to 750 V/m in the direction opposite to the fair weather field a short time later Also, the dc electric field was observed to decay back to its pre-flash value after each flash The data suggest that Hy-wire was at the field reversal distance for this storm and suggest that charge realignment was taking place in the cloud with a time constant on the order of 20 seconds

INTRODUCTION

During a July 1982 flight of the Hy-wire experiment (see Holzworth et al., 1981) to measure atmospheric potentials a small air mass thunderstorm developed within a few kilometers of Hy-wire. This report will describe the observations from both Hy-wire and a nearby ground based electric field change system of the type conventionally used to study radiation from lightning (Uman, 1969 Krider et al., 1977). The balloon flight was designed to be a fair weather experiment but the thunderstorm developed in a location which posed no immediate threat to the tethered balloon. Consequently, the balloon and wire remained aloft until ground winds became unsafe, which was 50 minutes after the first lightning strokes were recorded. Four cloud-to-ground strokes were simultaneously observed by Hy-wire and by the electric field change system. They occurred prior to any evidence of charge build-up in the cloud. This paper will 1) describe the Hy-wire measurements and weather conditions during this flight, 2) present Hy-wire observations of the cloud-to-ground lightning strokes which suggest that they transferred from 0.3 C to 5.2 C to ground, 3) present fast and slow electric field changes measured on the ground during the early lightning strokes which clearly show that these were nearby cloud-to-ground discharges and 4) discuss the implications of the measurements to the charge structure of this storm.

INSTRUMENTATION

Figure 1 shows a plan view of NASA's Wallops Island indicating the experiments and the thunderstorm at 1740 UT on July 17, 1982 The Hy-wire apparatus and tethered balloon were located on the coast near the rocket launching sites and the electric field change system was located about 3 km northwest at the Spandar radar facility. The thunderstorm was in the position indicated in Figure 1 when the first lightning strokes occurred.

The Hy-wire system (Figure 2) consists of a long insulated conductor connected at the top to a braided wire mesh and terminated at the bottom inside a large diameter corona ball mounted on 1 meter Teflon legs. The tethered balloon is used to raise the insulated wire which hangs slack (vertically) below the balloon and otherwise is electrically isolated from the system. The Hy-wire instrumentation has been described by Holzworth et al. (1981), and Holzworth (1983) in conjunction with earlier experiments from the same location on Wallops Island. The actual high voltage wire used during the July 1982 flight was an improved version of the one used earlier The July 1982 flight was the first flight test of a new system designed to go up to heights of 2 km and potentials of 250 kilovolts. However, this flight used the same small tethered balloon which had been used previously and it was not capable of lifting the new wire above about 350 m altitude. The data obtained by Hy-wire during the thunderstorm was primarily from an altitude of 275 m.

The new wire itself was specially designed by the Belden wire company It has an inner core of braided Kevlar for strength and this is surrounded by a conducting wire braid of 34 gauge wire which is embedded in an extruded layer of conductive polyethylene Another nonconducting layer of polyethylene is extruded around the outside. The outer diameter is 1 05 cm, and there is no abrasion jacket (to keep the weight down) The wire has been leakage-tested at 100kV in grounded salt water to have a resistance of more than 10^{12} ohms which is two orders of magnitude larger than the measured source impedance (Holzworth et al . 1981).

In its raised position, the Hy-wire senses the atmospheric potential at the top of the wire (exposed mesh) relative to the ground This potential appears on the corona ball at the base of the wire and is measured with an electrostatic field meter placed close to the ball (Monroe model No 1445) At low frequencies the wire responds like any other electrically short antenna and an equivalent circuit for the Hy-wire system is shown in Figure 3 The source voltage V_s represents the potential induced in the wire due to an external electric field. It is the potential difference between the mesh at the top of the wire and the ground, and in a uniform field is just the electric field times the height to which the wire has been raised. The wire itself has a capacitance C_w which depends on its length and is approximately 5500 pf/km (Holzworth, 1983) The capacitance is not perfect because the wire can be charged and discharged to the atmosphere through the exposed mesh at the top and to a less extent through the insulating jacket. R_w represents this leakage resistance. It has been measured to be on the order of 10^{10} ohms (Holzworth, 1983) Leakage from the corona ball is much less and is represented in the equivalent circuit by the resistor R_c This resistor is on the order of 10^{14} ohms (Holzworth, 1983) Under dc conditions, the output voltage V_o measured by the field meter is $V_o = V_s R_c/(R_c + R_w)$ and the step response of the system (i e , the output voltage $V_o(t)$ due to a sudden change ΔV_s in the source potential due, for example, to a nearby lightning flash) is $V_o(t) = V_s[1 - \frac{R_w}{R_w + R_c}(1 - \exp(-t/C_w R_{eq}))]$ where $R_{eq} = R_c R_w/(R_c + R_w)$ Defining the relative error between input and output to be (output – input)/(input), one finds that when R_c is larger than R_w, the error is on the order of R_w/R_c for both the dc and step response. In the case of Hy-wire, $R_c \gg R_w$ and consequently, both the dc and step response of the system are very good representations of the input.

The electric field change system used in the experiment was of the Krider et al. design (Krider, et al., 1977, Le Vine and Krider, 1977). It consists of a flat plate antenna (about 40 cm diameter) followed by an integrator and recording device. The integrator compensates for the capacitive response of the antenna and also provides gain (Uman, 1969, Krider et al , 1977). The equivalent circuit for this system is similar to Figure 3 with the load R_c replaced by a resistor and capacitor in parallel. Two such systems, similar except for the integrator's time constant, were used to record electric field changes The time constant for the "slow" electric field change system was about 1 second and for the "fast" electric field change system was about 1 millisecond The slow electric field changes were recorded on magnetic tape and also on a chart recorder, a combination having an effective frequency response from a few Hertz to a few kilohertz The slow electric field changes are indicative of the quasi-static electric fields at the ground due to changes in the charge in the cloud (Uman, 1969). The fast electric field change system was designed to record the electric field waveform during sharp transients in the field. These waveforms tend to have shapes which are characteristic of the discharge process (return stroke, stepped leader, etc.) which produced them (Tiller, et al , 1976, Weidman & Krider, 1979, Krider et al., 1977) The signal from this antenna normally goes directly to a high speed digital sample and hold device (Biomation Model 8100 waveform recorder) capable of sampling at (selectable) rates up to 10^8 samples/second and storing 2000 samples per record The digital record is transferred to a buffer (in about 1 ms) and the Biomation is then re-armed. The buffer can store up to 10 records and after the lightning flash ends the information in the buffer is transferred to magnetic tape for permanent storage. These data are also recorded in analogue form on magnetic tape for post processing using a system substantially the same as described by Le Vine and Krider (1977) The tape recorder permits continuous recording but incurs a penalty in the form of the increased noise and bandwidth limitations of the tape recorder (about 100 KHz). The fast field changes to be presented here were obtained after the storm was over from the tape recorded data using the digital system.

In addition to the electric field measurements, optical lightning transient measurements were made with a prototype unit being prepared for long duration stratospheric flights (see Holzworth, 1982) This sytem consists of a stroke counter and a peak power detector using optical photodiodes Two photodiodes are used, one of which is preceded by a narrow wavelength interference filter between 700 and 710 nm and one which is a bare photodiode In this system, the transients are detected and counted using the filtered diode output, and the peak power measurement is obtained using the bare photodiode The instrument was calibrated on an optical bench in a darkroom using a broadband lightning simulator (Edgar, private communication, 1982). The instrument covers the range of 6×10^7 watts to 5×10^9 watts at 10 km range

OBSERVATIONS

Figure 4 presents the Hy-wire measurements and meteorological parameters (temperature and winds) during balloon flights on July 17, 18, and 19 Hy-wire was operated for two 12 hour shifts beginning near 1600 UT on July 17 until near 0300 UT on July 18 and then beginning near 2200 UT on July 18 until about 0900 UT on July 19 The dc variations during this period compare favorably to previous fair weather data collected in 1981 but were interrupted by the thunderstorm The nighttime data were mostly near 30 kilovolts and collected at an antenna (Hy-wire) height of 365 m This yields an average electric field of 82 volts/meter, which is about a factor of two below measurements made in May 1981 (Holzworth, et al , 1981), but except for the presence of the thunderstorm, the data between 1500 and 2200 UT are very similar to the earlier observations

The most prominent feature in Figure 4 is the signature of the thunderstorm which first produced a brief field reversal just before 1800 (July 17), then a very strong reversal up to the point where ground winds forced the temporary termination of the tethered balloon flight at 1827 UT The lightning transients to be discussed below occurred near the time labelled A in Figure 4. Aside from the thunderstorm itself, this was a period of clear to partly cloudy weather with a visibility of 7 to over 10 miles most of the time.

Figure 5 shows an expanded view of the Hy-wire measurements between 1730 and 1825 UT on July 17, 1982 The two panels are the same data with different gains The lightning strokes to be discussed below are numbered 1-6 It is of interest to note that prior to the first stroke, the electric field was constant and in the fair weather direction (positive voltage) Also, all numbered lightning strokes are enhancements in the direction of the fair weather field as would be the case for decreasing negative charge overhead as is typical of cloud-to-ground strokes Figure 6 shows a further expanded view of lightning strokes 1-5 In this figure it can be seen that the transients vary from 3 to 20 kilovolts which is equivalent to 10 to 73 V/m and a charge transfer of about 0 1 to 0 5 coulombs (Table 1) Note in particular that after the first few strokes, the electric field decays back to near the starting level and that it is not until after stroke number 5 that a noticeable decrease occurs in the dc electric field. Figure 6 also indicates the readings from the optical lightning sensors Each measured lightning flash was between 2 4 x 10^8 and 4 0 x 10^8 watts at 6 4 km horizontal range (no data was recorded for flash number 1)

The slow electric field changes recorded on the ground during these lightning flashes are shown in Figure 7. Clearly identifiable field changes were recorded for each of the events seen with the Hy-wire except for the first. These field changes are in the direction of enhanced fair weather electric field, and have the sign and abrupt transition characteristic of return strokes which lower negative charge to the ground (Uman, 1969; Livingston and Krider, 1978, Le Vine, 1978) In the fifth event (at 17 42.18) two transients are present, suggesting a cloud-to-ground flash with two return strokes. Fast electric field changes during this period were recorded on magnetic tape and analyzed later using a Biomation waveform recorder. Fast electric field changes were detected on the tape corresponding to flashes 3, 4, and 5. Each of these fast field changes were in the direction associated with return strokes lowering negative charge to the ground. As expected, two fast field changes were found for Flash 5 corresponding to the two abrupt transitions on the slow electric field change record. These were the strongest field changes observed among these flashes. Figure 8 shows an expanded record of the slow electric field change for flash 5 at the top and the fast electric field change for each of the transitions (A and B) at the bottom. The fast electric field changes were obtained using a Biomation 8100 with a sample rate of 0 2 μs/sample (5 x 10^6 samples/second). The transient waveform recorder stores 2000 samples yielding the data window of 400 μs shown. The fast field changes in Figure 6 have shapes typical of the radiation from return strokes of close cloud-to-ground flashes (Tiller, et al., 1976, Krider, et al., 1977, Lin, et al., 1979) and are consistent with the hypothesis that they came from a storm about 5 km away (Figure 1). The fast field changes recorded for events 3 and 4 are shown together with the associated slow field changes in Figure 9 These were of marginal quality but also have a shape consistent with close return strokes which lower negative charge to ground

DISCUSSION

The data at the time of the cloud-to-ground flashes (Figure 6) exhibit two features of particular interest 1) no changes were observed in the dc electric field prior to the first cloud-to-ground flash, and 2) the dc electric field after each cloud-to-ground flash decays back toward its preflash fair weather value. Based on a conventional dipole model for the charge distribution in a thunderstorm, one would have expected to observe changes in the electrostatic field before the first lightning flash (i e , to have seen evidence of the dipole as it developed) and to have seen a net dc change in the electric field after each return stroke (due to charge neutralization in the cloud)

One possible explanation for the absence of a change in the dc electric field prior to the first lightning flash is that the Hy-wire was located near a field reversal point (Uman, 1969, Chalmers, 1967) for this storm Assuming a dipole model for the charge distribution with an upper positive charge Q at an altitude H^+ and a lower negative charge $-Q$ at H^-, the electrostatic field at the ground is negative (opposite to the direction of the fair weather field) close to the storm because of the proximity of the lower negative charge and eventually changes sign and becomes positive further from the storm. The location of this transition point depends on H^+ and H^- but not on Q, hence, an observer located at this point would not see a change in the electric field as charge began to separate in the thunderstorm. In fact, the storm-sensor geometry during this experiment is quite consistent with this hypothesis For example, assuming the negative charge to be located slightly above the freezing level at 2.7 km and placing the positive charge at 7 km which is just below the cloud tops measured by the Spandar radar (7 6 km) one finds a field reversal distance of 6.3 km which is the distance from Hy-wire to the storm. In fact, this field reversal distance is on the order of 6 km for a reasonable range of charge locations (6 km $< H^+ <$ 7 km and 2 5 km $< H^- <$ 3 5 km) and it doesn't change very much even if one modifies the charge distribution by assuming a small positive charge located at the base of the cloud (Uman, 1969, Malan, 1963)

The hypothesis that the Hy-wire was at the field reversal distance would explain why no electrostatic fields were seen prior to the first cloud-to-ground flashes It also is consistent with the Hy-wire observations of electric fields after these flashes which consisted of a slow oscillation between 17 40 and 18 10 (Figure 6) followed by a dramatic decrease which began about 18 10 (Figure 5) and continued to the termination of the Hy-wire flight The electric fields near a field reversal point are particularly sensitive to small changes in the separation between charges and could exhibit similar behavior in response to growth and decay cycles of the storm if these affect the magnitude and location of the charges. In particular, suppose that the upper positive charge, Q, of a dipole undergoes a change Δ in its altitude, H. If $\Delta << H$, the electric field at the field reversal point D is approximately $E(\Delta) = (Q\Delta/4\pi\epsilon_0)\,[1 + H^2/(H^2 + D^2)]\,[H^2 + D^2]^{-3/2}$. The change in electric field is in the direction opposite to the fair weather field (negative in Figures 5 and 6) and is directly proportional to Δ and Q. Assuming that H = 7 km and D = 6.4 km, as before, and letting Q = 10 C and Δ = 500 m, one obtains a change in the potential of the Hy-wire of about 50 kV, and if Q = 40 C which is more typical of an active storm (Uman, 1969), then the change in potential is on the order of 200 kV. These values are consistent with the changes measured by Hy-wire during the slow oscillation and rapid negative change after the first cloud-to-ground flashes. Thus, suppose that Hy-wire was at field reversal point and that following the cloud-to-ground flashes at 17 40 UT the storm began to intensify, slightly raising the upper positive charge center in the process. The result would be decreasing (more negative) voltage on Hy-wire. If the charge on the dipole were about 10 C and the maximum change in height was about 500 m, then the Hy-wire voltage would change from its preflash value of about 40 kV to −10 kV as in Figure 5. If the intensification died for some reason, only to begin again in earnest later, then one would expect an oscillation followed by a large negative change as occurs in the Hy-wire data. Bipolar cycles of this sort are not atypical of thunderstorms (e.g. Livingston and Krider, 1978). This picture of a weak cycle followed by a strong cycle is also supported by estimates of the charge transferred by return strokes during the cloud-to-ground flashes (Table 1). These were small (on the order of 0.3 C) for the initial flashes at 17 40 and much larger (5.3 C) for a flash (number 6, Figure 6) recorded just before the Hy-wire flight was terminated.

A second feature of the data that is interesting is the decay of the electric field between the cloud-to-ground flashes towards its pre-flash value (Figure 6). In the traditional model of a cloud-to-ground flash, the return stroke transfers charge from cloud to ground. The effect is equivalent to adding a positive charge to the cloud and should be manifested in an abrupt increase in the dc electric field in the direction of the fair weather field. In fact, evidence to support this picture can be seen in the fast and slow field changes recorded during these flashes (Figures 8 and 9). In the case of the fast field changes, an electrostatic contribution to the waveform is to be expected from close return strokes due to the accumulation of charge at the channel ends as current flows along the channel (e.g. Le Vine and Meneghini, 1983). This is clearly evident in Figure 8A where the fast field change shows a sharp initial peak (due to the radiation field) followed by a contribution which slowly rises as charge is transferred along the return stroke channel. The slow electric field change system, which has much less bandwidth, responds to the quasi-static conditions before and after the return stroke. Consequently, one would expect it to have a step-like response to the charge transfer that occurs during the return stroke. Such a response is clearly evident in Figures 8 and 9

The decay in the slow electric field change after the return stroke (Figures 8 and 9) reflects the time constant of the integrator employed in the electronics Presumably, a system with a good dc response would have measured a true step without this decay As mentioned previously, one of the unique features of the Hy-wire, one which permits it to measure the slowly fluctuating fair weather field, is that it has a very good dc response This is because of the large terminating impedance, R_C, designed into the system (Figure 3) Thus, during a return stroke one would expect the Hy-wire voltage to jump just like the slow electric field changes in Figures 8 and 9, but to remain constant after the jump. In fact, the jump is clearly evident in the Hy-wire data at each cloud-to-ground flash (Figures 5 and 6) and is in the direction indicating that negative charge has been removed from the cloud However, the electric field change is not constant but decays back toward its value prior to the flash. The time constant of this decay is on the order of 20 seconds.

The presence of this decay suggests that the charge transferred by the return stroke does not remain isolated in the cloud but is being, in some manner, neutralized (or shielded) by other charges in the cloud (e g Illingworth, 1971) Similar decays of the electric field to its pre-flash value are observed after cloud-to-ground flashes with traditional field mills on the ground (Wilson, 1920, Wormell, 1939, Illingworth, 1971, Jacobson and Krider, 1976) The times observed by Hy-wire are consistent with the observations made by Jacobson and Krider (1976) in Florida but appear to be somewhat larger than the data reviewed by Illingworth (1971) However, as Illingworth points out, there is evidence to suggest that the time constant of the decay is somewhat longer near the field reversal point

SUMMARY

Electric field data including several lightning flashes have been collected during the early phase of a small air mass thunderstorm on July 17, 1982. These data consist of electrostatic field measurements obtained with the long (~ 300 meter) vertical antenna called Hy-wire, fast and slow electric field changes using a flat plate antenna located on the ground, and optical radiation intensity obtained using a pair of photodiodes. The data clearly indicate that the several events recorded at the beginning of this storm were cloud-to-ground flashes.

These data are interesting for the comparison it provides of the Hy-wire measuring technique with the more traditional modes of observing electric fields on the ground. They are also interesting because no changes were observed by the Hy-wire in the dc electric field prior to the lightning discharges and because the field changes occurring after cloud-to-ground flashes decayed back to the pre-discharge value. The data suggest that Hy-wire was at the field reversal distance for this storm and give an estimate of the time involved in realignment of charge transferred during the cloud-to-ground flashes.

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Table 1

Lightning Flash Characteristics

Number	Time	Orientation	Number of Strokes	Total Field Change V/m	Total Charge Transferred* Q(coul)
1	1740 32	C-G	1	36,5	0.26
2	1740:57	C-G	1	10.9	0.08
3	1741.10	C-G	1	31.0	0 22
4	1741 37	C-G	1	55.4	0.40
5	1742 18	C-G	2	73.6	0.53
6	1825	C-G	n/a	729 1	5.3

*This value was obtained assuming that the observed field change was due to a point charge located at 2 5 km above the ground and 6.4 km away.

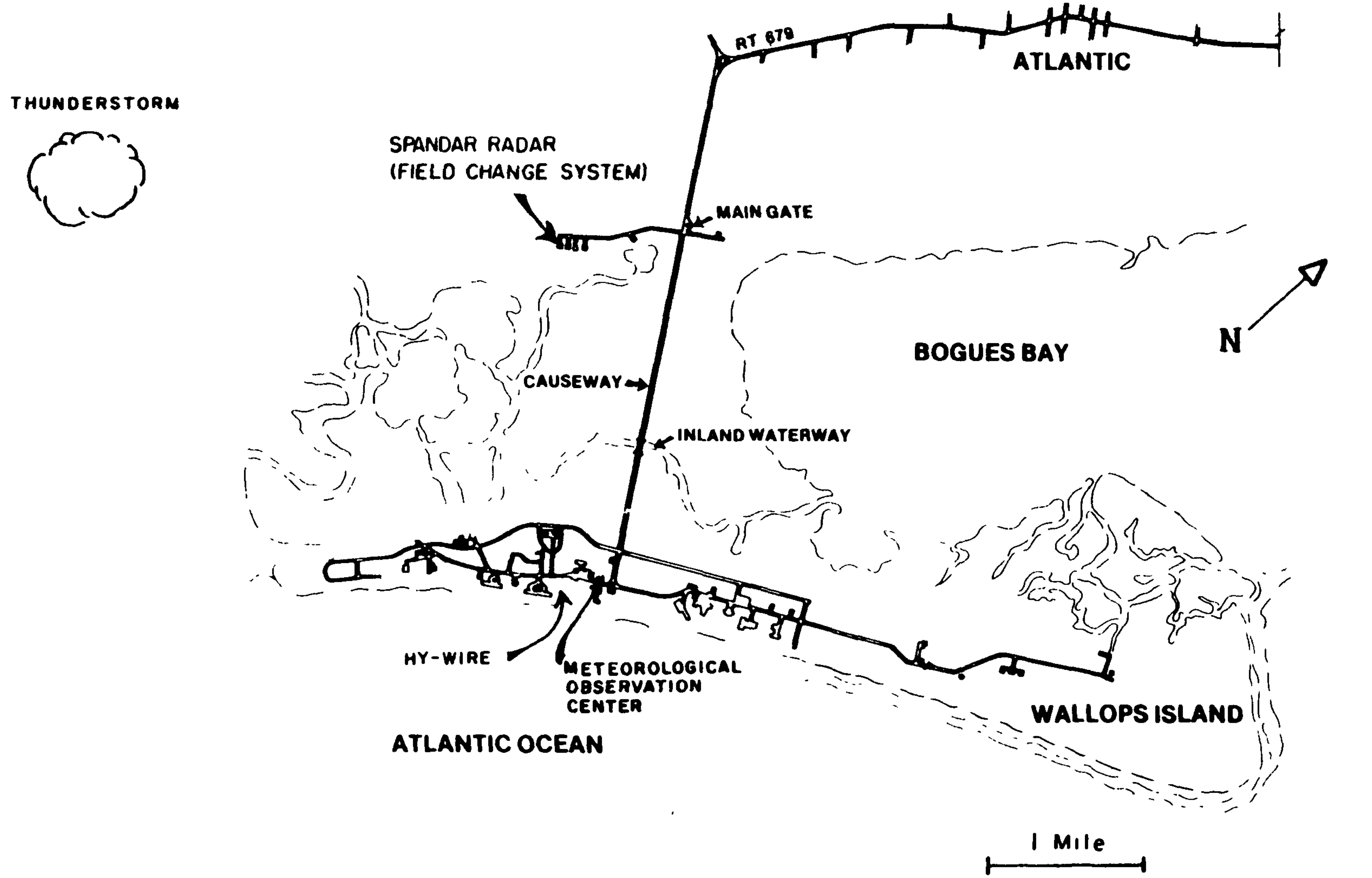

Figure 1 Plan view of Wallops Is , VA Hy-wire was located on the coast near the end of the causeway, the field change systems were at the Spandar radar facility, and the thunderstorm was approximately as indicated in the figure at 1740 UT July 17, 1982

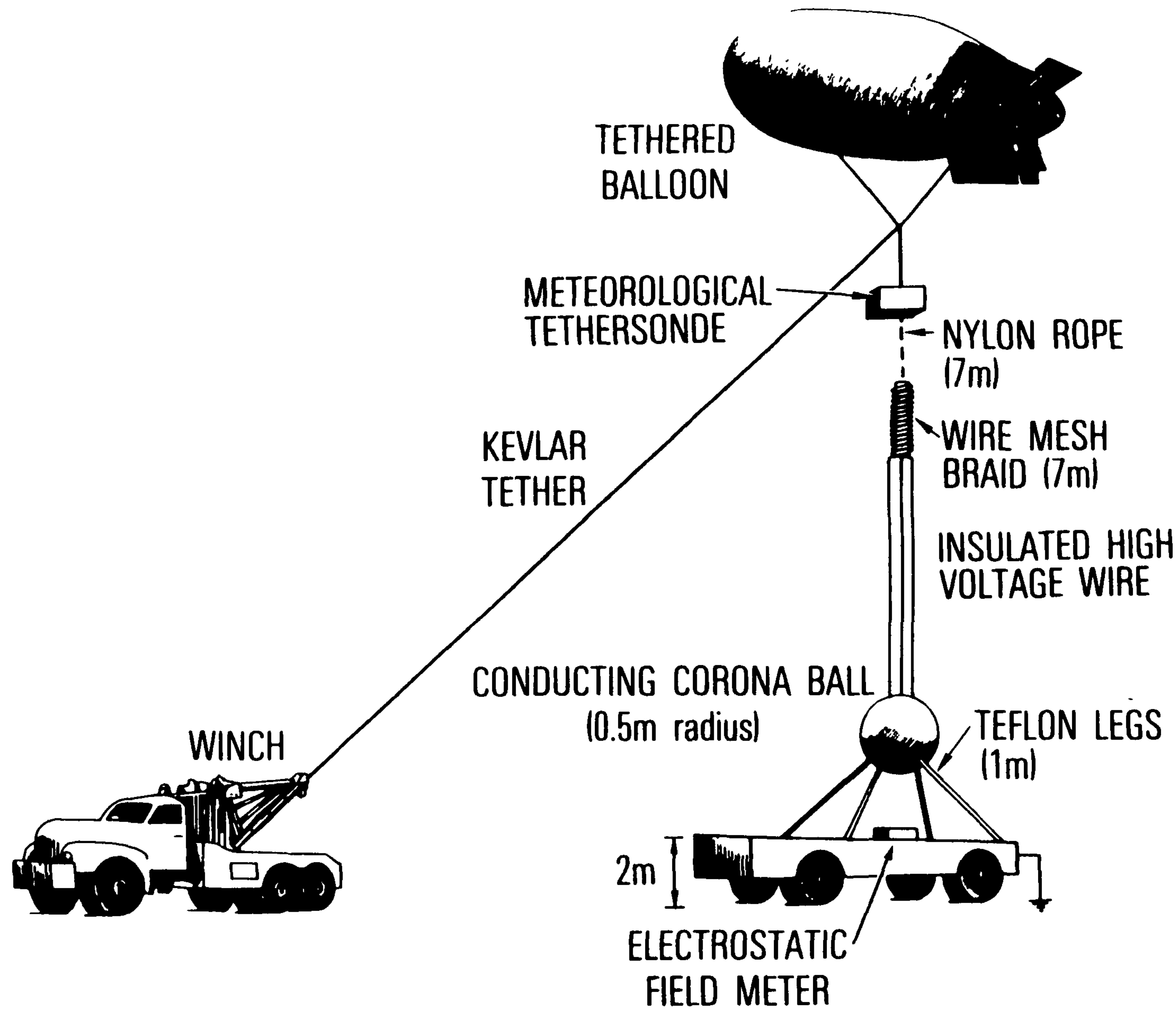

Figure 2. Schematic of the Hy-wire System.

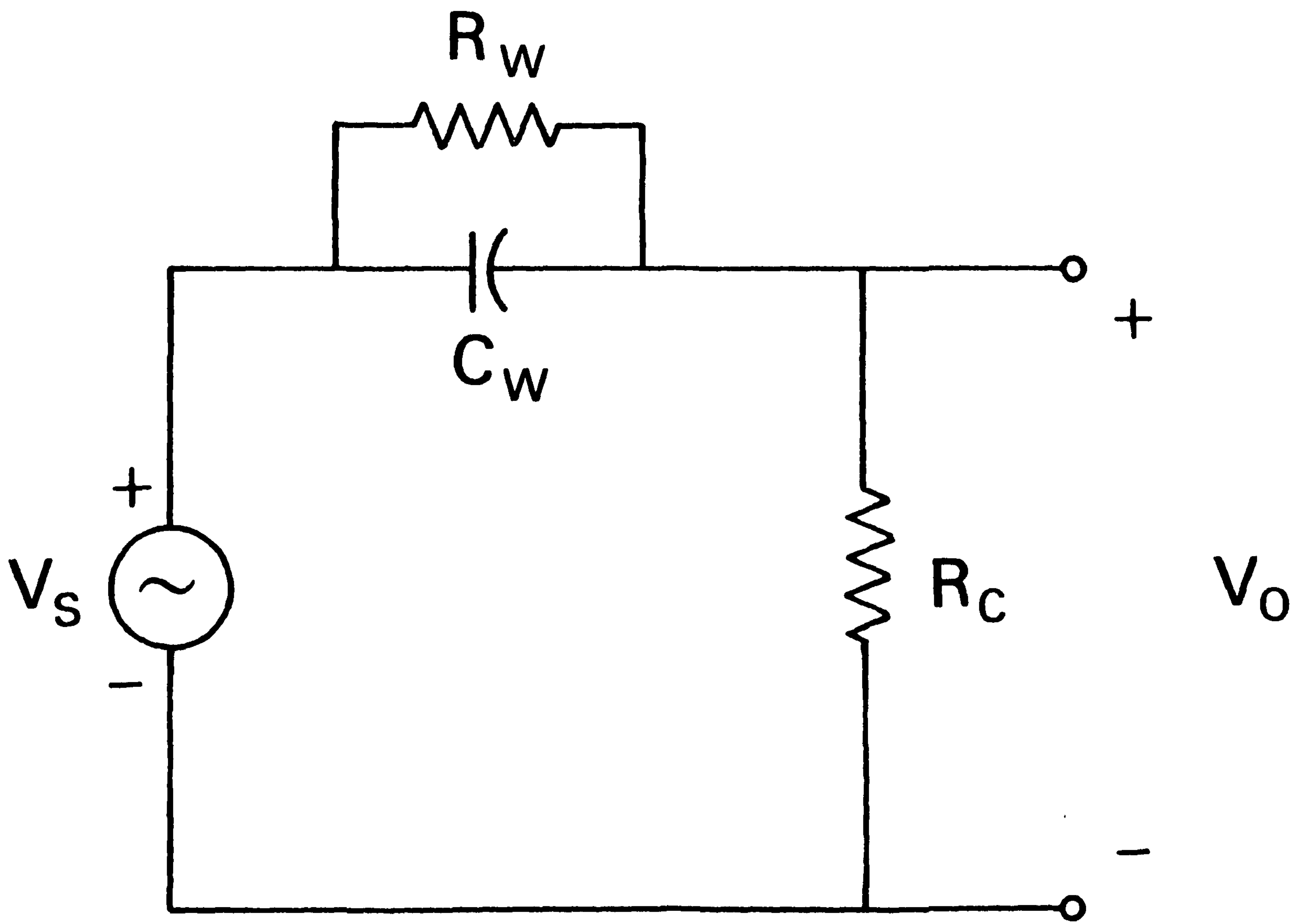

Figure 3. Equivalent circuit for Hy-wire

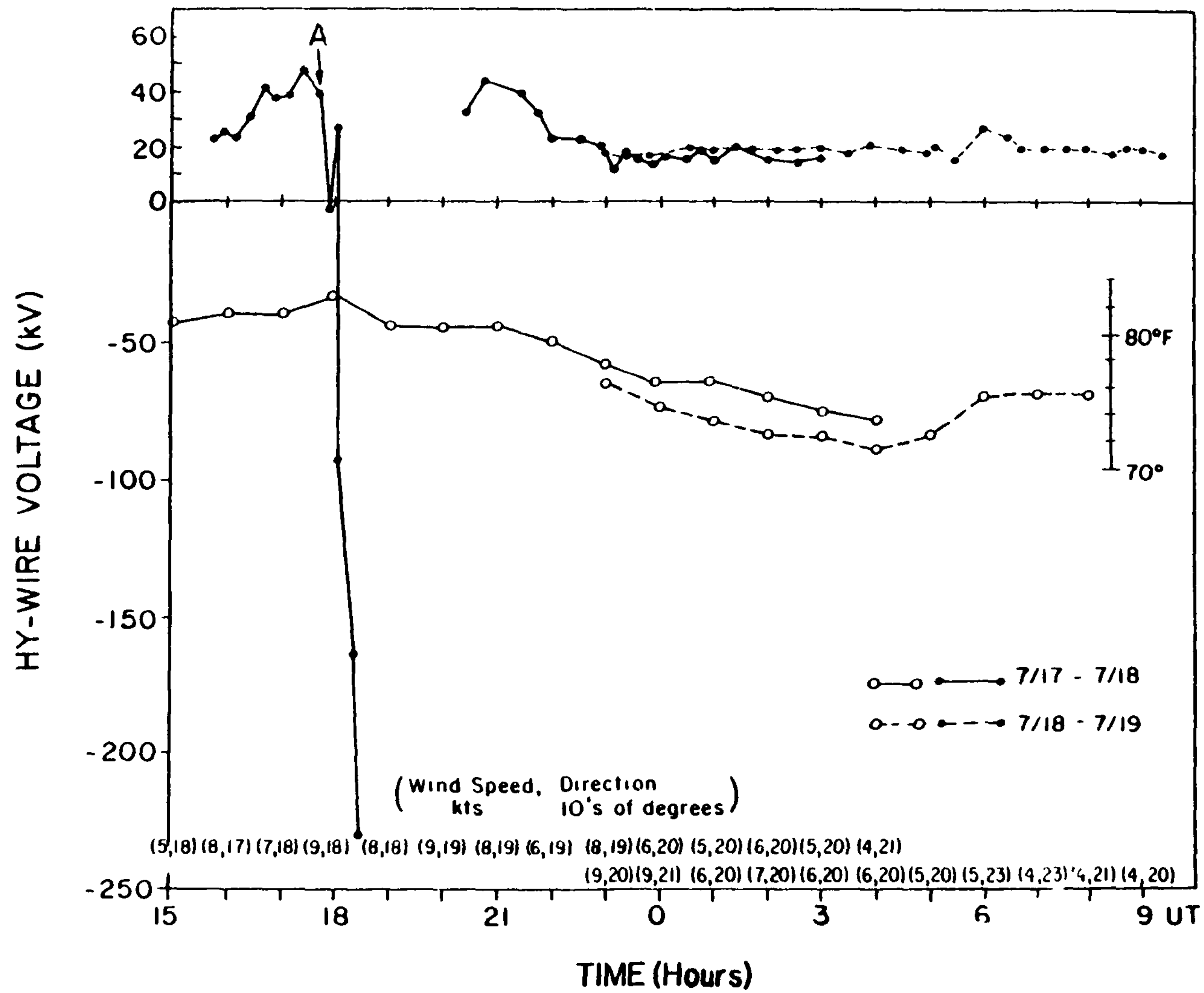

Figure 4 Hy-wire dc atmospheric potential from two flights in July 1982. These were from 1600 UT on July 17 to 0300 UT on July 18 (solid line) and from 2200 UT on July 18 to 0900 UT on July 19 (dashed line). The balloon was operated near 275 m throughout the experiment and the lightning flashes occurred near the time labelled "A" at about 1740 UT on July 17.

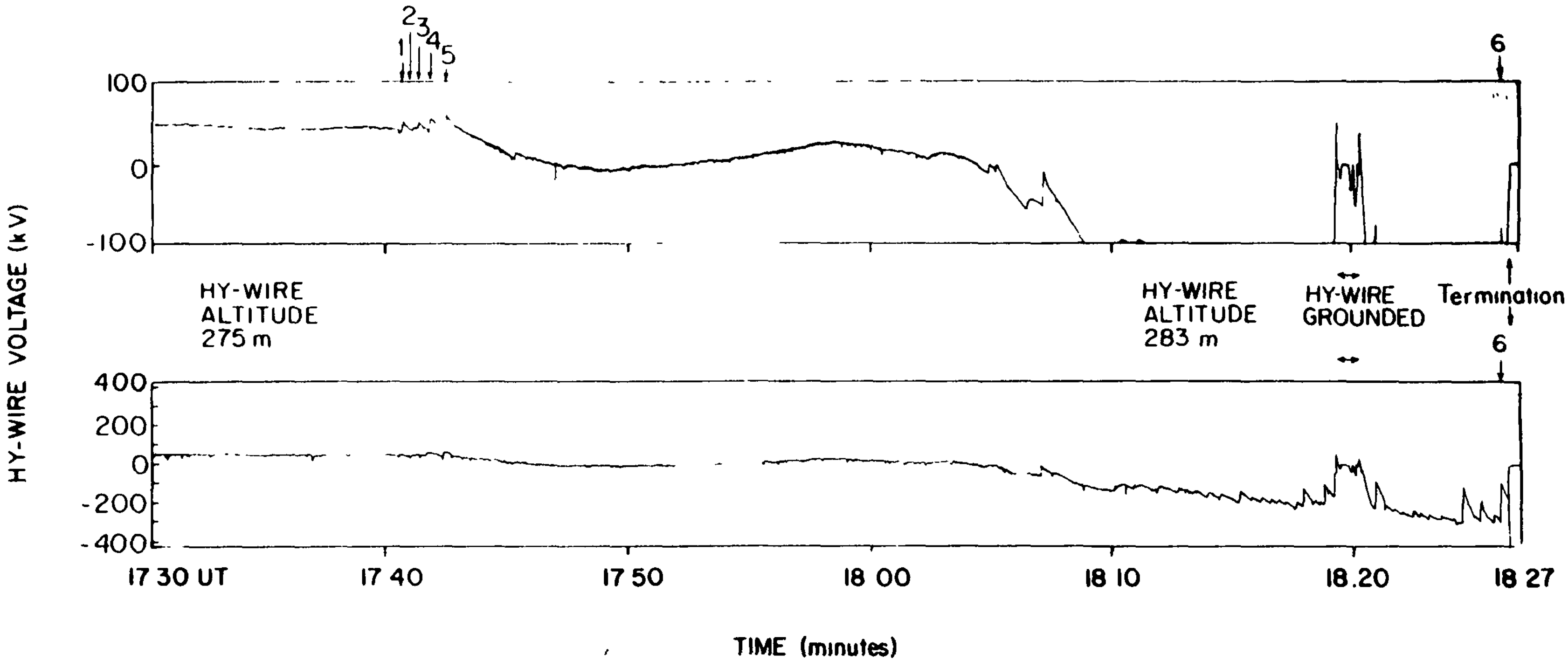

Figure 5 Hy-wire data at the beginning of the thunderstorm (point A in Figure 2) The upper and lower panels are the same Hy-wire data at two gains Lightning transients marked 1 - 5 are discussed in the text

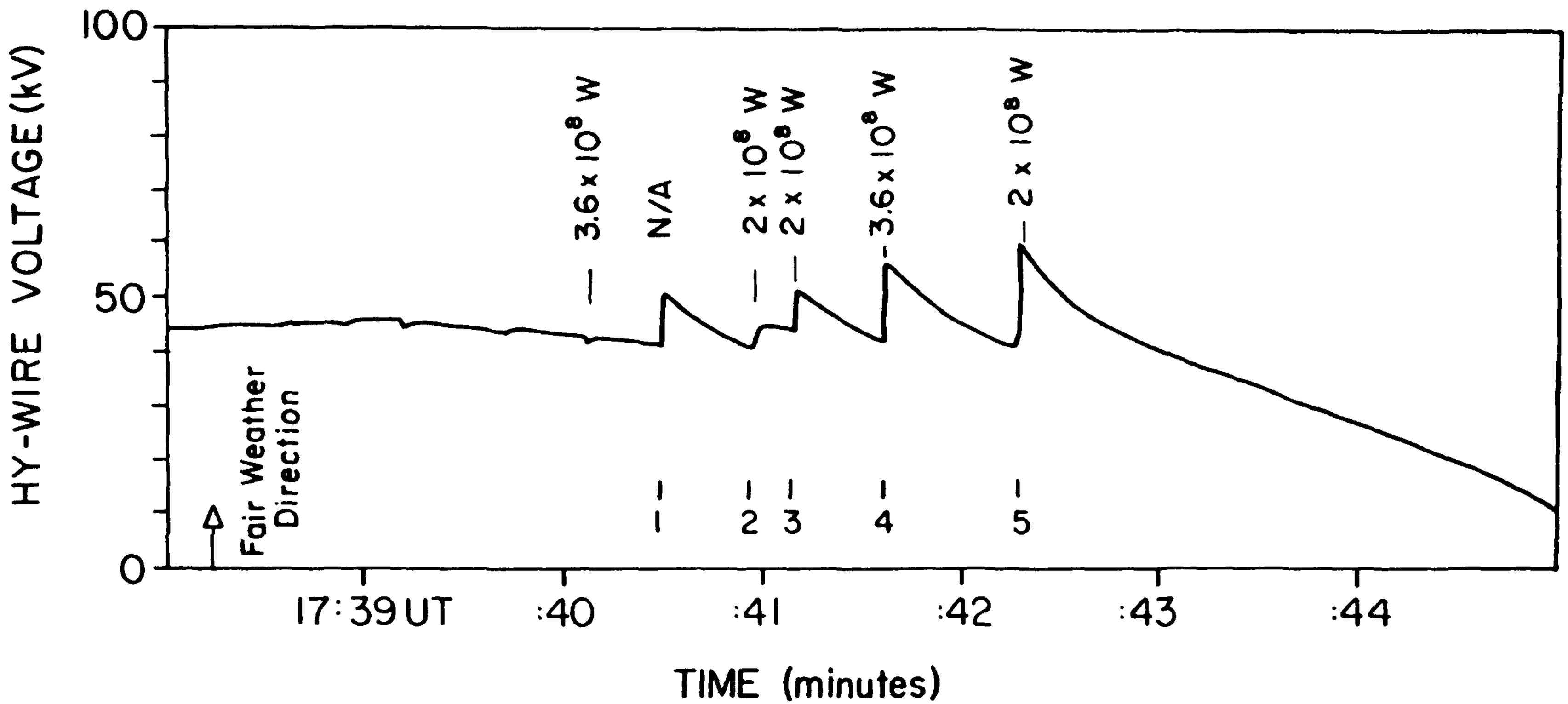

Figure 6 Expanded view of the Hy-wire data during the first few lightning strokes. Optical power density is also shown for flashes for which it was available

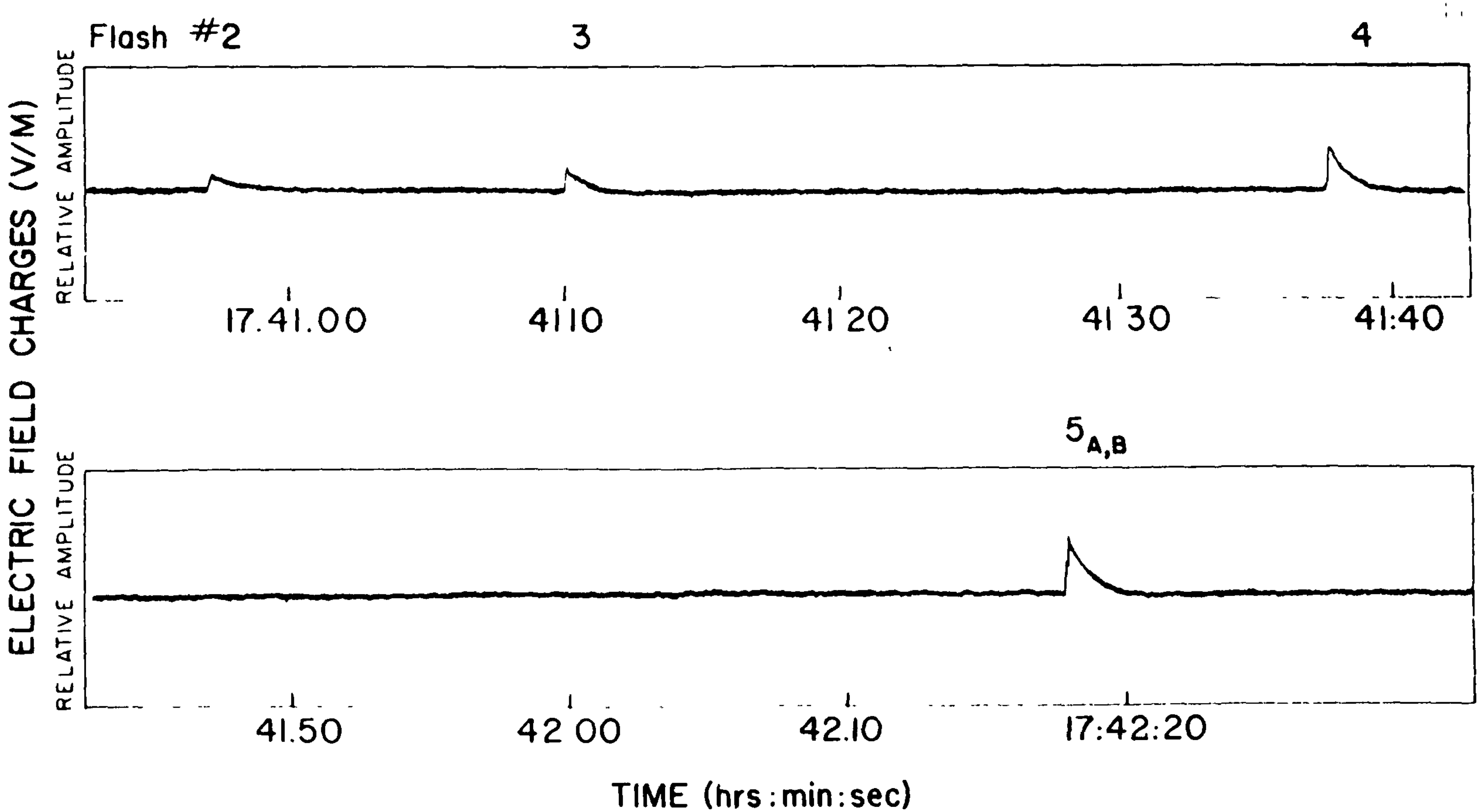

Figure 7 Slow electric field changes measured on the ground The field changes are in the direction of an enhancement of the fair weather field

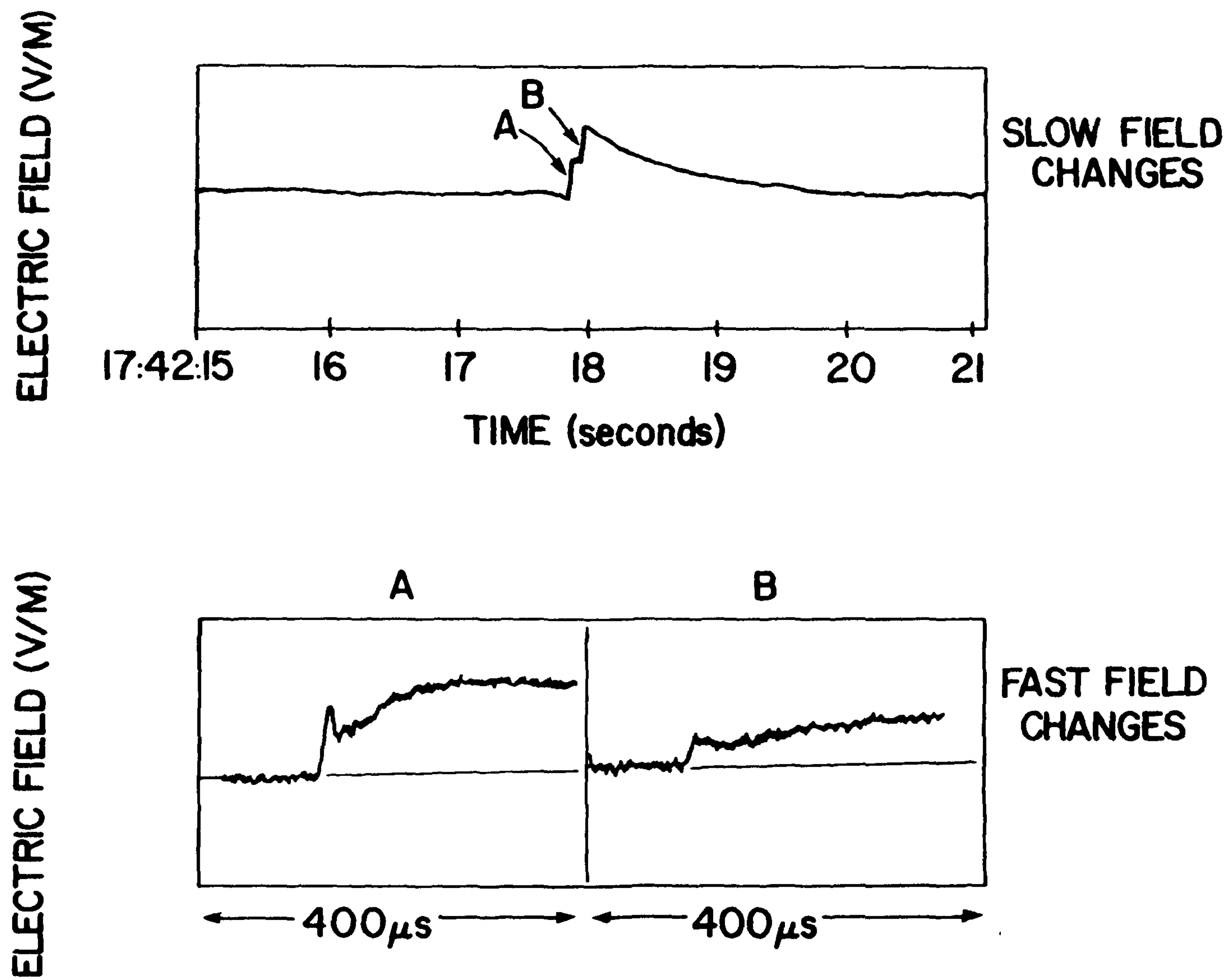

Figure 8 Fast and slow electric field changes for flash number 5. At the bottom are the fast field change obtained using a Biomation-8100 set to trigger on a fast rising pulse There are 2000 samples per Biomation record

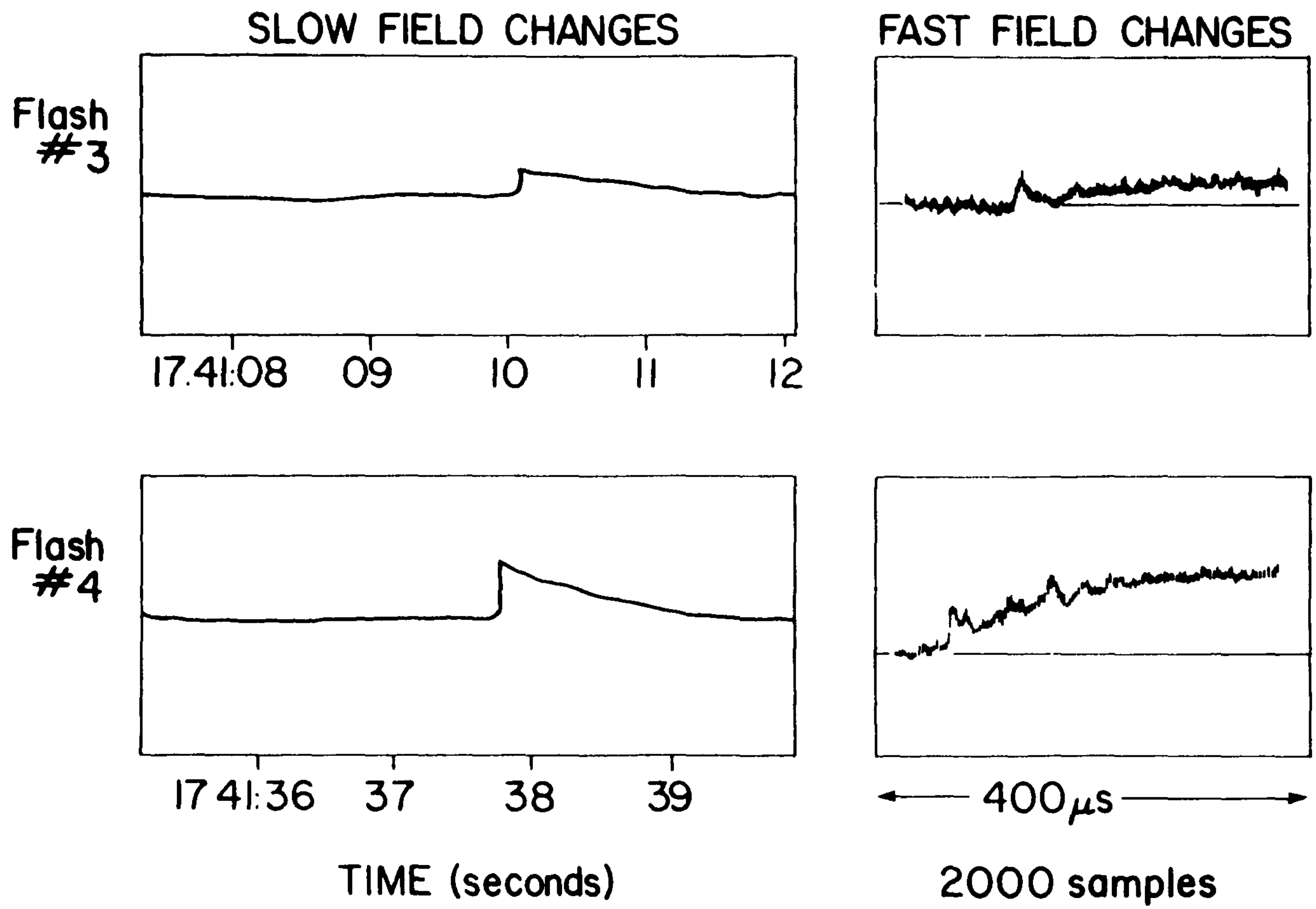

Figure 9 Fast and slow field changes for flashes 3 and 4

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15 Supplementary Notes

16 Abstract
Electric field measurements near an isolated thunderstorm at 6.4 km distance are presented from both a tethered balloon experiment called Hy-wire and also from ground based fast and slow electric field change systems. Simultaneous measurements were made of the electric fields during several lightning flashes at the beginning of the storm which the data clearly indicate were cloud-to-ground flashes. In addition to providing a comparison between the Hy-wire technique for measuring electric fields and more traditional methods, these data are interesting because the lightning flashes occurred prior to changes in the dc electric field, although Hy-wire measured changes in the dc field of up to 750 V/m in the direction opposite to the fair weather field a short time later. Also, the dc electric field was observed to decay back to its preflash value after each flash The data suggest that Hy-wire was at the field reversal distance from this storm and suggest that charge realignment was taking place in the cloud with a time constant on the order of 20 seconds.

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