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CHARACTERIZATION OF VERTICAL ELECTRIC FIELDS AND ASSOCIATED VOLTAGES INDUCED ON A OVERHEAD POWER LINE FROM CLOSE ARTIFICIALLY INITIATED LIGHTNING

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ABSTRACT

We characterize measurements, obtained during the Summer of 1986 at the NASA Kennedy Space Center, of simultaneous vertical electric fields and voltages induced at both ends of a 448 m overhead power line from artificially-initiated lightning return strokes. The lightning discharges were about 20 m from one end of the line. The measured line voltages could be grouped into two categories, those in which multiple, similarly shaped, evenly spaced pulses were observed, which we call oscillatory, and those dominated by a principal pulse with subsidiary oscillations of much smaller amplitude, which we call impulsive. Voltage amplitudes range from tens of kilovolts for oscillatory voltages to hundreds of kilovolts for impulsive voltages.

INTRODUCTION AND EXPERIMENTAL SETUP

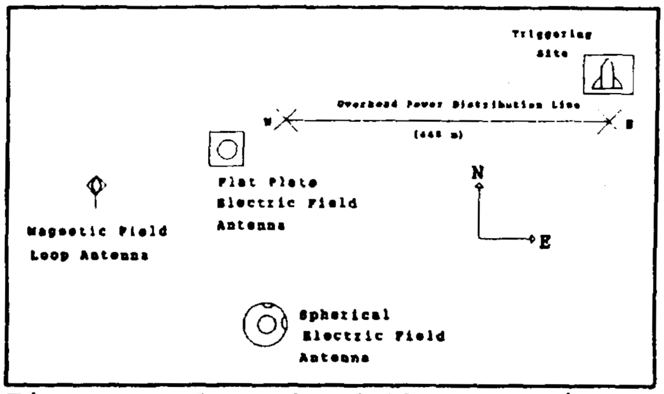

Figure 1. Layout of the experiment site.

A top view of the experiment is shown in Fig. 1. Induced voltages from triggered lightning return strokes at 20 m were measured on a specially constructed unenergized three phase power distribution line spanning about 450 m. The measurements were made on the open circuited top phase of the line, that phase being approximately 10 m above the ground. The two remaining phases were also left open-circuited throughout the experiment. The voltage at either end of the top phase was sampled by means of a specially constructed noninductive voltage divider with a total resistance of about 10 kOhm, the "open circuit" termination impedance. Additionally, the vertical electric field was measured at a distance of about 500 m from the triggered return strokes.

The signals out of the voltage dividers and the electric field antennas were amplified, transmitted through fiberoptics cables, and stored both on analog and on digital storage media. The digitization of the data was done in real time with a LeCroy high speed digitizer system. Simultaneously, the analog signals were recorded on direct and FM channels of a Honeywell 101 analog tape recorder. These analog data were later digitized with both a MassComp computer and an improved version of the LeCroy system. The voltage measurement system had a bandwidth of 750 kHz. The bandwidths of the direct and FM channels of the

Honeywell tape recorder are 400 Hz to 2 MHz and 0 Hz to 500 kHz, respectively, and they determined the bandwidth of the vertical electric field waveforms.

CHARACTERIZATION OF THE FIELDS

Examples of return stroke vertical electric field changes associated with a 7-stroke triggered lightning that occurred on day 232 in 1986, together with voltages measured at either end of the test line are shown in the top traces of Figures 2 and 3. To facilitate the characterization of the return stroke fields, a typical return stroke field has been sketched in Figure 4, in which all the parameters of interest (defined below) have been identified. The vertical electric field starts with a slow field change, presumably from the dart-leader. This slow change, which we label L for leader, precedes a fast positive field change termed R, for return stroke, which ends typically in a small glitch (not discernible in Figures 2 and 3). This fast change is followed by a slower change of the same polarity termed S in Figures 2 through 4. The overall S change, which typically exhibits a dip near its onset (which can be seen in Figures 2 and 3 and is not to be confused with the small glitch observed at the end of R), rises with constantly decreasing slope. The average amplitude of the R change is 878 V/m with a standard deviation of 445 V/m. The average 0 to 100% rise time of R is 803 nanoseconds with a standard deviation of 337 nanoseconds. The average time between the start of R and the bottom of the dip in the S field change is 2.5 μsec with a standard deviation of 0.87 μsec.

CHARACTERIZATION OF THE VOLTAGES

The voltages measured at either end of the test line can be grouped into two categories: (1) those in which a series of evenly spaced, similarly shaped pulses with decaying amplitudes can be observed, which we define as "oscillatory" voltages, of which six were recorded, and (2) those that present a clearly dominant pulse with subsidiary oscillations of much lower amplitude, which we call "impulsive" voltages, and of which five were recorded. Voltage waveforms corresponding to impulsive and oscillatory voltages are shown in figures 2 and 3, respectively. For the discussion that follows, refer to figures 5a and 5b where we have sketched typical impulsive and oscillatory voltages and where we have included the definitions of the parameters to be discussed. Both oscillatory and impulsive voltages were observed to occur for different strokes in the same 7-stroke flash recorded on day 232. The mean amplitude of the R electric field changes associated with oscillatory voltages on the line, 500 V/m, is less than half the mean amplitude of the R changes associated with impulsive voltages, 1.33 kV/m. As we shall see, the maximum induced oscillatory voltages are on average, a factor of 8 to 10 times less than the maximum impulsive voltages, indicating that there are other factors than the measured vertical field amplitude involved in the coupling.

Oscillatory Voltages

In the following characterization, all amplitudes are measured with respect to zero level, where zero is marked by the initial horizontal segment of the waveform. The oscillatory voltages measured at the end nearer to the triggering site (east end) start with a positive pulse whose front rises to peak in some 20 μsec. This pulse, which we term U_o, has a mean amplitude of 19 kilovolts with a standard deviation of 9 kilovolts. After this initial positive-going pulse a series of negative pulses ensues. We call the first three of these pulses T_o, subsidiary 1, and subsidiary 2, respectively. Typically, these pulses have monotonically decaying amplitudes although for the oscillatory voltages recorded on day 232 the second negative pulse is larger than the first. The mean amplitudes of the T_o, subsidiary 1, and subsidiary 2 pulses are −47, −43, and −29 kilovolts, respectively, with corresponding standard deviations 21, 10 and 5 kilovolts. The mean width at half amplitude maximum of T_o is 744 nanoseconds (standard deviation 149 nanoseconds). The average time between the peaks of the T_o and the subsidiary 1 pulses is 3.3 μs (standard deviation 0.3 μs), whereas between the peak of the two subsidiary pulses this time is 3.1 μs (standard deviation 0.2 μs).

The oscillatory voltages measured at the end farther from the triggering site (west end) exhibit features very similar to those described for the voltages measured at the near end: a slow positive pulse followed by a series of sharper negative pulses. We have labeled the positive pulse N_o and the first negative pulse M_o. As in the case of the oscillatory voltages at the east end, we call the two next negative pulses subsidiary 1 and subsidiary 2, respectively. At the west end, the voltages present monotonically decaying pulses in all the events recorded. The mean peak amplitude of N_o is 27 kilovolts (standard deviation 5 kilovolts). The mean peak amplitudes of the M_o, subsidiary 1, and subsidiary 2 pulses are −72, −53, and −39 kilovolts, respectively, with corresponding standard deviations 20, 10, and 3 kilovolts. The mean width at half amplitude maximum of M_o is 1.1 μsec with standard deviation 0.4 μsec. The average time between the peak of the M_o and the peak of the subsidiary 1 pulses is 3.3 μs (standard deviation 0.2 μs), and between the peaks of the subsidiary 1 and the subsidiary 2 pulses this time is also 3.3 μs (standard deviation 0.1 μs).

The main difference observed between typical voltages of the oscillatory type observed at the east and the west ends of the line is that the west end voltage is larger and the east end voltage has a higher negative offset on the voltage reflections.

Impulsive Voltages

Impulsive voltages at the end nearer to the rocket triggering site (east end) are now characterized. Recall that all amplitudes are defined with respect to the initial waveform level. The waveforms start with a slow positive pulse which rises to peak on a 10 to 20 μs time scale and which ends in finer structure, typically characterized by two positive-going peaks. The overall initial positive pulse is termed U_i. It has an average peak amplitude of 98 kilovolts (standard deviation 21 kilovolts). The mean width at half height of this pulse is 1.7 μsec (standard deviation 0.17 μsec). A large negative pulse, which we have labeled T_i in the figure, succeeds the positive pulse U_i. This pulse has a mean peak amplitude of −354 kilovolts and a standard deviation of 44 kilovolts. The mean width of T_i is 783 nanoseconds with standard deviation 123 nanoseconds. After this pulse has dropped to zero, or near zero, a smaller positive-going pulse occurs with mean amplitude 76 kilovolts (standard deviation 20 kilovolts), followed by a slow upward hump of some 25 μsec width.

We now characterize the impulsive voltages observed at the end farther from the triggering site (west end). These voltage waveforms start with a positive pulse which exhibits some structure much like the start of the impulsive voltages at the near end. We call this pulse N_i. The width at half amplitude maximum of this pulse has a mean value of 2.2 μsec and a standard deviation of 0.9 μsec. The end of this pulse is marked by a sharp positive peak. The peak amplitude of this pulse has a mean of 329 kilovolts with standard deviation 68 kilovolts. A large negative pulse which determines the maximum amplitude of the waveform follows with an average peak amplitude of -870 kilovolts (standard deviation 102 kilovolts). This large negative pulse, which we call M_1, exhibits a mean duration of 493 nanoseconds (standard deviation 86 nanoseconds). After this pulse has dropped to near zero, it is followed by a small negative pulse and a small positive pulse. The mean peak amplitudes of the negative and positive pulses are -149 kilovolts (standard deviation 35 kilovolts) and 128 kilovolts (standard deviation 39 kilovolts), respectively. A slow hump similar to that encountered in the east end ensues, lasting about 20 μsec. A series of small pulses is superimposed on this slow change.

Although the wave shapes for the east-end and west-end impulsive voltages are similar, the waveforms differ in that (1) the west end voltages have amplitudes that are about twice the amplitude of the voltages measured at the east end of the line, (2) the west end voltages exhibit two small pulses, one negative and one positive, after the main negative pulse, while the voltages at the east end of the line have only one small positive pulse, and (3) a series of oscillations, absent in the east end voltages, is observed to follow the second subsidiary pulse in the west end voltages.

DISCUSSION

Preliminary modeling of the experimental data presented above have been given in Rubinstein et al. [1] for the case of an oscillatory voltage (flash 1, day 232, event 2 shown in Figure 3 in this paper). Analysis is in progress to improve the modeling of the oscillatory voltages and to model the larger impulsive voltages for which it is thought that electrical flashover occurred at the voltage dividers at or during the voltage rise to peak, thereafter changing the voltage divider ratio and the termination impedance.

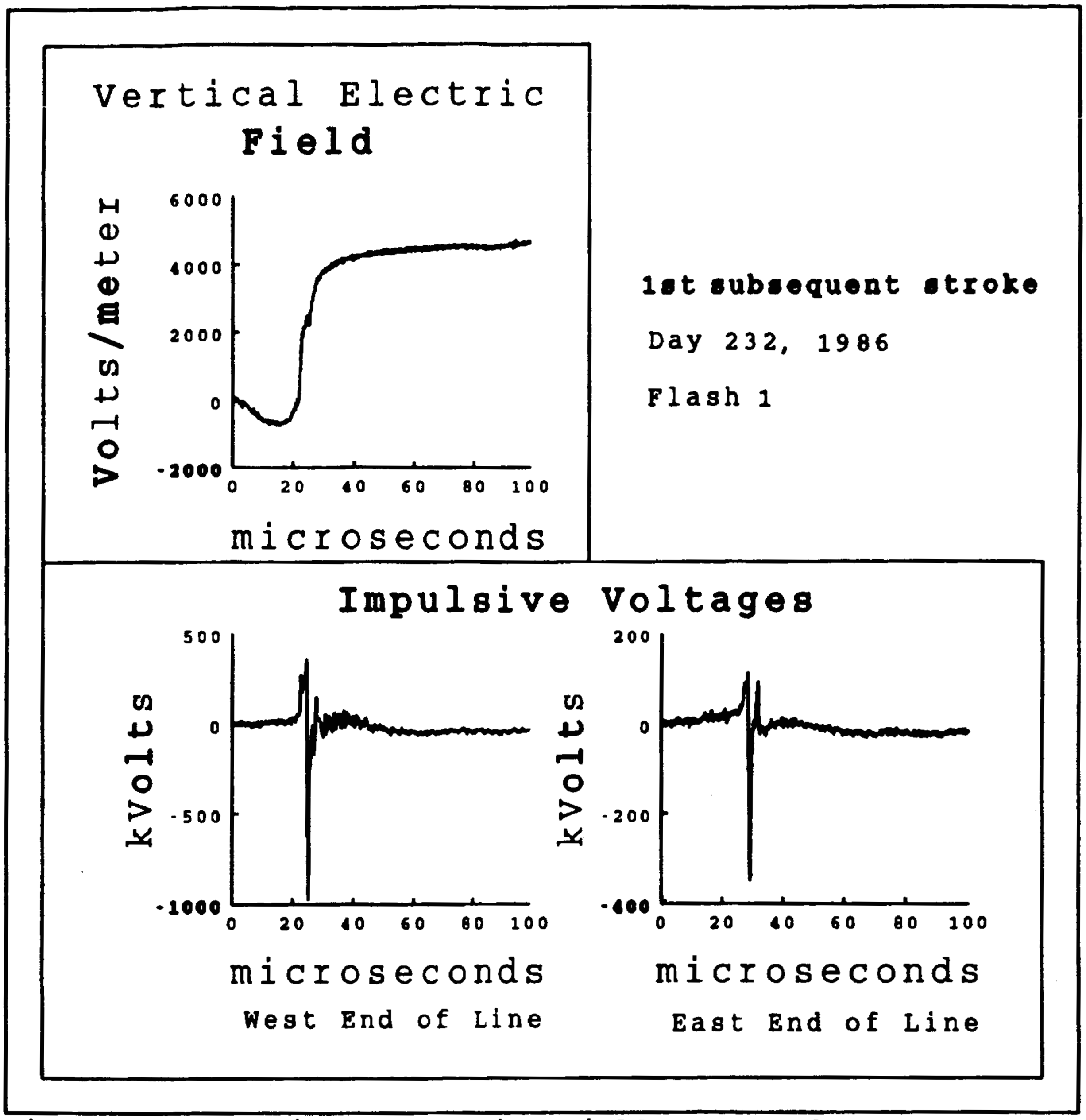

Figure 2. Vertical electric field measured 500 m from artificially initiated lightning return stroke and impulsive voltages at both ends of the test line for flash 1, stroke 1, on day 232, 1986, at KSC, Florida.

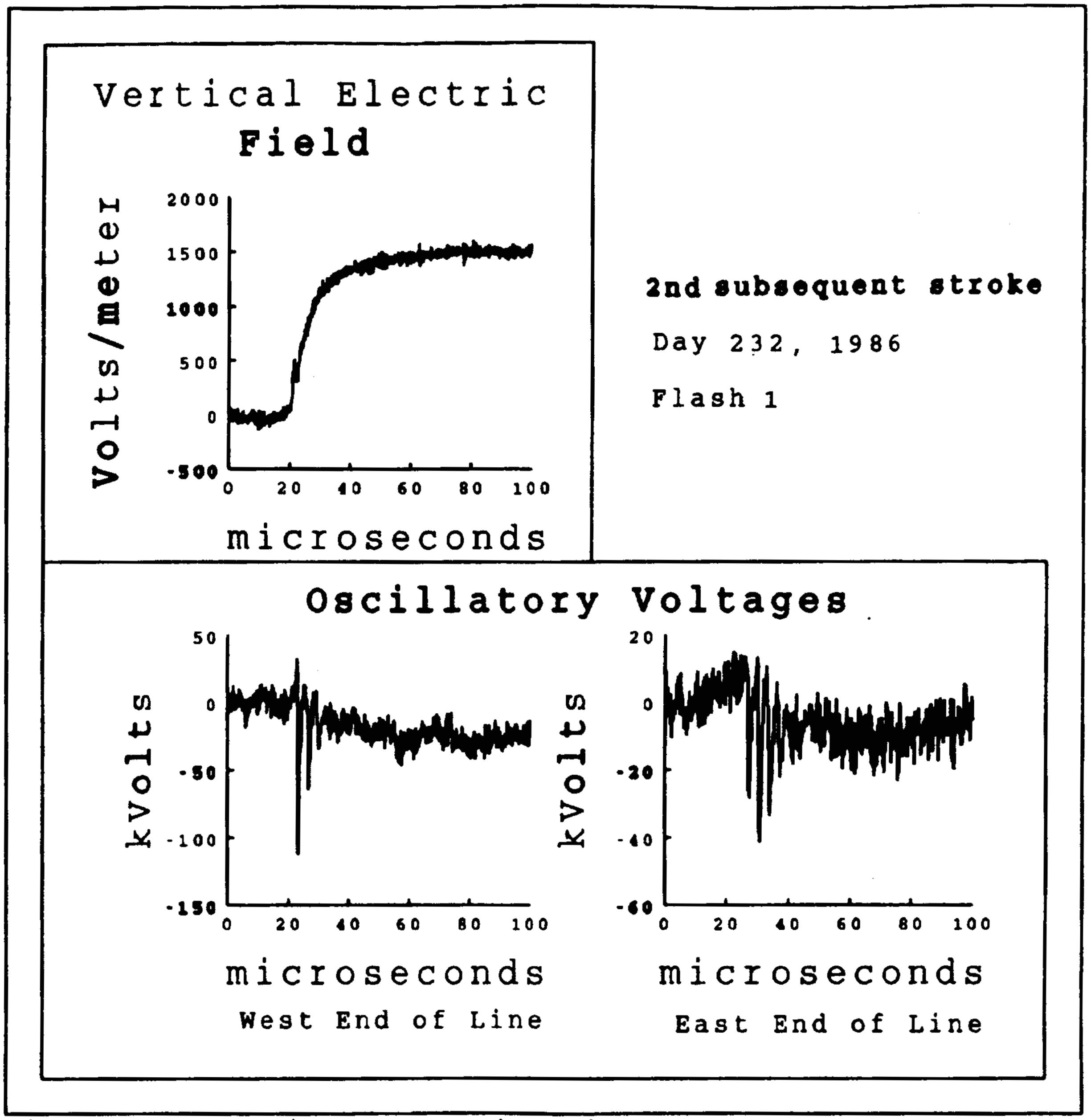

Figure 3. Vertical electric field measured 500 m from artificially initiated lightning return stroke and oscillatory voltages at both ends of the test line for flash 1, stroke 2, on day 232, 1986, at KSC, Florida.

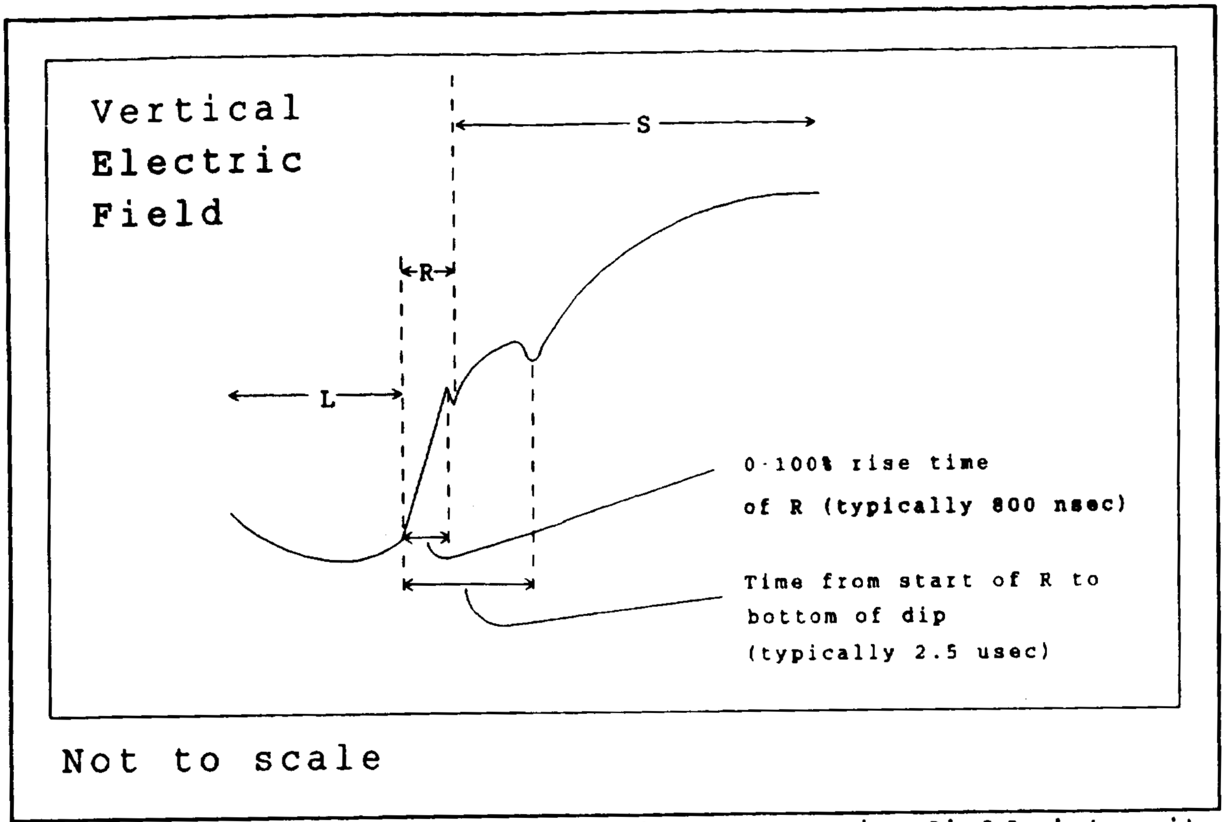

Figure 4. A sketch of the vertical electric field intensity showing definitions of some salient parameters. These parameters are defined in text.

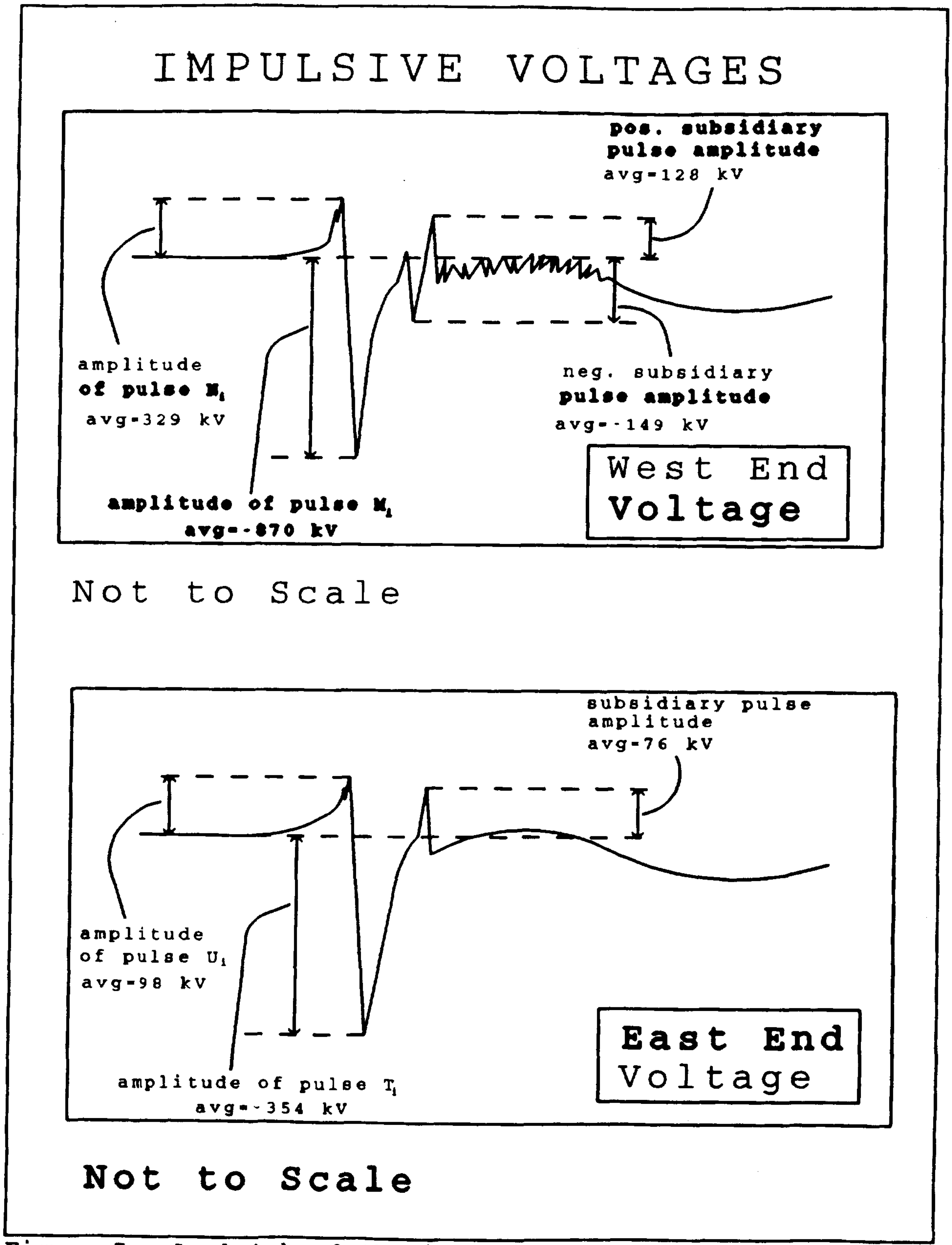

Figure 5a. A sketch of the impulsive voltages showing salient parameters. These parameters are defined in the text.

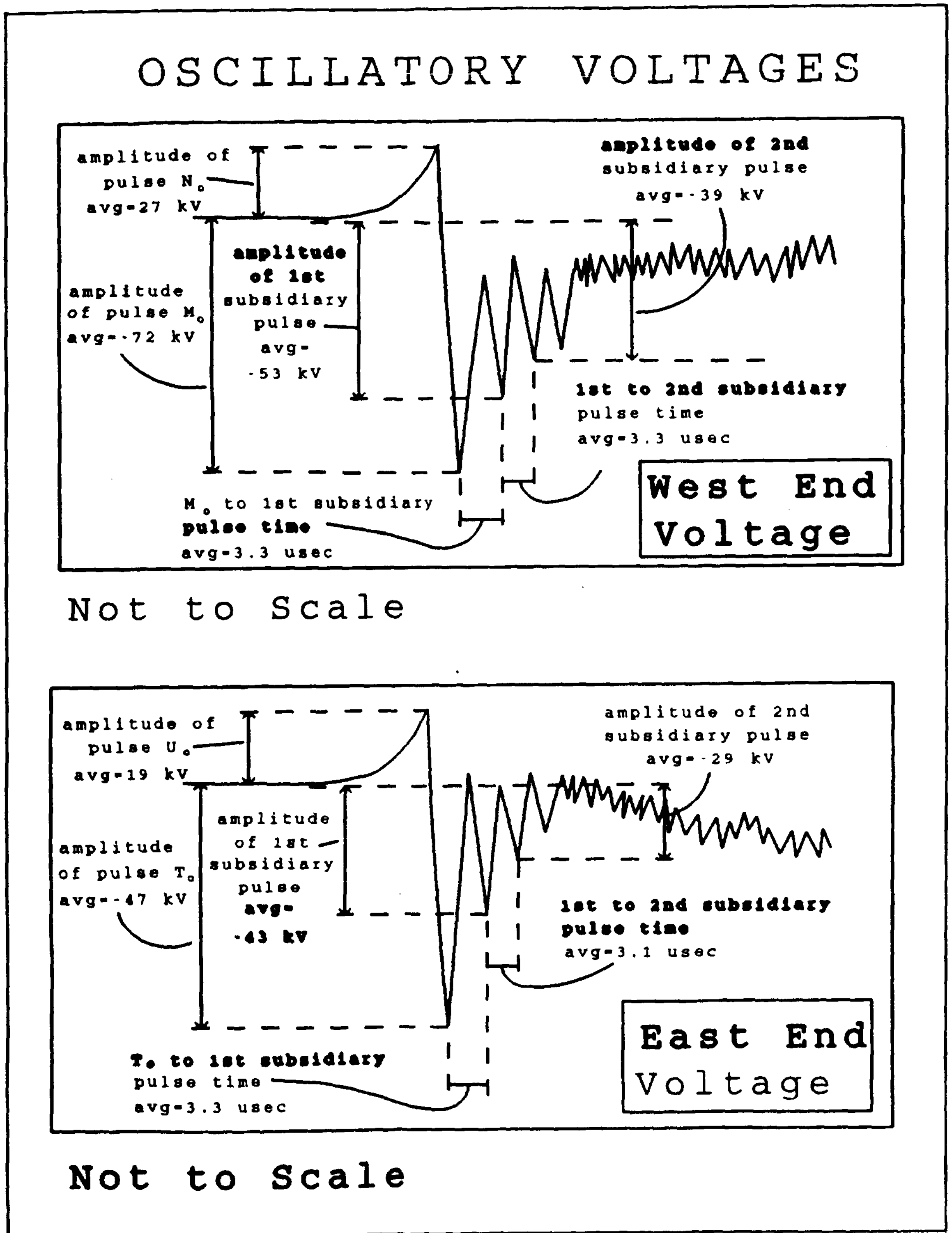

Figure 5b. A sketch of the oscillatory voltages showing salient parameters. These parameters are defined in the text.

REFERENCES

[1] M. Rubinstein, M.A. Uman, E.M. Thomson, and P.J. Medelius, Voltages Induced on a Test Distribution Line by Artificially Initiated Lightning at Close Range: Measurement and Theory, 20th International Conference on Lightning Protection, Interlaken, Switzerland, 1990.

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