Lightning Induced Disturbances in Buried Cables—Part II: Experiment and Model Validation

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***Abstract*—This paper presents experimental results obtained at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida during the summers of 2002 and 2003. Currents induced by triggered and natural lightning events were measured at the terminations of a buried power cable, in the cable shield, and in the inner cable conductor. Measurements of the horizontal component of the magnetic field above the ground surface for both natural and triggered lightning are also presented. For distant natural lightning events, locations of ground strike points were determined using the U.S. National Lightning Detection Network (NLDN).**

Based on the theoretical developments presented in Part I of this paper [14], the field-to-buried cable coupling equations are solved in both the time domain and in the frequency domain. The obtained experimental results are then used to validate the numerical simulations provided by the relevant developed codes.

***Index Terms*—LEMP-to-buried cables electromagnetic coupling, power cables, power system lightning effects, underground power distribution lines.**

I. Introduction

Even though extensive experimental investigations have been performed on the effect of nearby lightning on overhead lines (e.g., [1], [2]), to the best of our knowledge, such an experimental characterization for buried cables is not available in the scientific literature. This paper presents experimental results for buried cables obtained using rocket triggered lightning [3] at Camp Blanding, Florida, USA. The recorded data are used to test the theory and the developed computer code presented in Part I of this paper [14] to compute lightning induced voltages on a shielded buried cable.

The experimental results were obtained at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida, where, during the summers of 2002 [4] and 2003 [5], currents induced by triggered and natural lightning events were measured at both ends of a buried coaxial 15 kV power cable, both in the cable shield and in the inner conductor. Simultaneously, the horizontal magnetic field above the ground surface and, for triggered events, the lightning return stroke current at the channel base, were also measured. For the natural lightning events, the locations of ground strike points were determined using the U.S. National Lightning Detection Network (NLDN) [6].

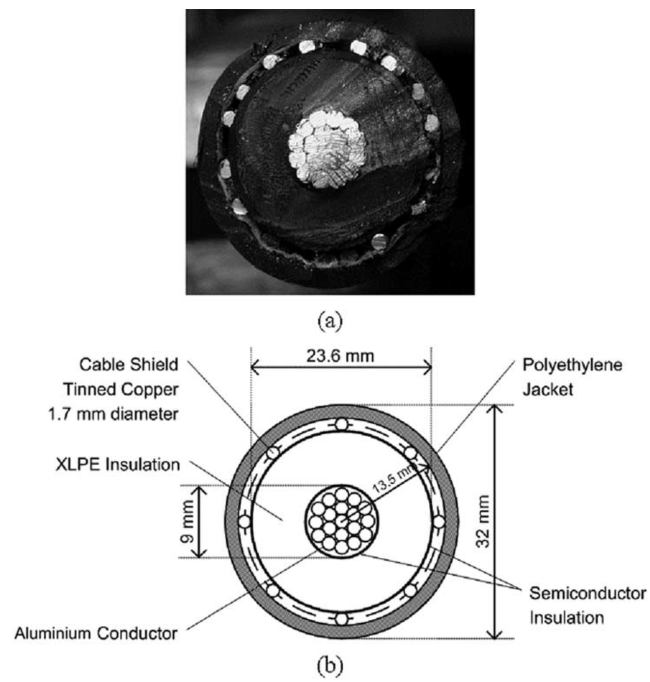

Fig. 1. Geometrical characteristics of the experimental buried cable. (a) Picture of the cross section. (b) Dimensions of the cross section.

II. Cable Characteristics

The underground cable is a 15 kV XLPE coaxial power cable, 133 m long, covered with an insulating jacket. The geometrical characteristics of the cable are given in Fig. 1. The cable is contained inside an 11 cm external diameter, 0.35 cm thickness PVC pipe buried at 0.9 m.

The transfer impedance of the cable (e.g., [7]) was measured at the EMC laboratory of the Swiss Federal Institute of Technology in Lausanne using a triaxial adapted measurement setup [8]. The results are presented in Fig. 2.

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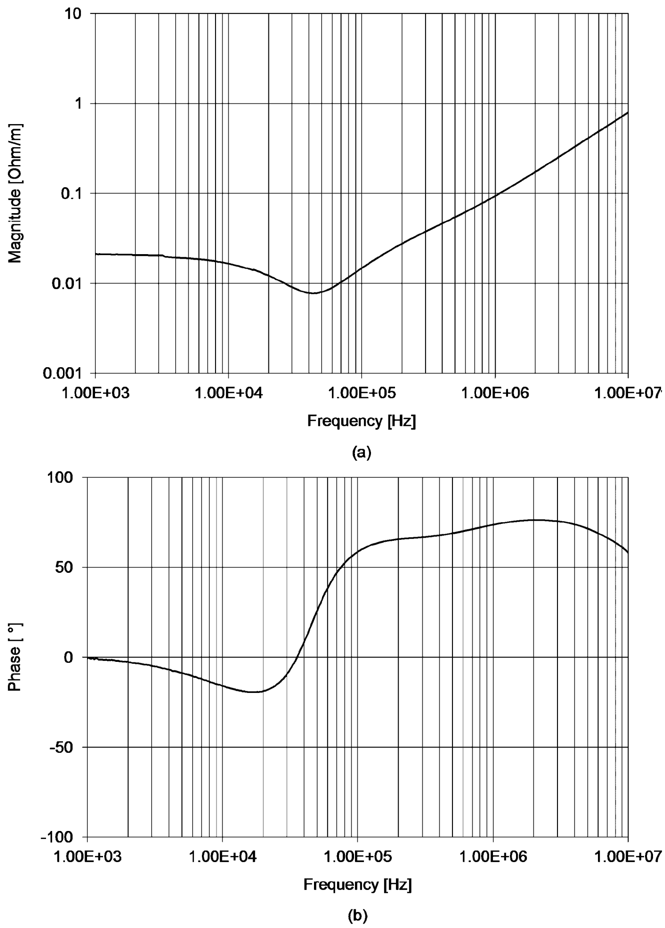

Fig. 2. Transfer impedance of the coaxial cable shown in Fig. 1. (a) Magnitude. (b) Phase.

The magnitude of the transfer impedance as a function of frequency exhibits the typical behavior, namely a decrease as the frequency increases from about 3–30 kHz due to the skin effect, and an increase in the higher frequency range due to the field penetration into the cable shield. It can be seen that the magnitude of the transfer impedance approaches a value of about 1 Ω/m at 10 MHz.

III. Experimental Setup

The topology of the experimental setup is shown in Fig. 3. The triggering rockets were launched using a mobile launcher, placed at different positions, as indicated in Fig. 3. The mobile launcher was installed on a bucket truck (see Fig. 4), grounded, and remotely controlled from the launch control trailer. The channel base current was measured using a 1.25 mΩ coaxial shunt (T&M Research Products, Inc., model R-5600-8) having a bandwidth of 0–12 MHz. Fiber optic links, with a 15 MHz bandwidth, were employed to relay the signals to the digitizer.

The 133-m cable extended between two instrument stations (IS1 and IS2), as illustrated in Fig. 3. The inner conductor was terminated at each end with a 50-Ω resistor located inside a metallic box (see Fig. 3), a value close to the surge impedance of the cable (about 58 Ω). The shield of the cable was connected directly to vertical ground electrodes at each of its extremities

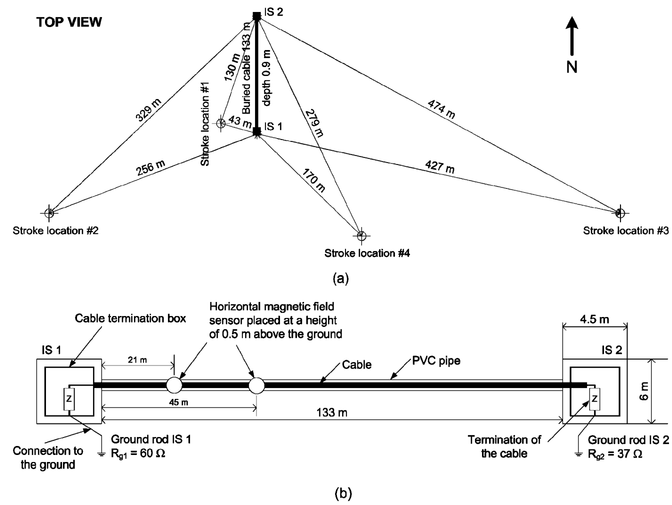

Fig. 3. (a) Positions of the four lightning strokes. (b) Buried cable experimental setup. The cable shield is connected to the ground rods at IS1 and IS2.

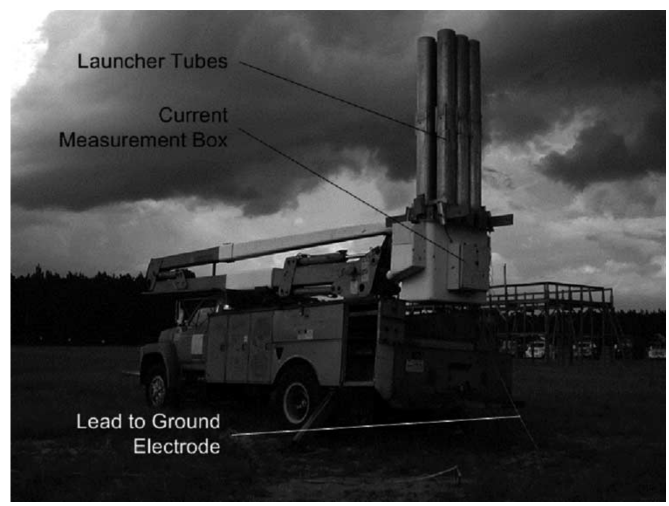

Fig. 4. Mobile launcher used to trigger lightning.

(at IS1 and IS2). The ground electrodes were copper cylindrical vertically driven rods of 12 m (IS1) and 24 m (IS2) in length, respectively. The measured value of DC grounding resistance as of August 2002 was 60 Ω for the ground electrode at IS1 and 37 Ω for the one at IS2. Although long term variation of the grounding resistance should be small, short term variation could be significant due to sporadic rainfall in Florida, particularly during the summer months [9], [10]. Due to the nonhomogeneity of the Camp Blanding sandy soil, different values for the ground conductivity have been obtained apparently depending on measurement location. A measured value of about $2.5 \cdot 10^{-4}$ S/m is given in [9]. On the other hand, we inferred a value of about $1.6 \cdot 10^{-3}$ S/m to $1.8 \cdot 10^{-3}$ S/m from the measurements of the DC grounding resistance of the ground rods and rod geometry. In addition, note that the ground conductivity depends strongly on the water content of the soil [11]. Longmire and Smith [12] have shown that an increase of the soil water content (due to rainfall) results in an increase in the ground conductivity of more that one order of magnitude.

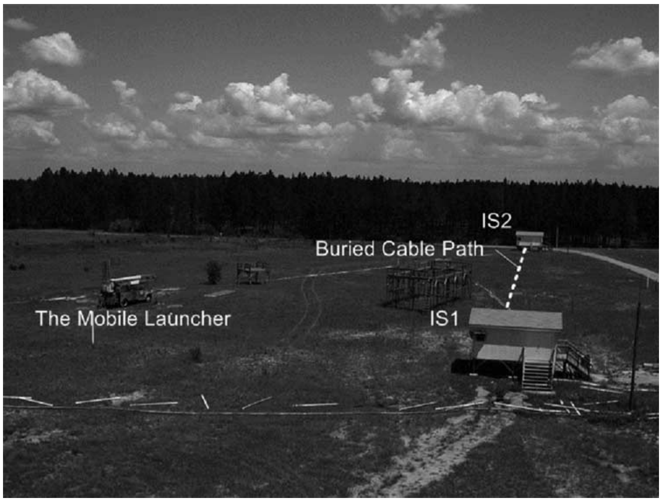

Fig. 5. Instrument stations IS1 and IS2, buried cable path, and position of the mobile launcher corresponding to stroke location #1.

During summer of 2002, both triggered and natural lightning events were recorded. Simultaneous measurements of lightning return stroke current (in the case of triggered lightning), horizontal magnetic field component perpendicular to the cable, and currents induced in the shield and in the inner conductor of the cable at the IS2 termination were obtained [4].

During summer of 2003, more experimental data were gathered using the same experimental setup for additional strike locations. Moreover, lightning induced currents were recorded at both ends of the cable [5]. Fig. 3 illustrates the four positions (stroke locations) for which experimental data were recorded. Positions #1, #2 and #3 correspond to the triggered events and position #4 to one close natural event. The following quantities were measured simultaneously: lightning return stroke current (in the case of triggered lightning only), horizontal magnetic field (horizontal component perpendicular to the cable), and currents induced in the shield and in the inner conductor of the cable.

The magnetic field was measured using a magnetic field sensor (TSN 245-H32, Thomson CSF) with an overall bandwidth of 1 kHz to 130 MHz, located at one of the two positions shown in Fig. 3.

The induced currents were measured using the following sensors: for the inner conductor, Eaton 112 current transformers with a bandwidth of 10 kHz to 200 MHz were used during the 2002 experiments, and Pearson 410 current transformers with a bandwidth of 1 Hz to 20 MHz were used in 2003. For the shield, Pearson 110 current transformers with a bandwidth of 1 Hz to 20 MHz were used both in 2002 and 2003.

The measured signals from all the sensors were relayed via optical fiber links to an 8 bit digitizing oscilloscope operating at 100 MSamples/s. The digitizer features a segmented memory which allows one to record waveforms for up to 10 strokes per lightning flash with a time window of 100 μs per stroke, in four channels (250 kbytes per channel).

Fig. 5 shows instrument stations IS1 and IS2, and the position of the mobile launcher corresponding to stroke location #1.

IV. Measurement Results

A. Induced Currents From Triggered Lightning

During experimental campaigns in 2002 and 2003, a total number of 15 flashes with 42 strokes were recorded. We present in this section three sets of typical experimental data obtained for stroke locations #1, #2, and #3, shown in Fig. 3.

1) Stroke Location #1 (Recorded on August 18th, 2002), 1st Return Stroke[1]*:* For this event, the magnetic field sensor was placed 45 m from IS1 along the path of the buried cable (see Fig. 3).

Fig. 6 presents simultaneous measurements of the lightning return stroke current [Fig. 6(a)], magnetic field [Fig. 6(b)], induced current in the cable shield at IS2 [Fig. 6(c)], and induced current in the inner conductor at IS2 [Fig. 6(d)]. Note that in the measured waveforms presented in this paper, the fiber and through-the-air time delays have not been accounted for. Additionally, the magnetic field waveform includes both leader and return-stroke portions.

One can see that the current induced in the cable shield reaches a peak value of 120 A. Its risetime is similar to that of the lightning channel base (incident) current. The shield current is characterized by a half-peak width of about 2 μs, significantly shorter than that of the incident current (about 40 μs). The current in the inner conductor has a relatively short duration, oscillatory waveshape with the first zero-to-peak risetime of about 300 ns and a zero-crossing time (the first one) of about 0.5 μs.

2) Stroke Location #2 (Recorded on July 22nd, 2003), 3rd Return Stroke: Fig. 7 presents the waveforms corresponding to the third return stroke of a four-stroke flash recorded on July 22nd, 2003. The stroke location was 256 m from IS1 and 329 m from IS2, as seen in Fig. 3.

Shown in Fig. 7 are simultaneous measurements of the lightning channel base (incident) current [Fig. 7(a)], induced currents in the cable shield at both ends [Fig. 7(b)] and induced currents in the inner conductor at both IS1 and IS2 [Fig. 7(c)]. In this case, the current induced in the cable shield [Fig. 7(b)] reached about 50 A for a stroke located over 250 m from one cable termination. The shield current is characterized by a half-peak width of about 3 μs, significantly shorter than that of the incident current (about 30 μs). The current exhibits a zero crossing at 5 μs.

The current in the inner conductor [Fig. 7(c)] has a bipolar waveshape with a zero-crossing time of about 2 μs. One can observe additionally that the amplitude of the shield current is larger at the cable end that is more distant from the stroke location (see Fig. 3).

3) Stroke Location #3 (Recorded on August 15th, 2003) 1st Return Stroke: Fig. 8 presents a set of measured waveforms for stroke location #3. The induced currents in the cable shield and in the inner conductor are again bipolar. The zero crossing time for the shield current is about 10 μs, whereas for the inner conductor current the zero crossing occurs at 3 μs. As for the stroke location #2, the amplitude of the shield current is larger

[1]Note that all strokes in classical triggered lightning are similar to subsequent strokes in natural lightning.

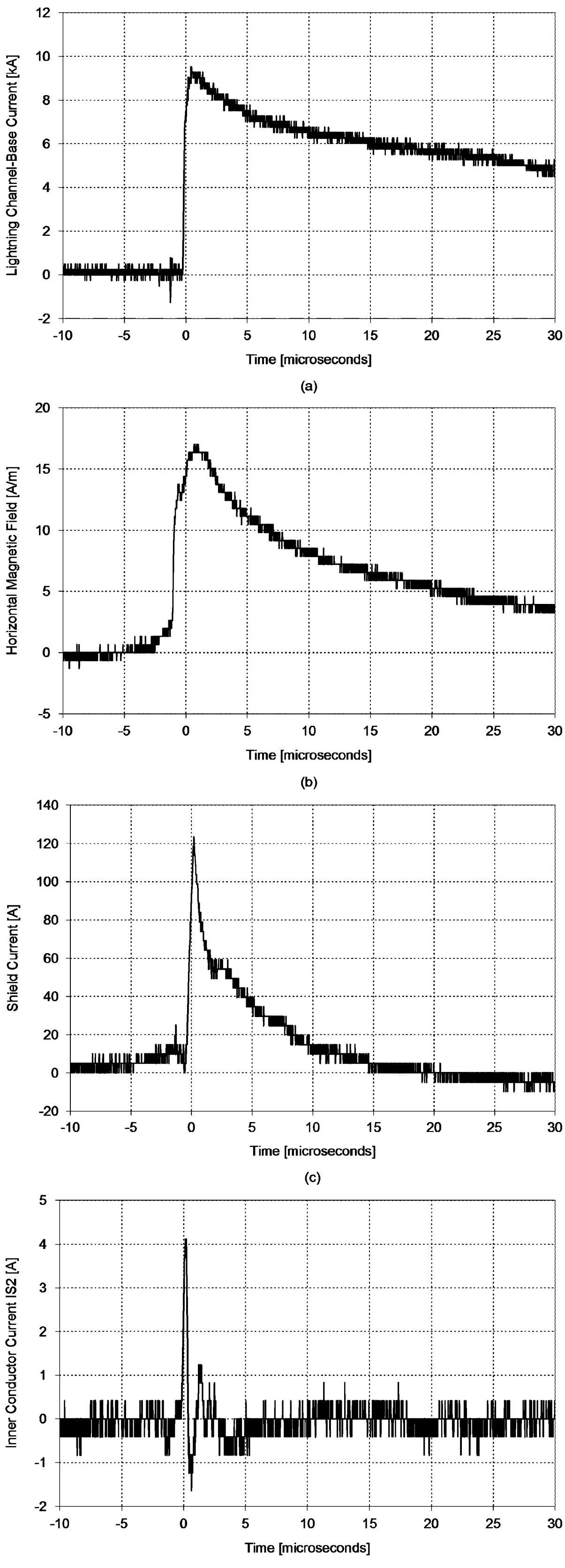

Fig. 6. Triggered lightning event recorded on August 18th, 2002. Stroke location #1. (a) Lightning channel base (incident) current. (b) Horizontal magnetic field (45 m from IS1). (c) Induced current in the cable shield at IS2. (d) Induced current in the inner conductor at IS2.

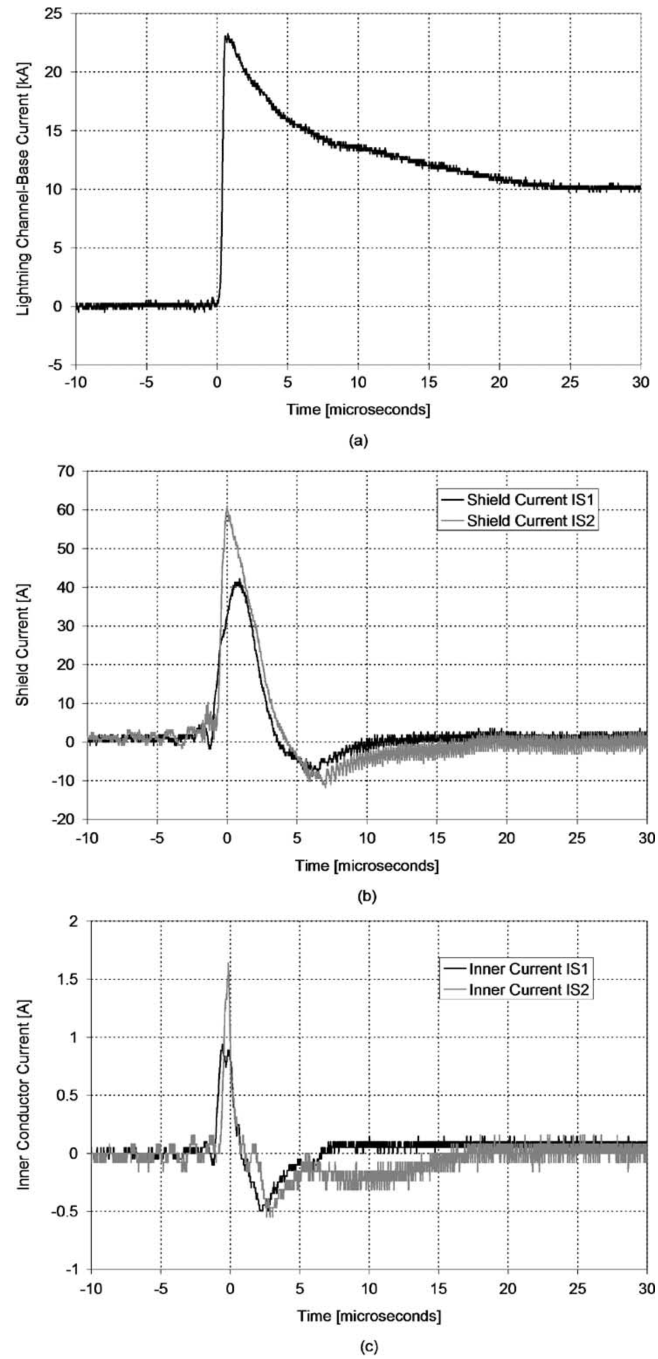

Fig. 7. Triggered lightning event recorded on July 22nd, 2003. Stroke location #2. (a) Lightning channel base (incident) current. (b) Induced currents in the cable shield at IS1 and IS2. (c) Induced currents in the inner conductor at IS1 and IS2.

at the cable end that is more distant from the stroke location (see Fig. 3).

B. Induced Currents From Close Natural Lightning

1) Stroke Location #4 (Recorded on July 18th, 2003), 8th Return Stroke: During the summer of 2003 experiment, a natural lightning flash containing more than ten strokes was recorded. A careful examination of the soil allowed us to find

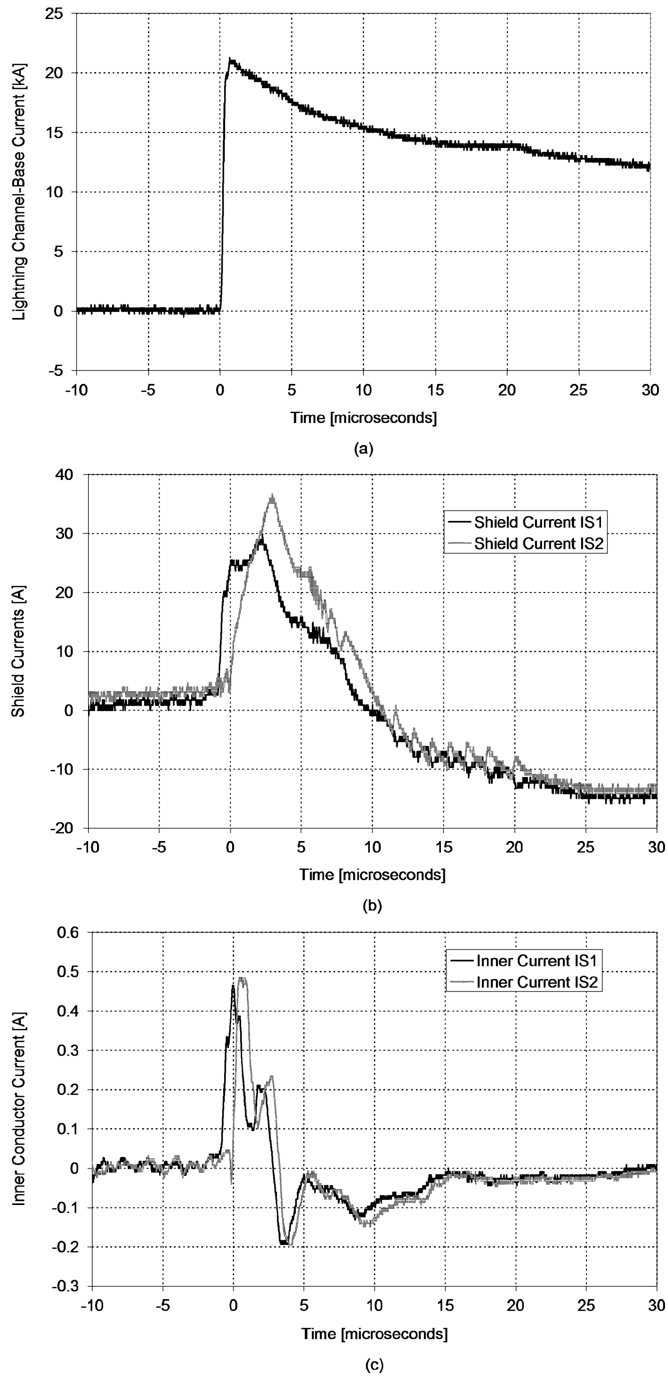

Fig. 8. Triggered lightning event recorded on August 15th, 2003. Stroke location #3. (a) Lightning channel base (incident) current. (b) Induced currents in the cable shield. (c) Induced currents in the inner conductor.

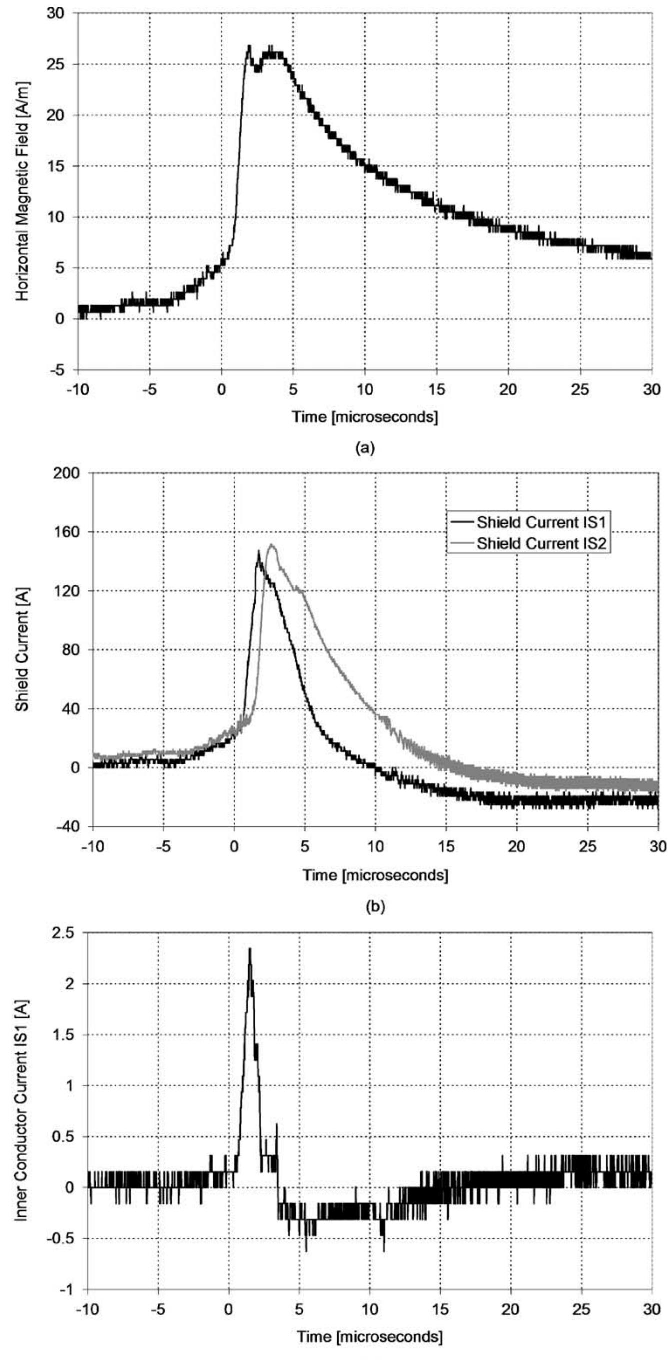

Fig. 9. Natural lightning event recorded on July 18th, 2003. Stroke location #4. (a) Horizontal magnetic field (21 m from IS1). (b) Induced currents in the cable shield. (c) Induced current in the inner conductor at IS1.

the channel termination point on ground, and the distances from IS1 and IS2 were estimated to be 170 and 279 m, respectively (see Fig. 3). The magnetic field sensor was placed 21 m from IS1 along the path of the buried cable (see Fig. 3).

Fig. 9 shows measured waveforms for the 8th return stroke of the flash. For this event, we do not have recorded inner conductor current at IS2 due to a failure of the measurement equipment. The estimated return stroke peak current (from the measured magnetic field) is 42 kA. Both the shield current and the inner conductor current are characterized by a bipolar waveshape with a zero crossing time of 10–15 μs for the shield current and 3 μs for the inner conductor current.

It is seen in the above typical examples that the induced current in the cable shield can reach relatively large values of about 100 A for stroke locations within 200 m of the cable. The induced currents in the cable shield and in the inner conductor are characterized by a significantly shorter duration than that of the corresponding incident current. Further, for the considered configurations, the induced currents in the shield and in the inner conductor exhibit bipolar waveshapes [except for the shield current shown in Fig. 6(c)].

C. Induced Currents From Distant Natural Lightning

In this section, we present two sets of data for which the ground strike point was determined by time matching our records to the output of the US National Lightning Detection Network (NLDN) [6].

The magnetic field sensor was placed 45 m from IS1 (see Fig. 3), oriented to measure primarily the magnetic field component perpendicular to the cable.

Fig. 10 presents data corresponding to the two natural events that occurred on August 26th, 2002 at 19:14:51 GMT (Strike #N1) and 19:32:12 GMT (Strike #N2), respectively. The positions of the two flashes relative to the orientation of the cable path are indicated in Fig. 11.

It is interesting to observe that for the distant natural events, the waveform of the induced current in the cable shield is very similar to the waveform of the magnetic field. This can be explained by considering the fact that the horizontal electric field along the buried cable [7] can be approximately related to the magnetic field through the surface impedance [13]. The relation is such that the horizontal electric field has a waveform similar to the time derivative of the magnetic field. Since the induced current in the cable shield is obtained by integrating the horizontal electric field along the cable (see Section III, Part I of this paper [14]) and since the far field is essentially radiation, the induced current should be expected to have a waveshape similar to that of the magnetic field.

V. Testing the Validity of the Simulation Codes

The models proposed in Part I of this paper [14] are implemented in two computer codes. The first is a time domain code in which the field-to-buried cable coupling equations are solved using the FDTD technique. This code allows the calculation of lightning induced voltages and currents along the cable shield. In the second code, the coupling equations are solved in the frequency domain. The frequency domain code allows in addition the computation of induced in the inner conductor of the coaxial cable. In both computer codes, the lightning return stroke electromagnetic field penetrating the ground is calculated using Cooray's expression [13], [14, eq. (9)].

In order to represent more complex terminations of the cable, the developed time-domain code has also been interfaced with the EMTP96 using the procedure described in [15], [16]. In particular, the numerical procedure for the calculation of the induced currents is carried out at each time step in two phases:

- The response of the cable is calculated using the FDTD method, and
- The task of solving the boundary conditions (which can involve rather complex differential equations) is assigned to the EMTP96.

In this section, the simulation codes will be tested against the experimental data for triggered lightning presented in Section IV.

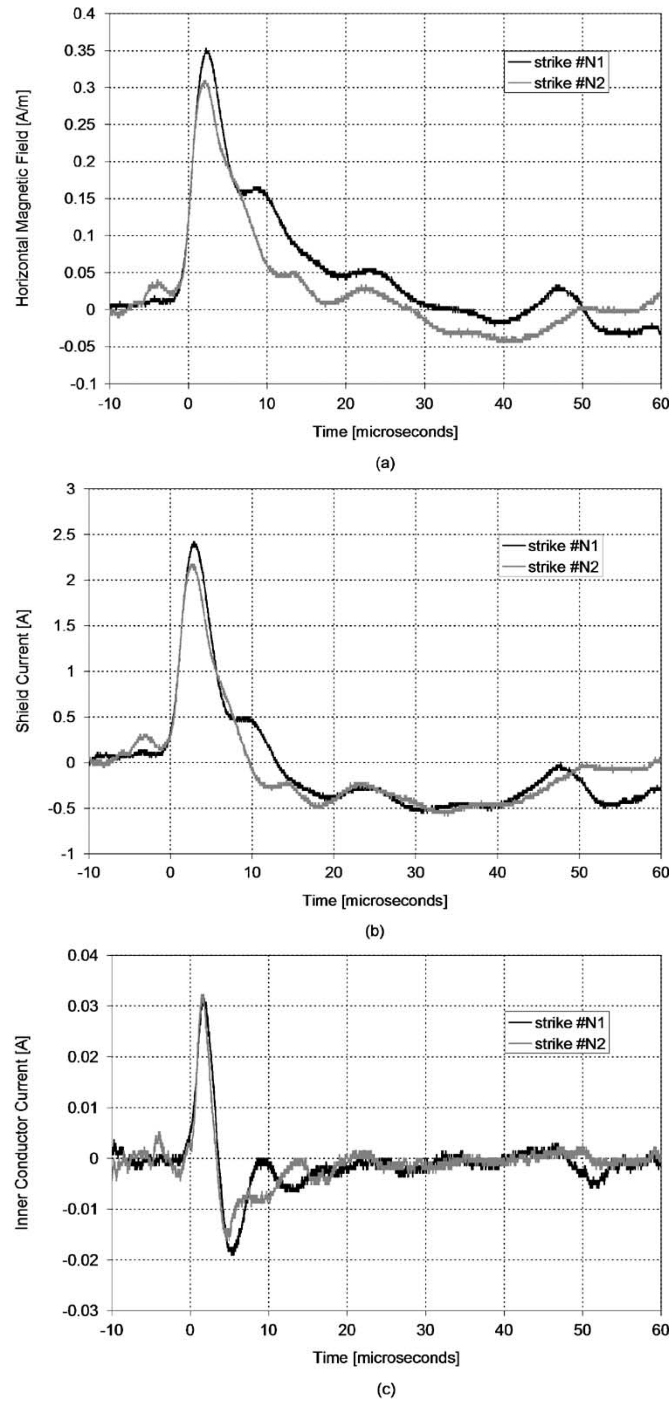

Fig. 10. Two distant natural lightning return strokes (from the two different flashes whose locations are shown in Fig. 11); black line: strike #N1; grey line: strike #N2. (a) Horizontal magnetic field (45 m from IS1). (b) Induced current in the shield at IS2. (c) Induced current in the inner conductor at IS2.

A. Analytical Representation of the Channel Base Current

Parameters of the analytical expression of the channel base current [17] were found using a genetic algorithm developed in Matlab [18].

Fig. 12 presents a comparison between measured lightning return stroke current waveforms for triggered lightning events considered in Section IV-A and their analytical representations using the sum of two Heidler functions [17]. Parameters of the

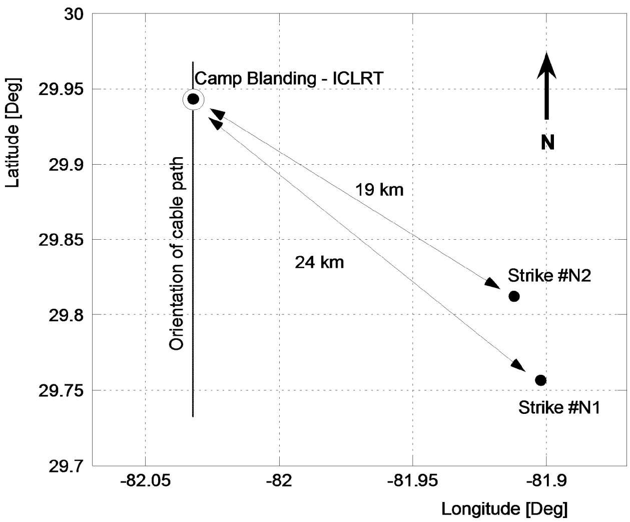

Fig. 11. Distant natural lightning strike locations relative to the orientation of the buried cable path.

Heidler functions are also given in Fig. 12. It can be seen that the measured channel base current can be represented in an accurate way using the sum of two Heidler functions.

B. Determination of Cable Parameters

The cable parameters are calculated considering the presence of the PVC pipe (see Fig. 13), making use of the EMTP Cable Constants routine [19]. The Cable Constants routine calculates the resistance, inductance, conductance, and capacitance of underground cables (e.g., single core or pipe-type). These routines can also be used to generate EMTP models for these cables, for either transient or frequency scan. The values obtained for the per-unit-length inductance and capacitance of the cable are: $L = 1.55 \cdot 10^{-7}$ H/m, $C = 7.17 \cdot 10^{-11}$ ($G = 0$ S/m).

In the simulations, values of $\sigma_g = 3 \cdot 10^{-3}$ S/m and $\varepsilon_{\rm rg} = 10$ have been assumed for the ground conductivity and relative permittivity, respectively. The cylindrical grounding rods, placed at both cable terminations and connected to the cable shield, were treated in a first approximation as simple resistances, each with a value equal to the DC grounding resistance of the rod. A more realistic model based on a lumped parameter circuit approach [15], [16], [20], illustrated in Fig. 14, was also used. The model comprised up to 50 RLC elements. However, no significant differences were observed between induced currents calculated using the two models for the ground rods.

C. Comparison Between Simulations and Measurements

1) Strike Location #1 (Recorded on August 18, 2002) 1st Return Stroke: Fig. 15 presents a comparison between the measured and computed horizontal magnetic field for the event recorded on August 18, 2002, strike location #1 (see Fig. 3). As previously mentioned, the magnetic field sensor was located above the cable path 45 m from the instrument station IS1. The calculation has been performed adopting the MTLE model [22], [23] for the spatial-temporal distribution of the lightning current and assuming an exponential decay height constant $\lambda = 2$ km and a return stroke speed $\nu = 1.3 \cdot 10^8$ m/s. Note that the initial part (between -10 to 0 μs) of the measured magnetic field waveform is due to the leader phase and hence is not reproduced by the return stroke model. Fig. 16 presents the calculated distribution of the horizontal electric field along the cable (at a

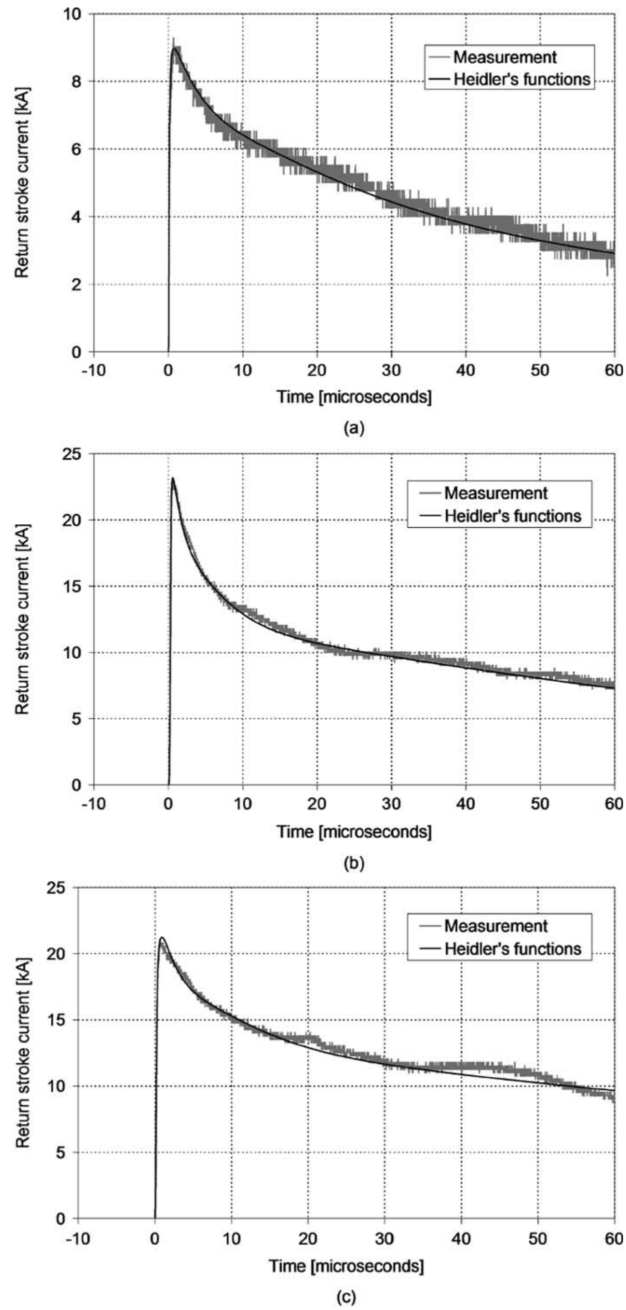

Fig. 12. Comparison between the measured return stroke current and its analytical representation using the sum of two Heidler functions. (a) Triggered lightning recorded on 18th Aug. 2002, 1st return stroke (stroke location #1), $I_{01} = 8.5$ kA, $\tau_{11} = 0.12$ μs, $\tau_{21} = 14$ μs, $n_1 = 2$, $I_{02} = 3.2$ kA, $\tau_{12} = 14$ μs, $\tau_{22} = 95$ μs, $n_2 = 2$. (b) Triggered lightning recorded on 22nd Jul. 2003, 3rd return stroke (stroke location #2), $I_{01} = 23.1$ kA, $\tau_{11} = 0.28$ μs, $\tau_{21} = 4.74$ μs, $n_1 = 5$, $I_{02} = 9.7$ kA, $\tau_{12} = 5$ μs, $\tau_{22} = 100$ μs, $n_2 = 5$. (c) Triggered lightning recorded on 15th Aug. 2003, 2nd return stroke (stroke location #3), $I_{01} = 19.8$ kA, $\tau_{11} = 0.21$ μs, $\tau_{21} = 7.84$ μs, $n_1 = 2$, $I_{02} = 10.5$ kA, $\tau_{12} = 7.86$ μs, $\tau_{22} = 157$ μs, $n_2 = 2$.

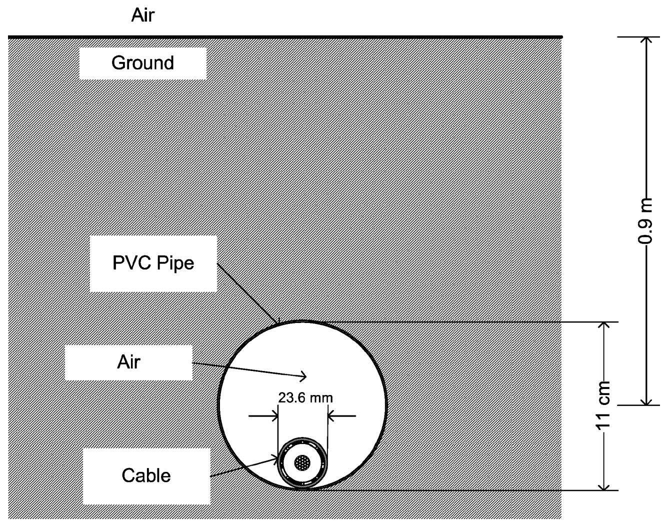

Fig. 13. Geometry of the buried cable.

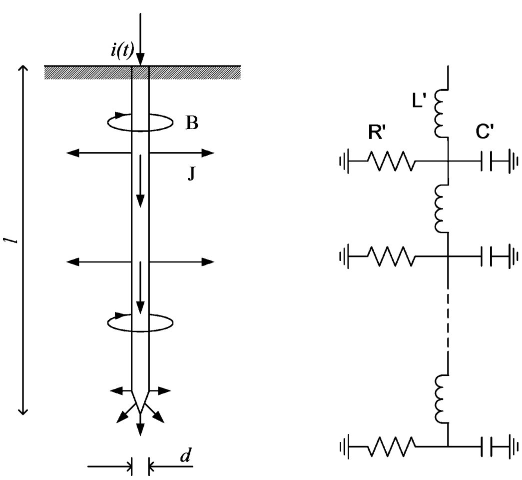

Fig. 14. Lumped parameters representation of grounding rods. Adapted from [21].

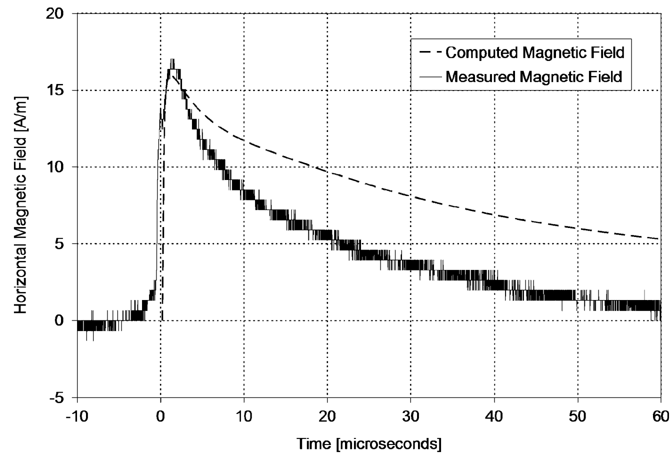

Fig. 15. Comparison between the measured and calculated horizontal magnetic fields for the case of the strike location #1. The magnetic field sensor was placed 45 m from IS1 (see Fig. 3). The leader part which appears in the measured horizontal magnetic field is not reproduced by the return stroke model. The corresponding current waveform is shown in Figs. 6(a) and 12(a).

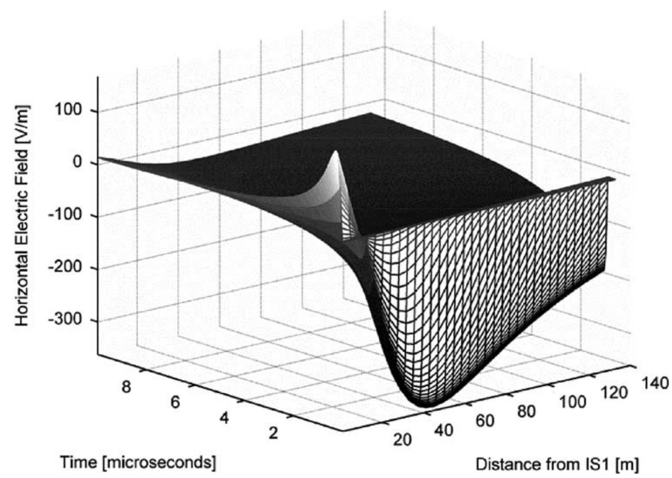

Fig. 16. Calculated horizontal electric field distribution along the buried cable at the cable depth (0.9 m), strike location #1.

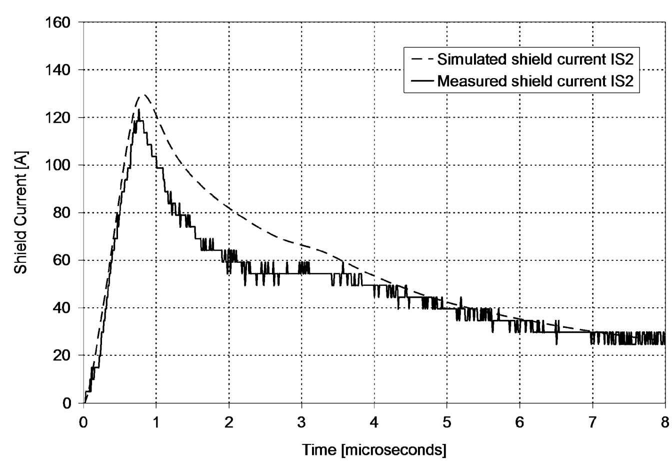

Fig. 17. Comparison between experimental and simulation results for the lightning induced currents in the shield of the experimental cable for the first return stroke of a single-stroke flash recorded on August 18th, 2002; strike location #1 (see Fig. 3).

depth of 0.9 m). The horizontal electric field component along the cable generated by lightning is characterized by a bipolar waveshape with a zero crossing which occurs at the point nearest to the stroke location. The calculated horizontal electric field reaches a maximum amplitude of nearly 400 V/m (absolute value).

A comparison between the measured currents in the cable shield at the IS2 termination, and those predicted by the time domain code is presented in Fig. 17. It can be seen that the simulation results are in very good agreement with experimental data. For this case, from the 2002 experiments, no measured currents at IS1 are available.

2) Strike Location #2 (Recorded on July 22nd, 2003), 3rd Return Stroke: Fig. 18 presents the distribution of the horizontal electric field along the cable (at a depth of 0.9 m), for strike location #2 (see Fig. 3). The horizontal field reaches an amplitude of about 100 V/m (absolute value) and its half peak width is about 3.5 μs.

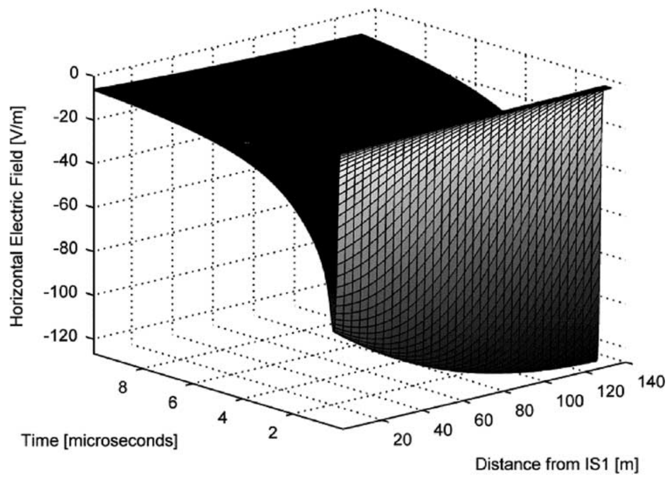

Fig. 18. Calculated horizontal electric field distribution along the buried cable (0.9 m depth).

Fig. 19 presents comparisons between the experimental data and the simulation results obtained using the developed time domain code for lightning induced currents in the shield of the experimental cable for the strike location #2 (see Fig. 3). The results are given for the observation points located at both terminations of the experimental cable.

It can be seen that the simulations are in reasonable agreement with experimental data. In particular, the early time response of the cable and the peak value of the induced current are very well reproduced by the simulations.

Noticeable differences appear, however, for the late time response. These disagreements can be attributed to simplifying assumptions of the model, uncertainties in the knowledge of the ground electrical parameters and their possible nonhomogeneities, as well as in the representation of the ground rods. In addition, the cable shield was connected to the ground rods using a metallic strip, introducing an additional impedance. Finally, at both ends of the buried cable, a vertical portion of the cable (about 2 m) was located above ground (up to the termination boxes). Although the vertical part of the cable was shielded by using meshed screen to minimize the electromagnetic field coupling to it [4], a contribution from a direct coupling to these vertical cable sections cannot be totally ruled out.

The frequency domain program described in Part I of this paper [14] was also used, and the results have been compared with the data. For the case of the lightning induced currents recorded on July 22nd, 2003, the comparison between the simulated shield current and the measurement is presented in Fig. 20. It can be seen that the results computed using the frequency-domain code are in excellent agreement with those obtained using the time-domain code (see Fig. 19).

3) Strike Location #3 (Recorded on August 15th, 2003) 1st Return Stroke: Fig. 21 present comparisons between the measured and computed shield currents for the event recorded on August 15th, 2003, strike location #3. The corresponding distribution of the horizontal electric field along the cable is shown in Fig. 22. For this case, the agreement between measured and simulated waveforms is less satisfactory compared to the two

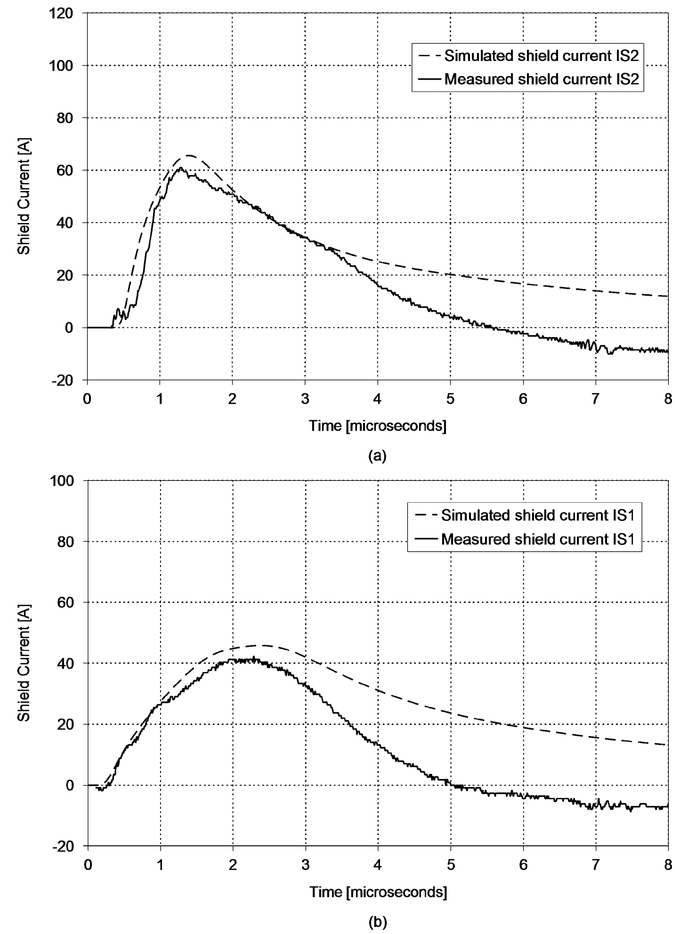

Fig. 19. Comparisons between experimental and simulation results for the lightning induced currents in the shield of the experimental cable for the third return stroke of a four-stroke flash recorded on July 22nd, 2003; strike location #2 (see Fig. 3). (a) At IS2. (b) At IS1.

other cases corresponding to strike locations #1 and #2. The observed discrepancies for this case can be partially explained by the fact that the propagation path from the strike location (#3) to the cable was longer than for the other strike locations, and included extensive swampy soil regions. In Fig. 21, we have shown simulation results obtained assuming different values for the ground conductivity, namely a) $1.7 \cdot 10^{-3}$ S/m, b) $3 \cdot 10^{-3}$ S/m and c) $2.5 \cdot 10^{-4}$ S/m. A better agreement with experimental data is seen for the conductivity values of the order of 10^{-3} S/m, particularly at early times.

This example shows the important effect of the ground conductivity on the amplitude and waveshape of the induced currents and the necessity to characterize accurately the ground electrical parameters to predict lightning induced disturbances in buried cables.

VI. Conclusion

Experimental results obtained at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida, in 2002 and 2003, have been presented and discussed.

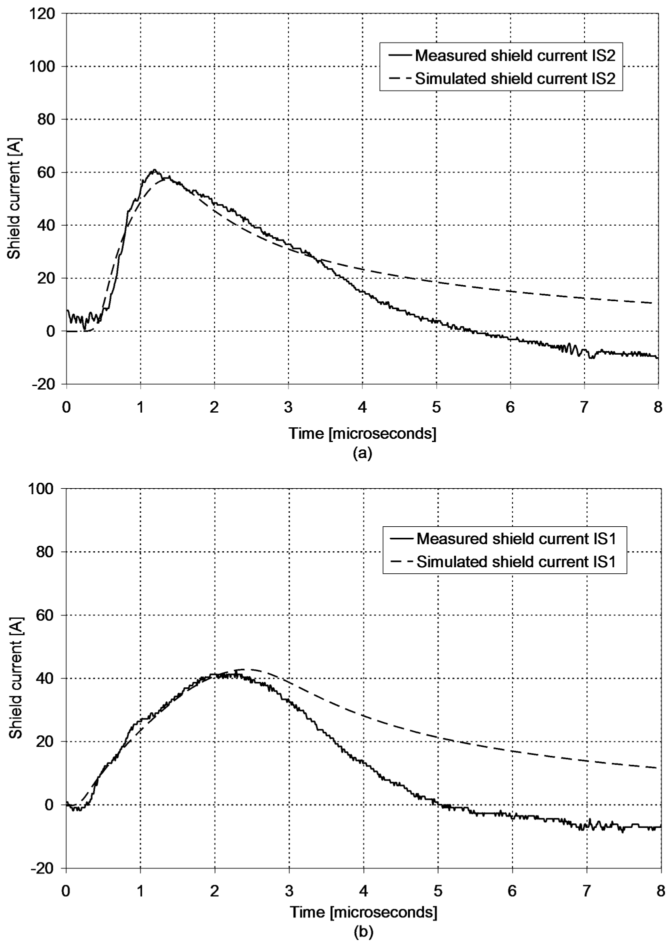

Fig. 20. Comparisons between experimental data corresponding to the strike location #2 (see Fig. 3) and simulation results obtained using the frequency-domain code described in Part I. (a) At IS2. (b) At IS1.

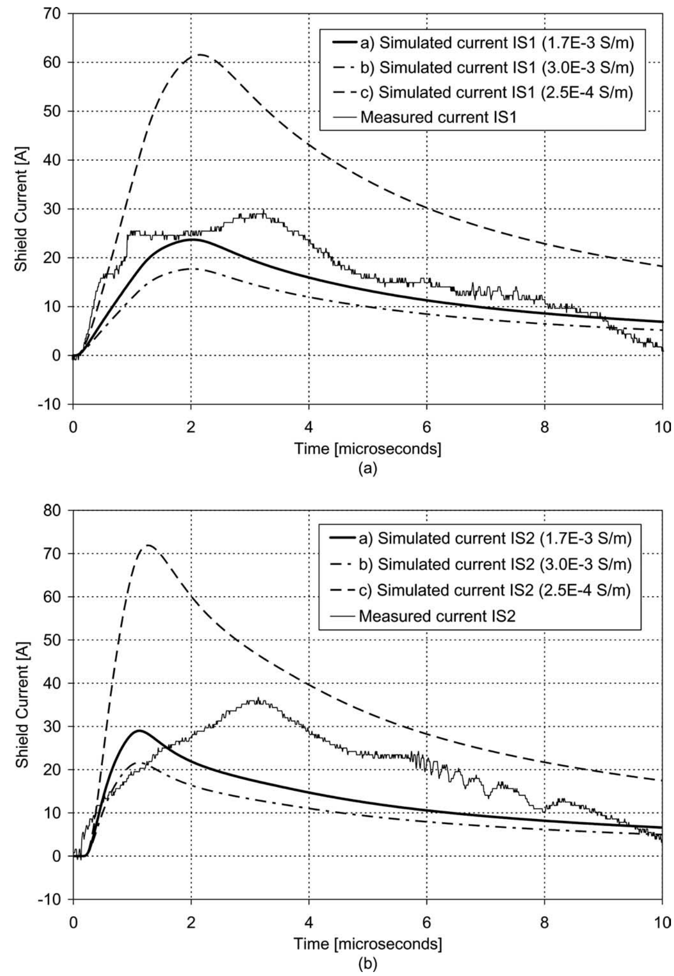

Fig. 21. Comparisons between experimental and simulation results for the lightning induced currents in the shield of the experimental cable for the first return stroke of the flash recorded on August 15th, 2003; strike location #3 (see Fig. 3). The computations have been performed for different ground conductivities, namely: $1.7 \cdot 10^{-3}$ S/m, $3 \cdot 10^{-3}$ S/m and $2.5 \cdot 10^{-4}$ S/m. (a) At IS1. (b) At IS2.

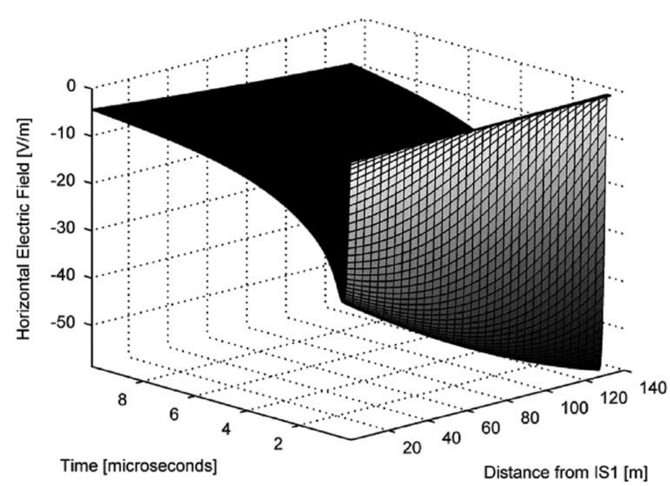

Fig. 22. Horizontal electric field distribution along the buried cable at the cable depth (0.9 m), strike location #3, calculated for ground conductivity of $1.7 \cdot 10^{-3}$ S/m.

Currents induced by triggered and natural lightning events were measured at the ends of a buried coaxial cable, both in the cable shield and in the inner conductor. The horizontal magnetic field above the ground surface was also measured. Additionally, two distant natural lightning events have been recorded in 2002 and one close natural lightning event has been recorded in 2003. For the distant natural lightning events recorded in 2002, the lightning locations were determined using the U.S. National Lightning Detection Network (NLDN).

The obtained experimental data have been used to test the theoretical models and the developed time-domain and frequency-domain computer codes. In general, a reasonably good agreement has been found between numerical simulations and experimentally recorded waveforms. In particular, the early time response of the cable and the peak value of the induced currents were generally well reproduced by the simulations. Possible causes explaining the observed disagreement are the simplifying assumptions of the model, uncertainties in the knowledge of the ground electrical parameters and their possible nonhomogeneities, and the representation of the ground rods and direct coupling of lightning electromagnetic fields to above-ground vertical sections of the cable. Further research is needed in this direction.

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