Current and Electromagnetic Field Associated With Lightning–Return Strokes to Tall Towers

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***Abstract*—In this paper, an analysis of electric and magnetic fields radiated by lightning first and subsequent return strokes to tall towers is presented. The contributions of the various components of the fields, namely, static, induction, and radiation for the electric field, and induction and radiation for the magnetic field are illustrated and discussed. It is shown in particular that the presence of a tower tends, in general, to increase substantially the electric and magnetic field peaks and their derivatives. This increase is mainly caused by the presence of two oppositely propagating current wavefronts originating from the tower top and by the very high-propagation velocity of current pulses within the tower (practically at the speed of light), and depends essentially on the wavefront steepness of the channel-base current. Because of the last factor, the increase of the field magnitudes is found to be significantly higher for subsequent return strokes, which are characterized by much faster risetimes compared to first return strokes. Furthermore, the presented results are shown to be consistent with recent experimental observations of current in lightning strokes to the Toronto CN Tower and of the associated electric and magnetic fields measured 2 km away. These findings partially explain the fact that subsequent return strokes characterized by lower current peaks but higher front steepnesses and return stroke speeds may result in higher field peaks. The results obtained in this study have important implications in electromagnetic compatibility. It is found that lightning strikes to tall metallic objects (towers, rods, etc.) lead to increased electromagnetic field disturbances. Also, subsequent return strokes are to be considered an even more important source of electromagnetic interferences than first return strokes. Indeed, electromagnetic fields from subsequent strokes are characterized by faster fronts and additionally, they may reach greater peaks than first strokes. Lastly, findings of this study emphasize the difficulty of extracting reliable lightning return stroke current information from remote electromagnetic field measurements using oversimplified formulae.**

***Index Terms*—Lightning, lightning electromagnetic pulse, lightning at tall structures, lightning-return stroke current.**

Manuscript received April 20, 2000; revised December 10, 2000. This paper was supported in part by the Swiss National Science Foundation, in part by the Natural Sciences and Engineering Research Council of Canada, and in part by the Italian Ministry of University and Scientific Research. This paper was presented in part at the 24th International Conference on Lightning Protection (ICLP), Birmingham, U.K., September 1998.

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Publisher Item Identifier S 0018-9375(01)07130-7.

I. Introduction

INFORMATION about lightning current parameters either comes from direct measurements, using, for example tall instrumented towers, or is based on quantification of lightning electromagnetic fields from which lightning currents are inferred adopting some empirical [1], [2] or theoretical [3] relations. Experimental observations and theoretical investigations have shown that the presence of an elevated strike object, such as a tall tower, could affect substantially lightning currents and their radiated electromagnetic fields (e.g., [4]–[14]). Accurate knowledge of lightning electromagnetic fields is essential for achieving an efficient insulation design of electric-power networks and for determining electromagnetic compatibility requirements of telecommunication systems, as many lightning-caused disturbances are due to lightning electromagnetic fields (e.g., lightning-induced overvoltages [15]).

In this paper, an analysis of electric and magnetic fields radiated by lightning return strokes to a tall tower is presented. Using the modified transmission line (MTL) model[1] Reference [16], [17], recently extended to take into account the presence of an elevated strike object [9], radiated electric and magnetic field waveforms are computed and analyzed. In the analysis, two channel-base current waveshapes, corresponding respectively to typical first and subsequent return strokes, are utilized. The effect of the presence of the tower on the magnitude and shape of 2-km distant fields is investigated, and the contributions of various field components, namely, static, induction and radiation for the electric field, and induction and radiation for the magnetic field are illustrated and discussed. Finally, electromagnetic compatibility implications of the theoretical findings are considered, and some explanations are given on recent experimental observations of lightning flashes to the CN Tower.

II. Computation of Radiated Electric and Magnetic Fields

A. Electromagnetic Field Radiated by a Vertical Antenna Above Ground

In our computations, we consider both, the lightning-return stroke channel and the elevated strike object, as vertical antennas above a perfectly conducting ground. At a general point in free space, the expressions for the vertical electric and azimuthal magnetic-field components, originated by a vertical

[1]The MTL model proposed in [16], [17] has been recently referred to as the MTLE model [18].

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dipole of infinitesimal length dz' along the z axis and at a height z' [19] are given by

$$dE_z(r, \phi, z, z', t) = \frac{dz'}{4\pi\varepsilon_o}\left[\frac{2(z-z')^2 - r^2}{R^5}\int_{R/c}^{t} i(z', \tau - R/c)\,d\tau + \frac{2(z-z')^2 - r^2}{cR^4}\, i(z', t - R/c) - \frac{r^2}{c^2R^3}\frac{\partial i(z', t-R/c)}{\partial t}\right] \quad (1)$$

$$dH_\phi(r, \phi, z, z', t) = \frac{dz'}{4\pi}\left[\frac{r}{R^3}\, i(z', t-R/c) + \frac{r}{cR^2}\frac{\partial i(z', t-R/c)}{\partial t}\right] \quad (2)$$

in which r, ϕ, z are the cylindrical coordinates of the observation point, R is the distance between the dipole and the observation point, $R = \sqrt{r^2 + (z'-z)^2}$, $i(z', t)$ is the dipole current, c is the speed of light, and, ε_o is the permittivity of free space. The first term in (1) is the electrostatic field, the second the electric induction or intermediate field, and the third the electric radiation field. In (2), the first term is the magnetic induction and the second the radiation field.

B. Lightning Return Stroke Model Including the Presence of an Elevated Strike Object

The problem of lightning-return strokes to tall towers was the subject of numerous recent studies (e.g., [4]–[14], [20], [21]). Different lightning-return stroke models, which, in their original forms, assume the return stroke to start at ground level, have been extended to take into account the presence of an elevated strike object [6], [9]–[11], [20]–[22]. In the present analysis, we will use the extended MTL model as described in [9]. For convenience, the main features of such a model are here summarized. As the leader descends toward the ground and reaches and attaches to an elevated object, an abrupt potential change generates a wave front (return stroke) that propagates toward the cloud. The current pulse $i_o(t)$ associated with the return-stroke phase starts at the top of the elevated object and propagates upward at the return stroke velocity v and with an exponentially-decreasing current amplitude, in accordance with the MTL model. Simultaneously, a similar current pulse $i_o(t)$ is assumed to be injected by the lightning channel at the top of the object. The object is modeled as an ideal transmission line characterized by a height h and reflection coefficients ρ_t and ρ_g, at its top and ground respectively. These reflection coefficients are assumed to be constant and independent of frequency.[2] The "noncontaminated"[3] return-stroke current pulse $i_o(t)$ travels downward the object at the speed of light and is first reflected at the bottom of the object (and part of it is transmitted to ground).[4] The reflected wave travels upward and is reflected at the top of the object (and part of it is transmitted to the lightning channel). This multiple-reflection process along the elevated strike object, assumed lossless, continues until the energy of the pulse dissipates in the ground and in the lightning channel [see (3)]. Concerning the current distribution in the lightning channel above the strike object, we assume that it can be described by the MTL return stroke current model, in that the current pulse $i_o(t)$ propagates upward in the channel with exponentially decreasing amplitude. This attenuation is not viewed as due to losses in the channel but is rather to take account of the effect of the distribution of charge stored in the corona sheath of the leader and subsequently discharged during the return stroke phase [25]. Clearly, the expression of the spatial-temporal distribution of the current along the channel has also to account for the portions of the pulses refracted into the channel following the multiple reflections at the ground and at the object top [see (4)].[5]

The expressions for the current distribution along the elevated strike object and the lightning return stroke channel, as derived in [9], [11], are given by

$$i(z, t) = \sum_{n=0}^{\infty}\left[\rho_g^n \rho_t^n i_o\left(t - \frac{h-z}{c} - \frac{2nh}{c}\right) + \rho_g^{n+1}\rho_t^n i_o\left(t - \frac{h+z}{c} - \frac{2nh}{c}\right)\right], \quad \text{for } 0 \le z \le h \quad (3)$$

$$i(z, t) = i_o\left(t - \frac{z-h}{v}\right)\exp\left(-\frac{z-h}{\lambda}\right) + \sum_{n=0}^{\infty}\left[\rho_g^n \rho_t^{n-1}(1+\rho_t) i_o\left(t - \frac{z-h}{c} - \frac{2nh}{c}\right)\right], \quad \text{for } z > h \quad (4)$$

where

ρ_t and ρ_g	reflection coefficients at the top of the object and at ground, respectively;
$i_o(t)$	"noncontaminated" return-stroke current pulse at the top of the object [11];
λ	decay constant of the MTL model [16], [17].

In the above expressions, possible reflections of the upward-propagating current pulses at the return-stroke wavefront [22], [23] are ignored, even though it is shown by Shostak *et al.* [26] that a better agreement with experimental data is found when considering such reflections.

Electromagnetic fields computed using the extended MTL model have been compared with experimental data and a satisfactory agreement has been found [9].

C. Non-Contaminated Channel-Base Current and Return Stroke Speed

In this study, we have considered two channel-base current waveforms corresponding, respectively, to typical first and

[2]Note that the reflection at ground level can be considered also in absence of any elevated strike object for return strokes initiating at ground level [23].

[3]Free of reflections from the struck object.

[4]While ground is assumed to be perfectly conducting for field computation (an approximation which is reasonable for the vertical electric and azimuthal magnetic fields [24]), its finite conductivity is taken into account when determining current reflections.

[5]Note that the MTL model can be seen also as the result of the contribution of a number of current sources distributed along the channel [25]. Each of these distributed sources delivers charges moving downward as the return stroke wavefront reaches its altitude. In this paper, however, we have disregarded for simplicity the reflections of these source contributions at the object top, an assumption that we consider will not alter qualitatively the obtained results, as it will be shown later.

TABLE I
PARAMETERS OF THE TWO HEIDLER'S FUNCTIONS USED TO REPRODUCE THE CHANNEL-BASE CURRENT WAVESHAPE

	I_{o1} (kA)	τ_{11} (μs)	τ_{21} (μs)	N_1	I_{o2} (kA)	τ_{12} (μs)	τ_{22} (μs)	N_2
First Stroke	28	1.8	95	2	-	-	-	-
Subsequent Stroke	10.7	0.25	2.5	2	6.5	2	230	2

subsequent return strokes, based on observations of Berger *et al.*[6] [27].

The "noncontaminated" channel-base currents are reproduced by means of a sum of two Heidler's functions [28]. The first return-stroke channel-base current is characterized by a peak value of 30 kA and a maximum steepness of 12 kA/μs, whereas the subsequent return stroke current has a peak value of 12 kA and a maximum steepness of 40 kA/μs. Note that recent experimental data from triggered lightning indicate values for the maximum steepness of about twice as large. However, the main results of this study remain qualitatively unchanged adopting a larger value than 40 kA/μs. The parameters of the Heidler's functions are given in Table I. Fig. 1 presents both channel-base current waveforms and their time-derivatives.

The values adopted for first and subsequent return-stroke speed within the lightning channel, are, respectively, 1.7×10^8 m/s and 1.9×10^8 m/s, corresponding to the average values for natural lightning over the bottom 500 m of the channel [29]. The decay constant λ in the MTL model is assumed to be equal to 2 km, a value which has been determined using experimental data [17].

III. SIMULATION RESULTS AND DISCUSSION

A. Lightning Return Stroke Initiated at Ground Level

Consider first the case of a return stroke initiated at ground level. Fig. 2(a) and (b) represents the first and the subsequent stroke vertical electric field computed at 2 km from the lightning channel. Such a value has been used since the distance from the CN tower to the *E*- and *H*-field measuring systems is 2 km (see [30]). The contributions of the static, induction and radiation components of the field are also included. It can be seen that the first-stroke field [Fig. 2(a)] is characterized by a fast rising part mainly due to the radiation component, followed by a ramp increase due to the static term. The rapid decrease of the radiation term for the subsequent-stroke field is responsible for the initial first peak [Fig. 2(b)].

Fig. 3(a) and (b) represents the azimuthal magnetic field waveforms for the same distance. The induction and radiation terms are separately included. In case of the magnetic field, the waves for both the first and the subsequent stroke show an increase to a peak and then a gradual decay, although for the subsequent stroke the peak is more pronounced and occurs at an earlier instant of time. For both waveforms, the typical azimuthal H-field is characterized by a fast rising part, again due to the radiation term, followed by a slight "hump" resulting from the induction component. The zero-crossing of the radiation term occurring at about 15 μs, is responsible for the faster decay of the total magnetic field in comparison to that of the induction term.

It can also be seen in Figs. 2 and 3 that the contribution of the radiation term to the total electric and magnetic field is more significant for the subsequent stroke. This is essentially due to

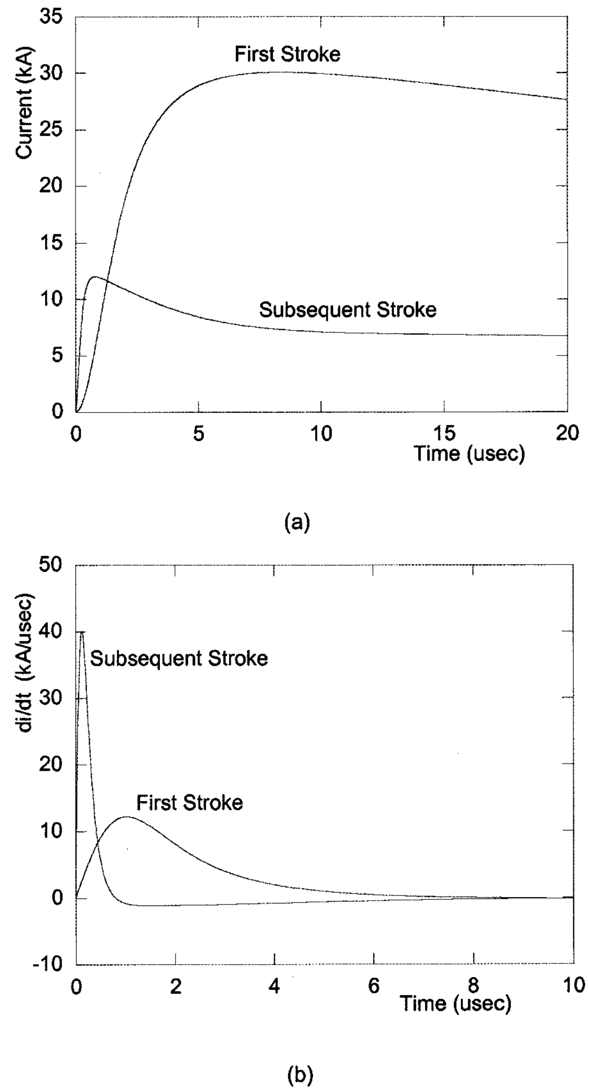

Fig. 1. (a) Idealized channel-base current. (b) Current derivative for typical first and subsequent strokes.

[6]It is worth noting that Berger's data are also obtained using instrumented towers. Hence, even though the various reflections are not discernible in measurement records due to the relatively short instrumented tower, some contamination might yet occur (see [11]). However, despite the above, in this study, we consider the Berger's current waveshapes as reference and exempt from tower contamination.

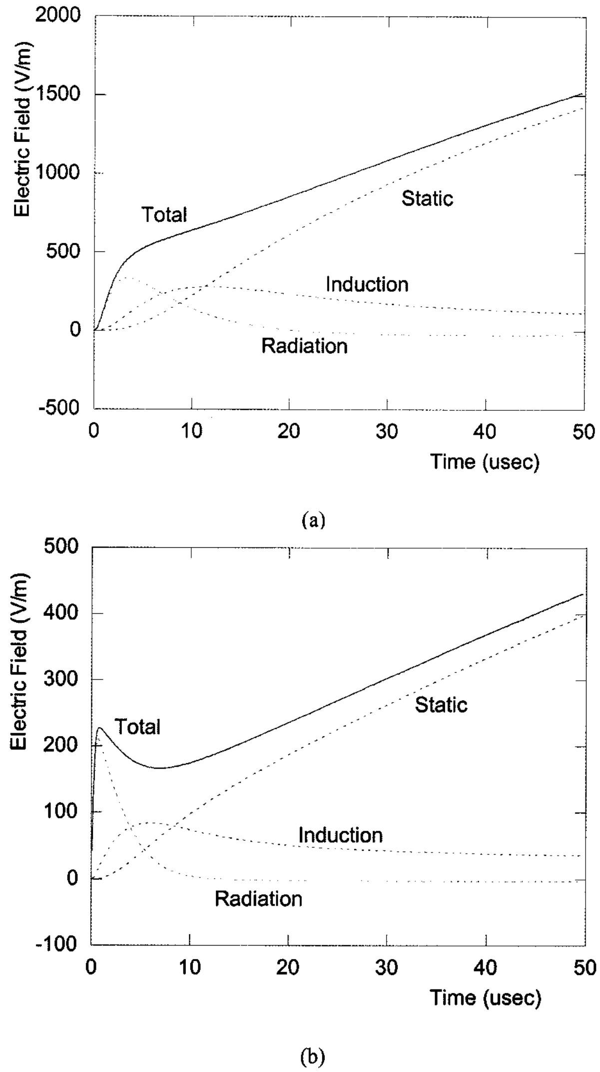

Fig. 2. Vertical electric field at 2 km from the lightning channel. Return stroke initiated at ground level. (a) First return stroke. (b) Subsequent return stroke.

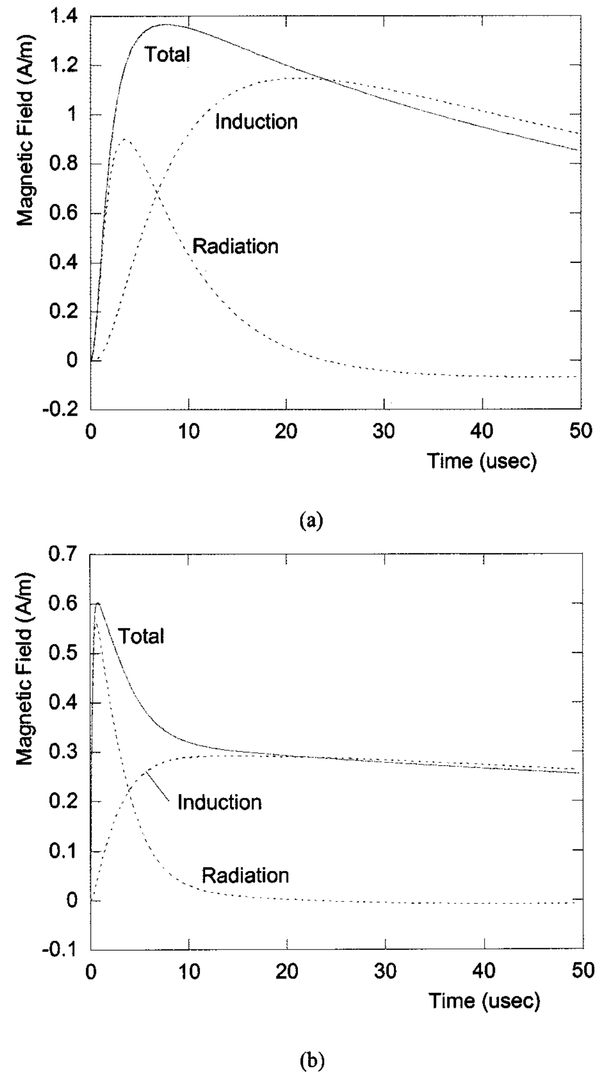

Fig. 3. Azimuthal magnetic field at 2 km from the lightning channel. Return stroke initiated at ground level. (a) First return stroke. (b) Subsequent return stroke.

the fact that subsequent strokes are characterized by faster return stroke speeds and higher front steepnesses of the current waveform.

It is worth mentioning that the contribution of the various components of the electric and magnetic fields depends strongly on the distance to the observation point. At closer observation points (less than a few hundred meters), the radiation-term contribution to the field magnitude is small compared to contributions from the static and induction terms. However, at distances beyond some tens of kilometers, the contribution of the radiation term will become predominant and the static and induction terms will have a negligible effect [31].

B. Lightning Return Stroke to a Tall Tower

Elevated Strike Object: Consider an elevated strike object characterized by a height of 553 m above ground, corresponding to the actual height of the CN Tower [32]. In this paper, the tower is modeled as a single, uniform and lossless transmission line (as described in Section II-B). Such an assumption does not alter the conclusions of our analysis, although it has been shown that for a more accurate representation of the tower, three or four transmission-line sections in cascade are to be considered [10], [33]. The reflection coefficients at the bottom and at the top of the tower are assumed to be 0.48 and -0.50, respectively. These values have been derived analyzing the fine structure of the lightning return stroke current measured at 474 m above ground level [10].

Current and Current Derivative Along the Tower: Fig. 4 shows the waveforms of current and current derivative evaluated at the top (553 m), the middle (276.5 m), and the base of the tower (0 m), starting from the typical first return stroke current[7] presented in Fig. 1, as the "noncontaminated current" at the top of the object and taking into account reflections at its two extremities.

It can be seen that moving toward the ground, the current experiences a higher peak value and a shorter time to its peak due to the contribution of the reflected wave at the ground level.

[7]Note that in the case of lightning strikes to a tall tower, the adopted first and subsequent stroke-current waveshapes represent, respectively, slow-front and fast-front strokes.

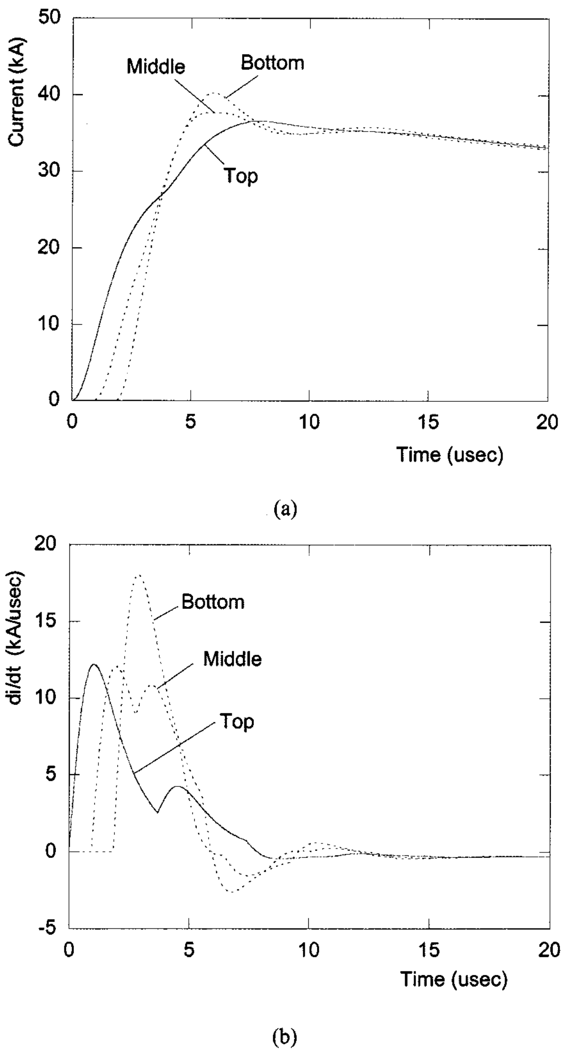

Fig. 4. (a) Current; and (b) current derivative along the strike object for a typical first return stroke.

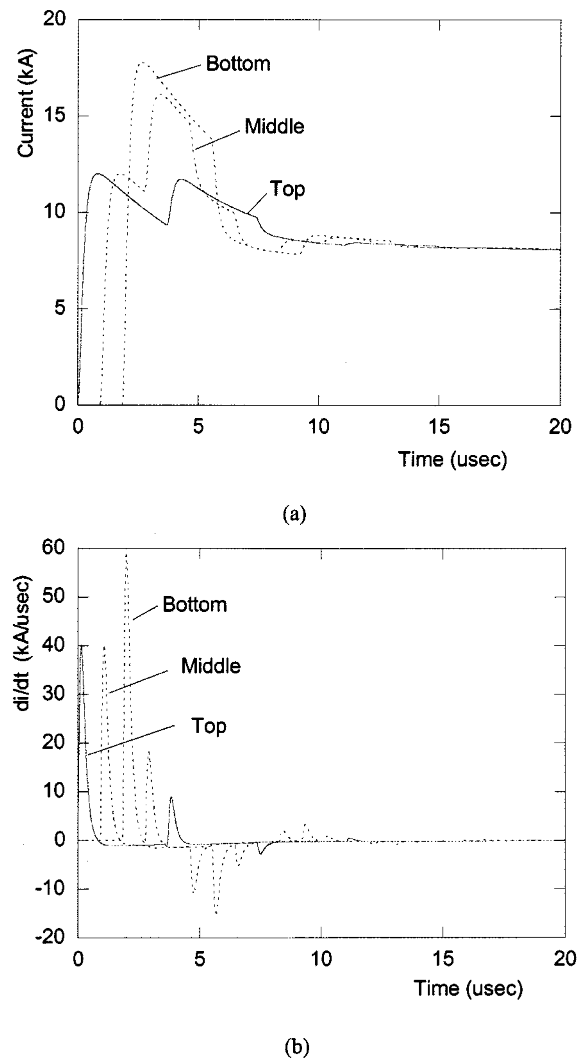

Fig. 5. (a) Current; and (b) current derivative along the strike object for a typical subsequent return stroke.

Fig. 5 presents similar results, using the typical subsequent return-stroke current. It can be seen that in case of subsequent strokes, both the current and the current time-derivative are more significantly affected by the presence of the tower. Furthermore, since the time to current peak is shorter than the wave traveling time along the tower, the current reflections can be clearly distinguished on the waveforms.

The main parameters of the current waveform at various observation points along the tower are summarized in Table II. It can be seen that the current peak value and maximum steepness at the bottom of the tower are 30% to 50% larger than those associated with the injected current. Furthermore, for the first stroke, the time to current peak decreases as the observation point moves toward the ground while for the subsequent stroke, it remains constant and equal to the time to peak of the injected current. This result can be explained considering that for the first stroke, the propagation time along the tower is smaller than the risetime of the injected current. The situation is reversed for the subsequent stroke where the propagation time along the tower is larger than the risetime of the injected current.

Electromagnetic Fields: Figs. 6 and 7 present the waveforms of the first and subsequent return stroke vertical electric field and azimuthal magnetic field at 2 km from the tower. In the same figures, the contributions of various electromagnetic field components (static, induction and radiation) are also illustrated. Note that current reflections along the tower can be identified, especially on the radiation term of the subsequent stroke field.

A comparison between Figs. 2, 3 and Figs. 6, 7 shows that, for both first and subsequent return strokes, the presence of the tower results in a significant increase of the electromagnetic field peak, and also in the appearance of subsidiary peaks. For the subsequent return stroke, however, the effect of the tower is much more pronounced [compare Figs. 2(b), 3(b) with Figs. 6(b), 7(b)]. For the considered case, the peak field associated with tower strokes is about 2 times (for the first stroke) to 3 times (for the subsequent stroke) as large as that corresponding to return strokes initiated at ground level. Furthermore, it can be seen that the radiation term of both electric and magnetic fields, responsible for the initial peak, is the one most affected by the presence of the tower.

TABLE II
PARAMETERS OF LIGHTNING RETURN STROKE CURRENT ALONG THE TOWER

	Peak Value (kA)		Maximum Steepness (kA/μs)		Time to peak (μs)	
	First	Subsequent	First	Subsequent	First	Subsequent
'Non-contaminated' channel-base current*	30	12	12	40	8	0.8
Tower top	37	12	12	40	8	0.8
Middle	38	16	12	40	5	0.8
Bottom	40	18	18	60	4	0.8

* See also note 3.

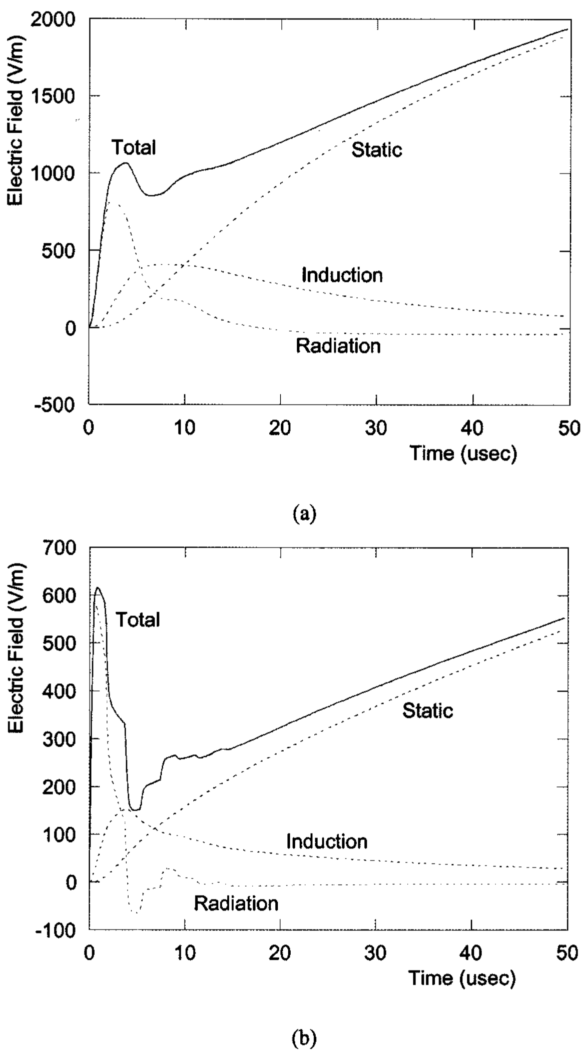

Fig. 6. Vertical electric field at 2 km from the 553-m high tower. (a) First return stroke. (b) Subsequent return stroke.

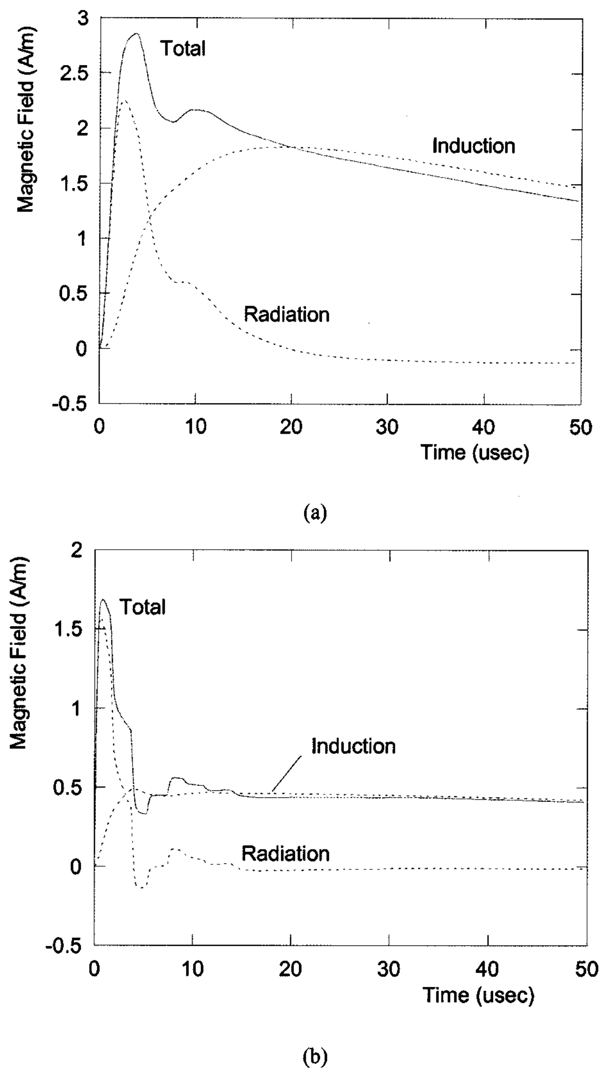

Fig. 7. Azimuthal magnetic field at 2 km from the 553-m high tower. (a) First return stroke. (b) Subsequent return stroke.

Table III-A and -B summarizes the main parameters of the electric and magnetic field waveforms for both lightning strike to ground and to the tower. It can be seen that the presence of the tower affects also the values for the maximum steepness. Note further that, in accordance with the results of Table II, the time to peak of subsequent stroke fields is not affected by the

TABLE III
(A) PARAMETERS OF LIGHTNING RETURN STROKE "NON-CONTAMINATED" CHANNEL-BASE CURRENT AND THE CORRESPONDING ELECTRIC AND MAGNETIC FIELDS AT 2 km. LIGHTNING STRIKE TO GROUND. (B) PARAMETERS OF LIGHTNING RETURN STROKE "NON-CONTAMINATED" CHANNEL-BASE CURRENT AND THE CORRESPONDING ELECTRIC AND MAGNETIC FIELDS AT 2 km. LIGHTNING STRIKE TO THE TOWER

Waveform	Peak Value			Maximum Steepness			Time to peak (μsec)	
	Units	First	Subsequent	Units	First	Subsequent	First	Subsequent
Current	kA	30	12	kA/μs	12	40	8	0.8
E-Field	V/m	-	230	kV/m/μs	0.21	0.76	-	0.8
H-Field	A/m	1.4	0.6	A/m/μs	0.6	2	8	0.8

Waveform	Peak Value			Maximum Steepness			Time to peak (μsec)	
	Units	First	Subsequent	Units	First	Subsequent	First	Subsequent
'Non-contaminated' channel-base current*	kA	30	12	kA/μs	12	40	8	0.8
E-Field	V/m	1100	600	kV/m/μs	0.6	2	4	0.8
H-Field	A/m	2.9	1.7	A/m/μs	1.7	5.6	4	0.8

* See also note 3.

tower and is determined by the time to peak of the originating current. On the other hand, the presence of the tower results in a decrease by a factor of two in the time to peak of first-stroke fields.

The contribution of the tower to the total electric field caused by a subsequent stroke is presented in Fig. 8. This figure shows that the tower, which in this case represents the bottom 553 m of the radiating antenna, has therefore a dominant effect upon the electromagnetic field at 2 km.

Similar results have been presented by Diendorfer [20] who extended the DU model [34] to take into account the presence of an elevated strike object. Although Diendorfer did not consider reflections at the top and at the bottom of the strike object, and while the strike objects considered in his study were not taller than 20 m, the theoretical results showed that the increase in the field peak and in the field derivative peak was more appreciable for lightning return stroke currents with faster risetimes. For a 20-m high strike object and a current 10%–90% risetime of 0.25 μs, an increase in the field peak by a factor of 2.4 was observed [20].

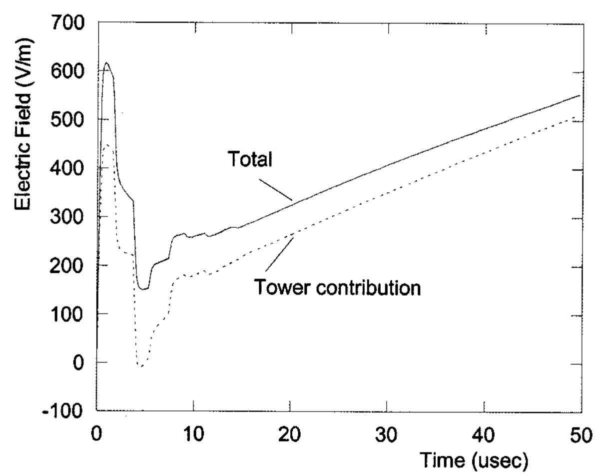

Fig. 8. Contribution of the tower to the vertical electric field calculated at 2 km from the tower (subsequent stroke).

IV. FIRST VERSUS SUBSEQUENT RETURN STROKE ELECTROMAGNETIC FIELD PEAK

Computed results presented in Section III have shown that the presence of the tower tends in general to increase the electromagnetic field peak and maximum steepness. This increase depends essentially on the wavefront steepness of the channel-base current, and it has been found to be significantly higher for subsequent return strokes, which are characterized by shorter risetimes compared to first return strokes. This finding is in agreement with recent experimental observations of lightning strikes to the CN Tower presented in [30], [35]. It is found in [30] that subsequent return stroke magnetic field peak is on average greater than that of first return stroke. This is illustrated in Figs. 9 and 10, in which two sets of simultaneous data (current derivative, current, *E*-field, *H*-field) corresponding to the first (Fig. 9) and to the third stroke (Fig. 10) of the same flash to the CN Tower are presented. It can be seen that despite a smaller peak current, the subsequent stroke electric and magnetic fields are larger than those from the first stroke.

The values of the average ratio of subsequent-to-first magnetic field peak to subsequent-to-first current peak are re-

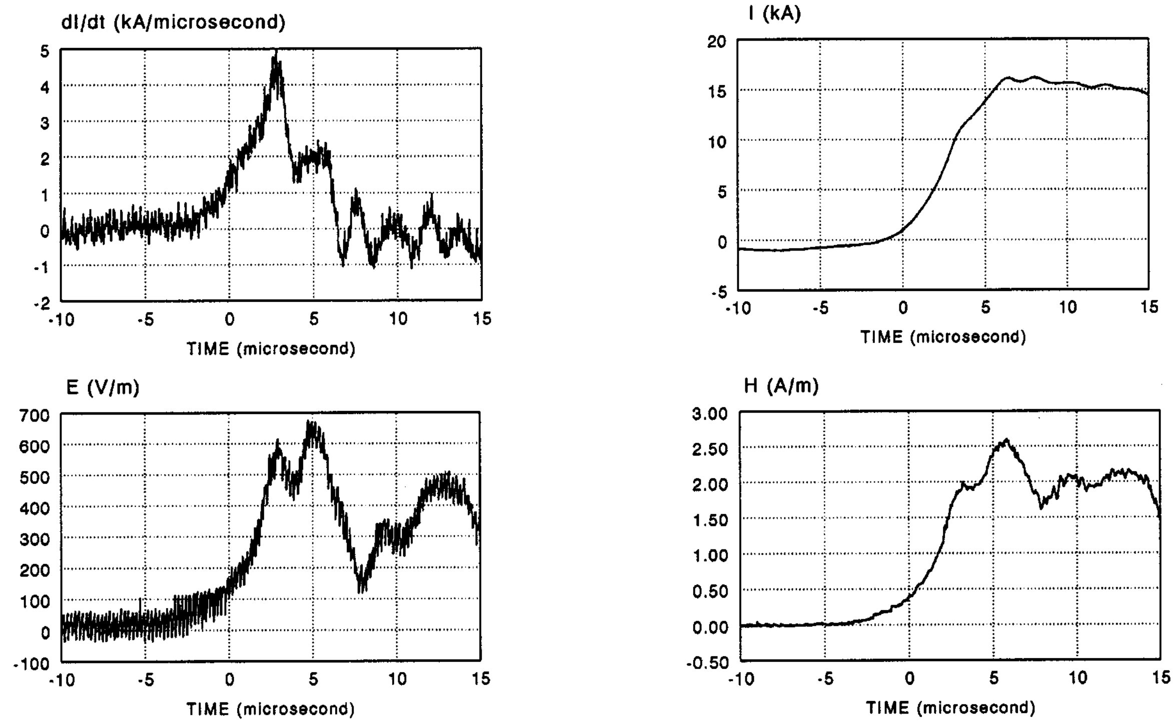

Fig. 9. Lightning current derivative (top left), lightning current (top right), vertical electric field at 2 km (bottom left), azimuthal magnetic field at 2 km (bottom right). First return stroke of a CN Tower lightning flash recorded on August 8, 1996.

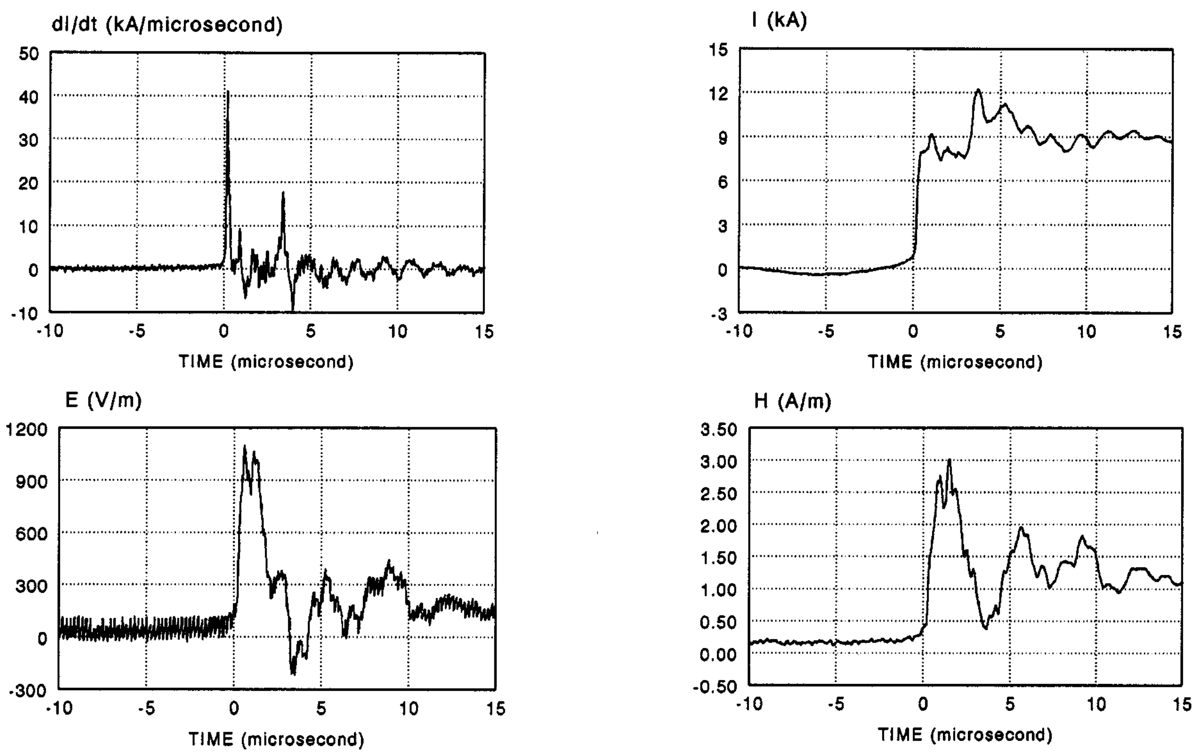

Fig. 10. As in Fig. 9. Third return stroke.

ported in Table IV. Although the comparison between computed results in Section III and experimental data in [30], [35] should be considered as only qualitative, it can be seen, however, that the computed value of the ratio of the field peaks to current peaks $(H_s/H_f)/(I_s/I_f) = 1.5$, agrees reasonably well with the value 1.67 which is obtained from measured fields and currents.

Similar observations, showing that the subsequent-stroke field peak might be greater than the first-stroke peak, have been made on natural lightning in Florida [36]. In [36], electric

TABLE IV
RATIO OF SUBSEQUENT-TO-FIRST MAGNETIC FIELD PEAK H_s/H_f TO SUBSEQUENT-TO-FIRST CURRENT PEAK I_s/I_f

	$(H_s/H_f)/(I_s/I_f)$
Average measured (CN Tower [30,35])	1.67
Computed, return stroke initiated at ground	1.1
Computed, taking into account the presence of the elevated strike object	1.5

field waveforms from 46 multiple-stroke flashes were analyzed and it has been found that 15 flashes (33%) had at least one subsequent stroke whose initial electric field peak was greater than that of the first return stroke.

Subsequent-stroke field peak greater than the first-stroke peak is generally attributed to subsequent-stroke current peak greater than the first-stroke peak (e.g., [36], [37]). Indeed, although on average first return stroke current peaks are higher than subsequent stroke ones, observed lightning data in Switzerland [38] and in Canada [35] have shown that a nonnegligible number of flashes contain subsequent strokes with higher current peaks than those of their first strokes.

— Five (15%) of the 33 negative downward multiple-stroke flashes striking instrumented towers in Switzerland contained one or two subsequent strokes with return stroke peak currents greater than their respective first stroke peak currents. The percentage of subsequent strokes with greater current peaks than the first stroke peak was about 7% (8 strokes out of 115) [36], [38].
— Data recorded at the CN Tower in Toronto (about ten times as high as the towers used in Switzerland) have shown that 40% of subsequent strokes had current peaks ranging from one to four times the value of the first stroke peak [35].

On the other hand, it is important to realize that even a subsequent return stroke with a lower current peak than the first, could result in a greater field peak. This can be due to several factors. One of these, is the fact that the subsequent return stroke velocity is in general greater than the first return stroke speed [29]. The electromagnetic field radiated by the lightning channel depends strongly on the value of the return-stroke velocity and a larger value for the return-stroke velocity results in a greater electromagnetic field peak. The other factor is the steepness of the current wavefront. Since subsequent strokes are associated with shorter risetimes than first return strokes, their increased steepness will make a larger contribution to the electromagnetic field. Finally, the mere presence of an elevated strike object increases the electromagnetic field and that influence is larger for currents with steeper wavefronts, as shown by the results obtained in the present study.

V. PEAK CURRENT ESTIMATES USING REMOTE ELECTROMAGNETIC FIELD DATA

Lightning channel-base currents are established by direct measurements using either instrumented towers (e.g., [4], [5], [7], [27], [38]–[41]) or artificially-initiated lightning by small rockets (e.g., [42]–[45]). Estimates of various lightning current parameters can also be obtained from the measurements of lightning electromagnetic fields assuming one or more empirical [1], [2] or theoretical [3] relations between electromagnetic field and lightning current.

The indirect estimation of lightning current parameters from measured fields has grown in importance in the last years due to the widespread dispersion of the lightning location systems (LLS). The basic aim of such systems is to provide density maps of lightning flashes. However, more recently, LLS have also been used to estimate lightning current parameters (e.g., [37]) using empirical formulae in which return stroke current peaks are assumed to be simply proportional to the remote electric and/or magnetic field peaks. Because of the enormous amount of data they can provide and the possibility of obtaining local statistical data, it is expected that LLS will become more and more important in the near future. However, the discussion given in Section IV supports the concept already presented in [6], [11] that such simple relations assuming a direct proportionality between currents and fields are not sufficient to extract reliable lightning current statistics. There are several reasons which make the application of this type of relations worth of more careful investigations. It is not only the peak value of the lightning current, but also the parameters discussed in the previous section, namely, the steepness of the current wavefront and the return stroke velocity, along with other parameters such as the tortuosity of the lightning channel trajectory [46], that are affecting the corresponding electromagnetic field. Furthermore, the presence of an elevated strike object influences profoundly the magnitude of the electromagnetic field, since lightning current propagates within an elevated strike object at practically the speed of light, and this must be taken into account when current data directly measured from instrumented towers are used to calibrate LLS performances relevant to lightning current statistics.

VI. CONCLUSIONS

In this paper, an analysis of the electric and magnetic fields radiated by lightning-return strokes to tall towers has been presented. Electric and magnetic field waveforms corresponding to typical first and subsequent strokes have been computed and analyzed making use of the MTL model extended to take into account the presence of an elevated strike object. The effect of the presence of a tower on the magnitude and shape of the fields has been investigated. The contributions of the various components of the fields, namely, static, induction and radiation for the electric field, and induction and radiation for the magnetic field have been illustrated and discussed. It was shown in particular that the radiation term of the electromagnetic field is the one most affected by the presence of the tower. Furthermore, it was found that the presence of the tower tends, in general, to increase substantially electromagnetic field peaks and their derivatives. This increase is mainly caused by the presence of two oppositely propagating current wavefronts originating from the tower top and by the very high velocity (practically speed of light) of current propagation within the tower, and depends essentially on the wavefront steepness of the channel-base current. For that reason, the electromagnetic field peak has been found to be significantly higher for subsequent return strokes, which are characterized by faster risetimes compared with first return strokes.

The obtained results have been shown to be consistent with recent experimental observations of lightning strokes to the CN Tower and they qualitatively explain the fact that, because of other parameters, subsequent return strokes with lower current peaks could result in higher field peaks. This observation is to be taken into account when data from tall instrumented towers are used to calibrate LLS performances relevant to lightning current statistics.

Acknowledgment

The authors wish to thank the Swiss Defense Agency for providing them with electromagnetic-field measuring equipment, Dr. V. Shostak for his helpful contributions to the manuscript, and Prof. V. Rakov for his valuable comments.

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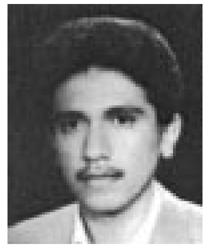

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