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VOLTAGES INDUCED ON A POWER DISTRIBUTION LINE BY OVERHEAD CLOUD LIGHTNING

Ziad Yacoub Marcos Rubinstein Martin A. Uman
Ewen M. Thomson Pedro Medelius

Department of Electrical Engineering
University of Florida, Gainesville 32611

ABSTRACT

Voltages induced by overhead cloud lightning on a 448 m open-circuited power distribution line and the corresponding north-south component of the lightning magnetic field were simultaneously measured at the NASA Kennedy Space Center during the summer of 1986. The incident electric field was calculated from the measured magnetic field. The electric field was then used as an input to the computer program, EMPLIN, written and provided by Dr. F. Tesche, that calculated the voltages at the two ends of the power line. EMPLIN models the frequency-domain field/power line coupling theory found, for example, in Ianoz et al. [1]. The direction of the source, which is also one of the inputs to EMPLIN, was crudely determined from a three-station time delay technique. We find reasonably good agreement between calculated and measured voltage waveforms.

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I. INTRODUCTION & EXPERIMENT

Lightning electromagnetic fields interact with electric power lines to induce currents and line voltages. There are two major types of lightning: ground flashes and cloud flashes. In general, lightning between cloud and ground causes higher voltages on power lines, either by direct strike or by the inducing effects of nearby events, than does lightning within or between clouds or from cloud to air (all commonly known as cloud lightning).

There have been several studies [e.g., 2-3] in which theoretical results obtained from the time domain model developed by Agrawal et al. [4] were compared to the corresponding measured waveforms. The comparison reveals reasonable agreement. These studies were conducted for fields from distant ground lightning.

Overhead or nearly overhead cloud lightning differs from ground lightning in that the source is elevated, producing total electric fields that are primarily horizontal, whereas in ground flashes at the same distance say 5 Km, the horizontal field component is, for the ground conductivity at the NASA Kennedy Space Center (KSC), about 30 to 50 times smaller than the vertical [5]. For this reason, cloud flashes can provide a unique simulation of the response of a power line to elevated electromagnetic sources such as nuclear weapons exploded in the upper atmosphere, so called HEMP, and to test available theory describing that interaction. In the present paper, an example of the measured induced voltages on an open-circuited 448 m long, 10 m high power distribution line due to overhead cloud flashes will be compared with the predictions of the computer program EMPLIN which is based on the frequency domain model of field/power line interaction described, for example, in Ianoz et al. [1]. The results given in this example consist of:

(1) the measured induced voltages at both ends of the power line, (2) the measured north–south component of the horizontal magnetic field, and (3) the calculated incident electric field that was obtained from the measured magnetic field using the theory of the reflection of radiation fields from a finite conducting earth and specialized approximations [6]. The data were recorded on day 232 in 1986 at the Atmospheric Science Field Laboratory of the NASA Kennedy Space Center. For more details regarding the experiment, consult the paper in this conference by Rubinstein et al.

II. DATA

A lightning waveform was classified as a component pulse of a cloud discharge if it was one of the cloud radiation pulses that have been documented by Krider et al. [7], Weidman and Krider [8], and Levine [9] and if the pulse peaks of the induced voltages at the two ends of the power line were of opposite polarity, an important characteristic of the response of an open–circuited power line to an elevated source producing essentially horizontal electric field [6]. About 385 cloud discharge events were identified.

III. ANALYSIS

To model the measured voltages for an overhead cloud event using the EMPLIN code, values for the conductivity σ, the elevation angle Φ, the azimuth angle ϕ, and the polarization angle α (see Figure 1) need to be chosen. We were able to use a three–station time delay technique, where the three stations are the two end voltages of the line and the north–south component of the magnetic flux density, to determine crudely the direction of the source. Other factors also helped us in narrowing the ranges chosen for the direction angles, such as comparing the properties of the measured end voltages for the particular cloud event with the ideal voltage response given in Yacoub [6].

Figure 2 shows the north–south component of the measured horizontal magnetic field, the corresponding calculated incident electric field, and the measured east–end and west–end voltages of the open–circuited line for a typical cloud discharge waveform. In the example given, the combination of the direction angles was first reduced to the smallest region possible using the factors mentioned earlier. The next step was to try different combinations of α, Φ, and ϕ in that region, searching for the best fit to the measured voltage waveshapes. The conductivity of the ground was then varied within a certain range to change subtle waveform characteristics, such as pulse widths and sudden and narrow amplitude variations. Varying the conductivity changes the overall amplitude of the induced voltages as well as the relative amplitudes of adjacent peaks.

The combination that gave the best similarity to the measured voltages was: $\alpha = 350°$, $\phi = 90°$, and $\Phi = 80°$. Conductivities of $1.6\text{x}10^{-2}$, $1.0\text{x}10^{-2}$, $0.5\text{x}10^{-2}$, and $0.25\text{x}10^{-2}$ were tried with the above combination of angles. The results are shown in Figure 3. Figure 3 clearly shows how, as we decrease the conductivity from $1.6\text{x}10^{-2}$ to $0.25\text{x}10^{-2}$, the pulse peak structure at the east and west ends of the line changes to best resemble the measured voltage responses in Figure 2. Also, note that the overall amplitude of the voltage responses in Figure 3 increases as the conductivity is decreased. Again, the conductivity of $0.25\text{x}10^{-2}$ gives the best comparison in overall amplitude and waveshapes between the calculated and measured voltages. Better amplitude agreement between theory and experiment is obtained if we double the calculated field. Reducing the elevation angle of the source reduces the overall amplitudes of the calculated voltages and also change the relative amplitudes of the initial pulse to the adjacent same polarity pulse. This is illustrated in Figure 4 where an elevation angle of 40° is used. This results in a voltage decrease of an order of magnitude, worsening the agreement with experiment.

IV. DISCUSSION

We have presented an example of a test of the computer code EMPLIN using induced voltages on a 448 open-circuited power distribution line from overhead lightning. In spite of the many parameters involved in the coupling of the overhead electromagnetic waves to the power line; the limitations experienced in determining the direction of the incident electric field to an acceptable degree of accuracy; the lack of exact knowledge of effective site conductivity for reflection of overhead electromagnetic waves; and the fact that the incident electric field, the input to EMPLIN, was not available for the cloud discharge events and had to be calculated from the north-south horizontal magnetic field component; we were able to show that EMPLIN can predict, fairly well, the induced voltage waveshapes on power lines from elevated sources while there is a factor of two discrepancy between calculated and measured voltage amplitudes.

V. ACKNOWLEDGEMENTS

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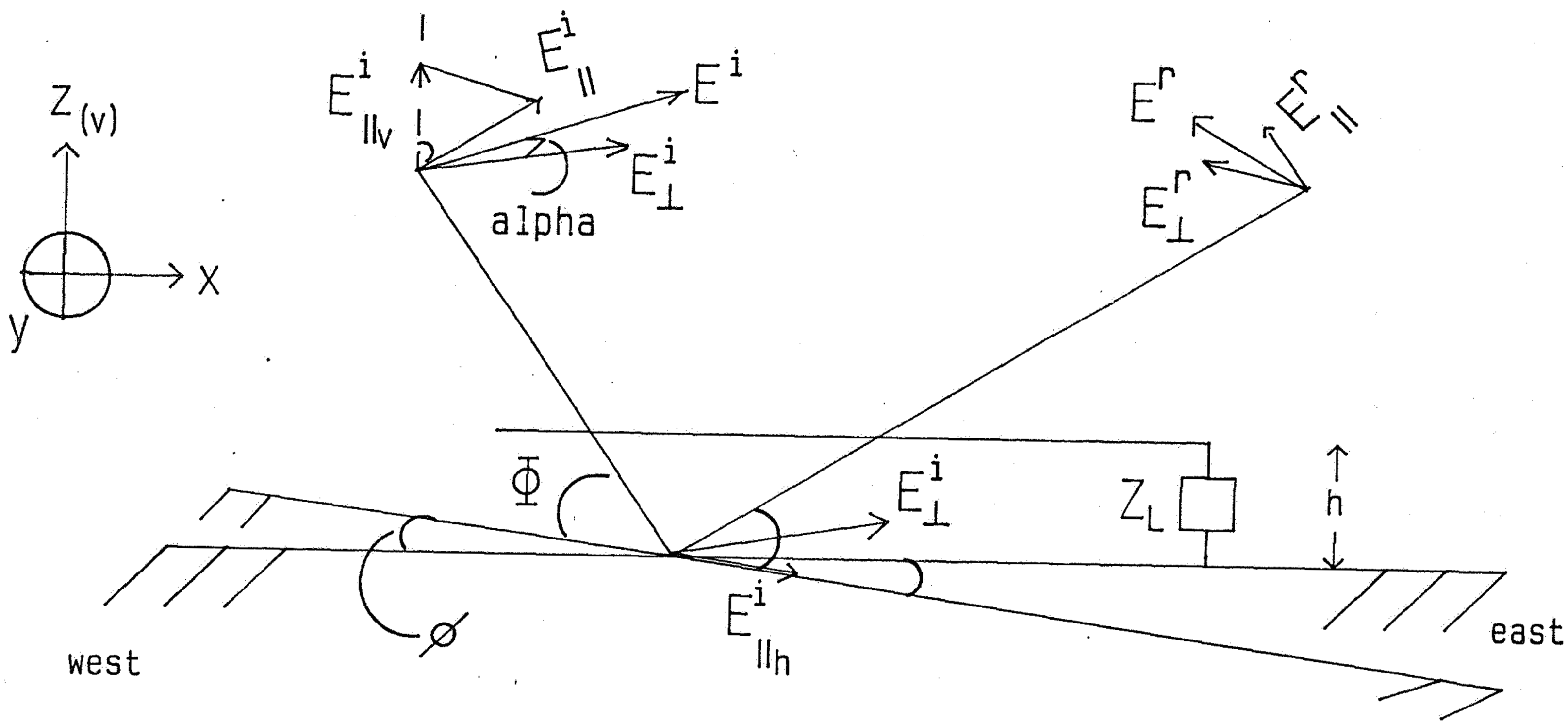

Figure 1. Geometry of an incident EM wave on an overhead power line. The direction angles α, ϕ, and Φ are also defined. E^i, $E^i_{\parallel}$, and $E^i_{\perp}$ are all in a plane perpendicular to propagation. Z_L is the load at either end of the power line which is at a height h above the ground.

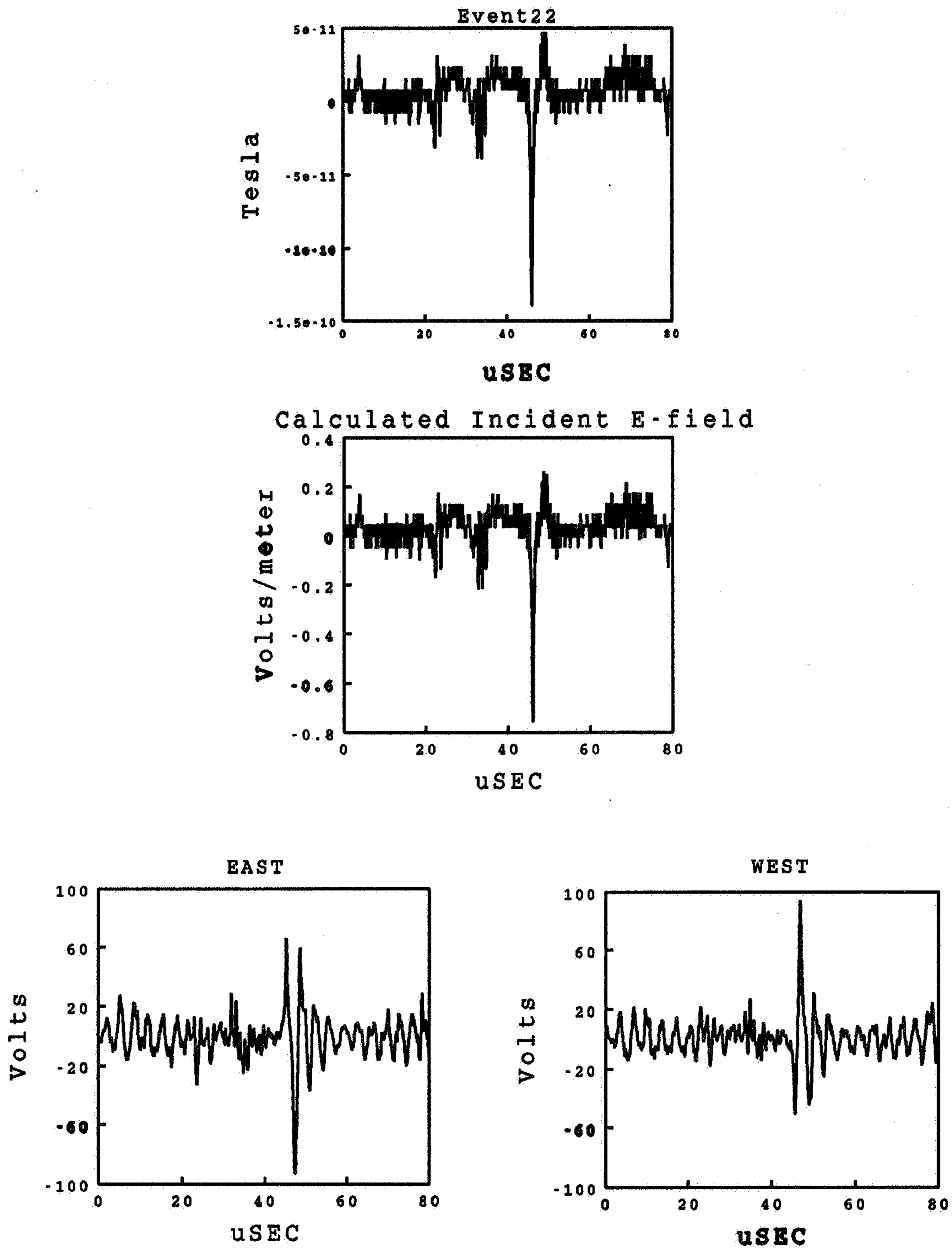

Figure 2. (top) Measured north–south component of the magnetic field, (middle) calculated incident electric field, (bottom) measured east and west end voltages.

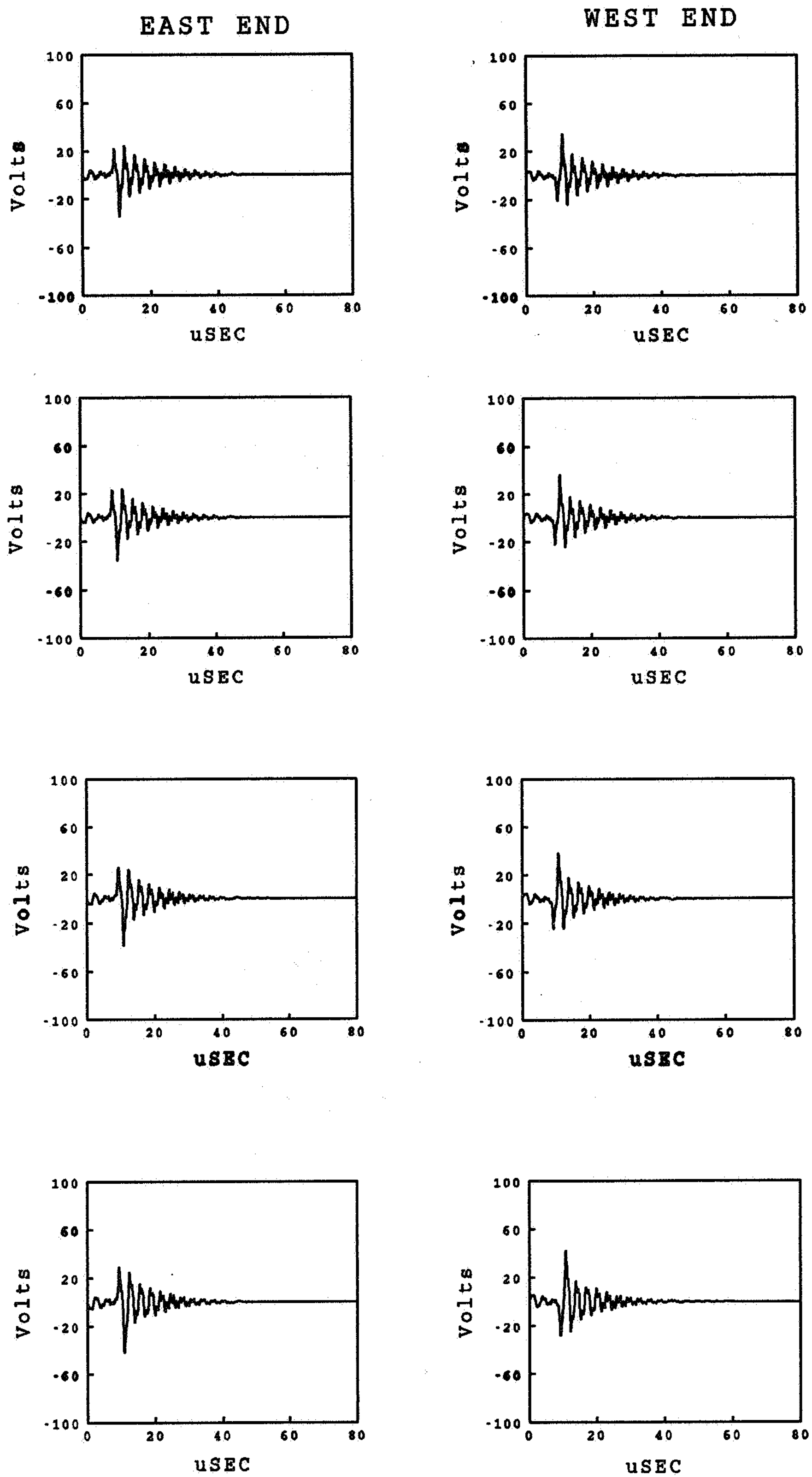

Figure 3. Calculated east and west end voltage responses: α = 350°, ϕ = 90°, Φ = 80°. From top to bottom, conductivity used is: 0.016 mho/m, 0.01 mho/m, 0.005 mho/m, and 0.0025 mho/m.

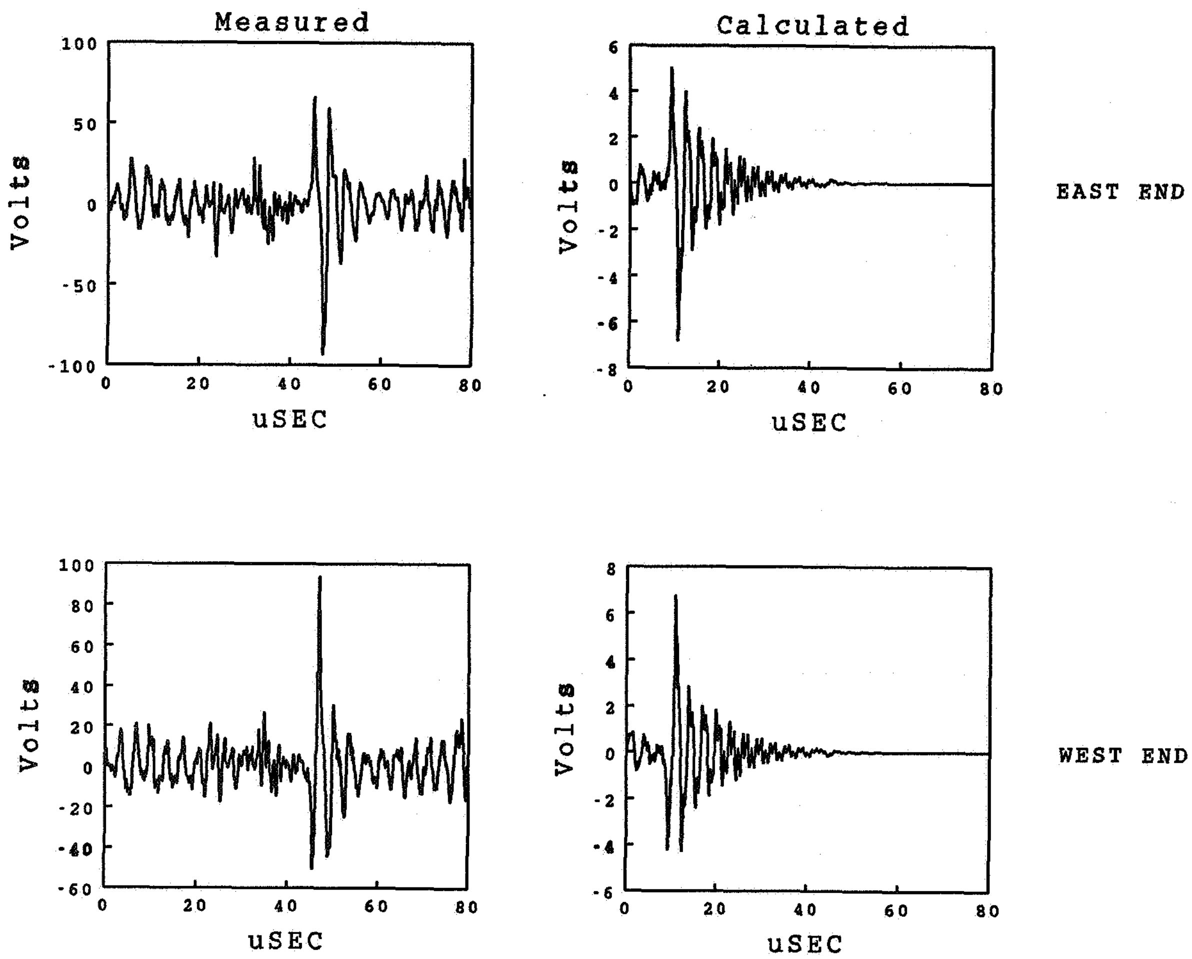

Figure 4. Measured and calculated voltage responses when the elevation angle is reduced to 40°. Conductivity is still 0.0025 mho/m. Note different scales on measured and calculated voltages.