Effect of Nearby Buildings on Electromagnetic Fields from Lightning

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Abstract: We present a discussion on the effect of nearby buildings on the electric and magnetic fields radiated by lightning. Electric and magnetic fields radiated from distant natural lightning have been measured simultaneously on the roof of a building (the Power Systems Laboratory of the Swiss Federal Institute of Technology, Lausanne, Switzerland) and on the ground at different distances away from it. The results suggest that the measured electric field on the roof of the 9-m tall building is enhanced by a factor of 1.7 to 1.9, whereas the electric fields on the ground experience a significant reduction due to the shadowing effect of the building. Also, it is shown that for a sensor located on the ground, close to a building, the magnetic field component perpendicular to the building can also experience a significant attenuation, presumably due to the effect of the induced currents in the building. The results are supported by numerical simulations, obtained using NEC-4, in which the building is represented using a simple wire-grid model.

1. INTRODUCTION

Sensors used for the measurement of lightning electric and magnetic fields are often placed close to or on top of buildings or other structures. Metallic beams and other conducting parts in those structures may cause enhancement or attenuation effects on the measured fields [1-6]. Rubinstein *et al.* [1] used simultaneous measurements of lightning electric fields at the top of a building and at ground level to estimate an enhancement factor for the electric field of about 1.5 for their 17-floor building. Bonyadi-Ram *et al.* [2] presented a theoretical analysis in which the building on which the electric field was evaluated was represented by a metallic wire-grid model. Their results imply that the enhancement factor for the electric field is about 2.3 for a 10-m high building and increases with the height of the structure. Bermudez *et al.* [4] and Pavanello *et al.* [5] compared electromagnetic fields associated with lightning strikes to the Toronto CN Tower measured on the roofs of buildings at different distances from the tower with theoretical estimations. Their results suggest that both the electric and the magnetic fields may have been enhanced by the presence of the buildings, although the degree of enhancement was actually more significant for the electric field than for the magnetic field. Baba and Rakov [6] applied the finite-difference time-domain (FDTD) method to evaluate the effect of a building on the vertical component of electric field radiated by nearby lightning. Their computation results show that the magnitude of the E-field on the roof of a 20-m building is about 1.5 times greater than that at the same horizontal distance on the ground surface in the absence of the building.

In this paper, we present an experimental analysis for the evaluation of the distortion introduced by a building on the electric and magnetic fields from lightning. Preliminary results were already presented in [7] and [8]. A numerical analysis using the Numerical Electromagnetics Code NEC-4 [9] is also presented to support the experimental data.

2. CONSIDERED CONFIGURATIONS AND SIMULATION PARAMETERS

Experimental waveforms from distant natural lightning were recorded during Summer 2006. Electric and magnetic field waveforms were measured simultaneously at two different locations, on the roof of a building (the Power Systems Laboratory of the Swiss Federal Institute of Technology, Lausanne, Switzerland) and on the ground. The building is located on the Campus of the Swiss Federal Institute of Technology in Lausanne, on the north of Lake Geneva.

The field derivatives were recorded using flat plate antennas (for the vertical *E*-field) and two magnetic loops (for the two magnetic field components H_x and H_y) [10]. The sensors outputs were connected *via* 20-m long 50 Ω double-shielded cables (RG214U type) to a digitizer.

The angle of incidence of the lightning electromagnetic field was determined using the magnetic direction finding technique [11] from the two components H_x and H_y of the magnetic field measured on the roof of the building. Here we implicitly made the assumption that the magnetic field components on the roof were not affected by the presence of the building, or that both components of the *H*-field were affected equally.

Three different setups were considered and are described hereafter.

Setup 1. Fig. (**1**) illustrates the placement of the antennas for the first setup. The coordinate system used throughout this paper is also shown in the same figure. The sensors on the roof are located approximately 1-m away from the southern edge and equidistant from the corners, while those on the ground are located about 2 meters away from the building façade and half way along it [7].

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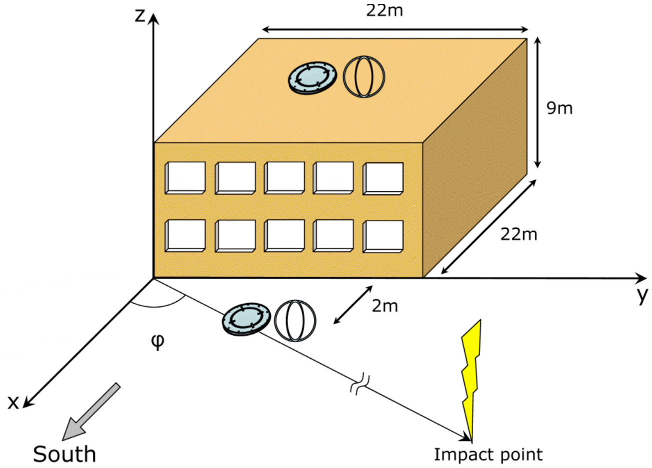
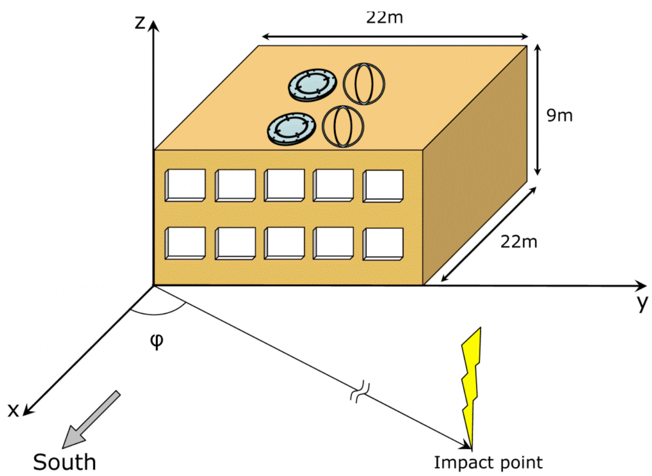


Fig. (1). Setup one.

Setup 2. Fig. (**2**) shows the location of the antennas for the second setup. Sets of electric and magnetic field sensors are located on the roof of the building, one in the center and the other near the southern edge (1m away from the edge and half way along it).

(**a**)

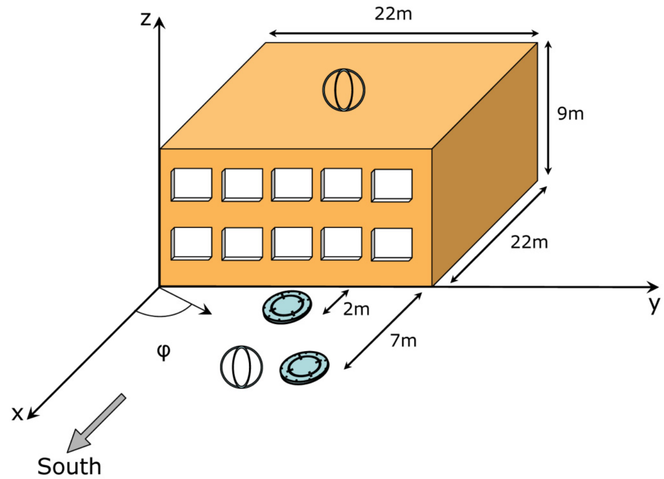


(**b**)

Fig. (2). Setup two (**a**) and location of the sensors on the rooftop (**b**).

Setup 3. The arrangement of the antennas used for the third setup is shown in Fig. (**3**). Both sets of electric field sensors are located on the ground at 2 and 7m from the southern edge, as shown in the figure. The magnetic field is measured on the roof center and at 7m from the southern edge.

(**a**)



(**b**)

Fig. (3). Setup three (**a**) and location of the sensors on the ground (viewed from the rooftop) (**b**).

3. EXPERIMENTAL RESULTS

3.1. Setup One

We analyzed 4 flashes occurred on July 5th, 2006. These flashes were identified as negative cloud-to-ground strikes by their field signatures.

Fig. (**4**) presents one typical set of measurements consisting of simultaneous records of vertical electric fields and horizontal magnetic fields (H_x and H_y) on the roof of the building and on the ground, corresponding to a single-stroke flash occurred at 02:30:20 local time, July 5th 2006. Stepped leader pulses are clearly visible in the waveforms before the onset of the return stroke pulse. Table **1** summarizes some salient parameters (angle of incidence, field peaks) for 13 strokes out of the four flashes recorded on July 5th, 2006. Table **2** presents the ratios of electromagnetic field peaks on the roof to those measured on the ground, as well as the values for the wave impedances.

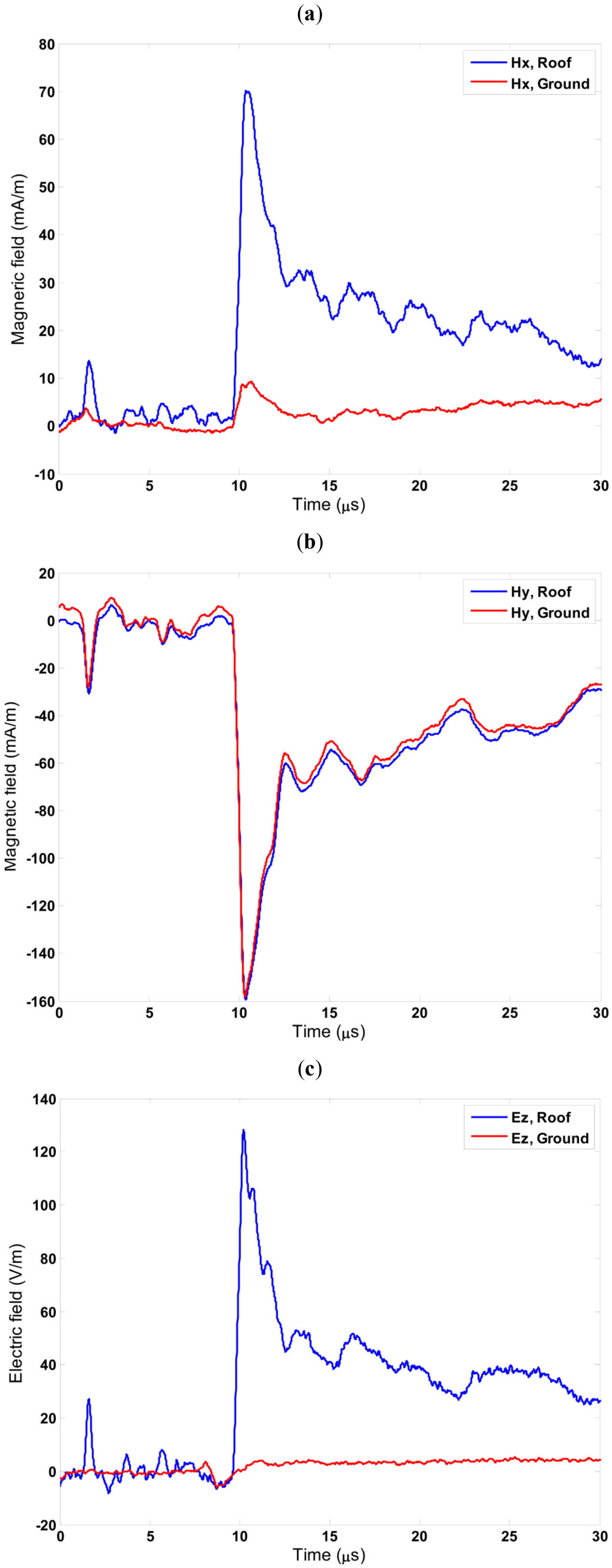


Fig. (4). Setup 1: Electric and magnetic fields recorded on July 5th 2006, 02:30:20 local time. Single-stroke flash. Solid lines: measured waveforms on the roof, dashed line: measured waveforms on the ground. (**a**) H_x, (**b**) H_y, (**c**) E_z.

It can be seen from Tables **1** and **2** that the electric field peak on the roof is one order of magnitude greater than that measured on the ground. On the other hand, the magnetic field component H_y is nearly identical on the ground and on the roof. However, the H_x component on the ground has a peak value 5 to 10 times lower than that of the same component measured on the roof.

As discussed in [7], the obtained results suggest an enhancement of the vertical electric field measured on the roof of the building, in line with the conclusions of [1-6]. The enhancement referred to in the mentioned studies is defined as the ratio of the fields on top of a building to the corresponding fields in the absence of the building. Since we measured our electric field two meters from the building, the fact that the ratio of the E-field peak on the roof to the E-field peak on the ground is about 10-30 suggests an attenuation of the E-field measured on the ground [7].

The fact that the magnetic field component at ground level perpendicular to the building façade, H_x, is considerably lower than the same component on the roof is thought to be essentially due to currents induced on the metallic structure of this façade [7]. These currents flow predominantly in the yz plane and they generate therefore a magnetic field in the x direction.

As can be seen in the 4th column of Table **2**, a great disparity can be observed for the ratio of the electric field on the roof and that on the ground. For example, the first flash presents ratios of 31.7, 12.3, 15.2 and 26.9. Since all the measured fields for those strokes come from the same direction and propagated along the same path, they are expected to be submitted to the same attenuation and distortion effects. The fact that the ratio varies to such significant extent can be essentially due to two reasons: (1) the differences in the risetimes of the fields and possible frequency dependence of the building effect, and (2) the fact that the E-field waveforms on the ground were characterized by very low magnitudes (see Fig. **4c**) and hence might have been affected by noise.

In order to estimate the amount of enhancement/ attenuation of the electromagnetic field components, the following approach based on the wave impedance is proposed. Since all the events recorded in this study correspond to distant lightning strikes (some tens of kilometers), the field is essentially radiation and the electric field peak to magnetic field peak ratio should be equal to the free space wave impedance, 377Ω. We also assume that the magnetic field components measured on the roof are not affected by the presence of the building. This assumption, which will be tested in Section 4, is supported by the fact that the two horizontal field components measured on the roof of the building are not expected to be significantly affected by the currents induced on the roof, which flow predominantly in the same horizontal plane. The last two columns in Table **2** present the ratio of the electric field peaks on the roof and on the ground to the magnetic field peaks on the roof. It can be seen that the ratio of the field peaks on the roof ranges from 630 to 735Ω, with a mean value of 640.4Ω and a standard deviation of 10.46Ω. These values indicate that the enhancement of the electric field on the roof is about 1.7 to 1.9. The ratio of the E-field peak on

Table 1. Setup 1: Parameters of the Events Recorded on July 5th 2006

Flash	Incidence Angle (Degrees)	Event Number	Inter-Event Interval (ms)	E^{Ground} (V/m)	E^{Roof} (V/m)	H_X^{Ground} (mA/m)	H_X^{Roof} (mA/m)	H_Y^{Roof} (mA/m)	H_Y^{Ground} (mA/m)
July 5th 2006, 02:28:00	63	1/5		5.8	183.5	42.5	247.8	-128.8	-136.2
		2/5	45.6	4.3	52.7	11.6	70.1	-35.5	-32.7
		3/5	67.9	5.9	90.2	17.6	122.3	-60.9	-62.9
		5/5	117.9	2.0	54.6	14.7	71.3	-35.2	-32.7
July 5th 2006, 02:30:20	23	1/1		3.7	128.1	9.22	70.1	-159.4	-158.1
July 5th 2006, 02:32:27	60	1/5		6.5	125.2	30.5	180	-66.6	-70.8
		2/5	66.0	5.4	101.4	22.1	148.9	-55.8	-58.7
		3/5	41.3	4.8	70.8	17.8	98.4	-36.5	-37.3
		4/5	50.2	5.1	67.8	19.5	100.1	-36	-45.6
		5/5	52.7	2.4	35.3	5.42	51.4	-19.2	-19.8
July 5th 2006, 03:07:47	107	5/8	35.1	22.4	179.2	44.2	263	85.8	86.2
		7/8	525.8	10.9	108.1	33.3	163.4	49.3	54.2

Table 2. Setup 1: Ratios of Electric and Magnetic Field Peaks and Wave Impedances

Flash	Incidence Angle (Degrees)	Event Number	$\frac{E_{Roof}}{E_{Ground}}$	$\frac{H_X^{Roof}}{H_X^{Ground}}$	$\frac{H_Y^{Roof}}{H_Y^{Ground}}$	$\frac{E_{Ground}}{H_{Ground}}$ (Ω)	$\frac{E_{Roof}}{H_{Roof}}$ (Ω)	$\frac{E_{Ground}}{H_{Roof}}$ (Ω)
July 5th 2006, 02:28:00	63	1/5	31.7	5.8	0.9	40.5	657.1	20.7
		2/5	12.3	6.0	1.1	123.9	670.7	54.7
		3/5	15.2	7.0	1.0	90.8	660.2	43.4
		5/5	26.9	4.9	1.1	56.6	686.7	25.5
July 5th 2006, 02:30:20	23	1/1	34.7	7.6	1.0	23.3	735.6	21.2
July 5th 2006, 02:32:27	60	1/5	19.1	5.9	0.9	84.8	652.3	34.1
		2/5	18.7	6.7	0.9	86.6	637.7	34.1
		3/5	14.9	5.5	1.0	114.9	675	45.2
		4/5	13.3	5.1	0.8	103.2	638	48.1
		5/5	15.0	9.5	1.0	114.5	643.2	42.8
July 5th 2006, 03:07:47	107	5/8	8.0	6.0	1.0	231.4	647.8	81
		7/8	9.9	4.9	0.9	170.9	633.0	63.7

the ground to the E-field peak on the roof (last column of Table **2**) ranges from 20 Ω to 80 Ω. Comparing these values to the free-space wave impedance suggests that the reduction of the electric field at ground ranges from 5 to 20.

3.2. Setup Two

We analyzed 10 flashes occurred on June 20 and 21, 2006. All these flashes were identified as negative cloud-to-ground strikes by their field signatures.

Fig. (**5**) presents one typical set of measurements consisting of simultaneous records of electric and magnetic fields recorded on July 20th 2006. Table **3** summarizes parameters for 12 strokes out of the recorded 10 flashes. It can be seen that the vertical electric field at the edge of the rooftop is only slightly enhanced compared to the same component measured on the roof center (average: 5.67%). No significant difference was found between the *y*-component of the magnetic field at the two locations. However, the magnetic field *x*-component on the edge was significantly larger than that of the center (average 29.75%).

Table **4** presents the ratios of electromagnetic field peaks on the roof to those measured on the ground, as well as the values for the wave impedances. Assuming again that the magnetic field components measured on the roof center are not affected by the presence of the building, the enhancement of the electric field can be evaluated by

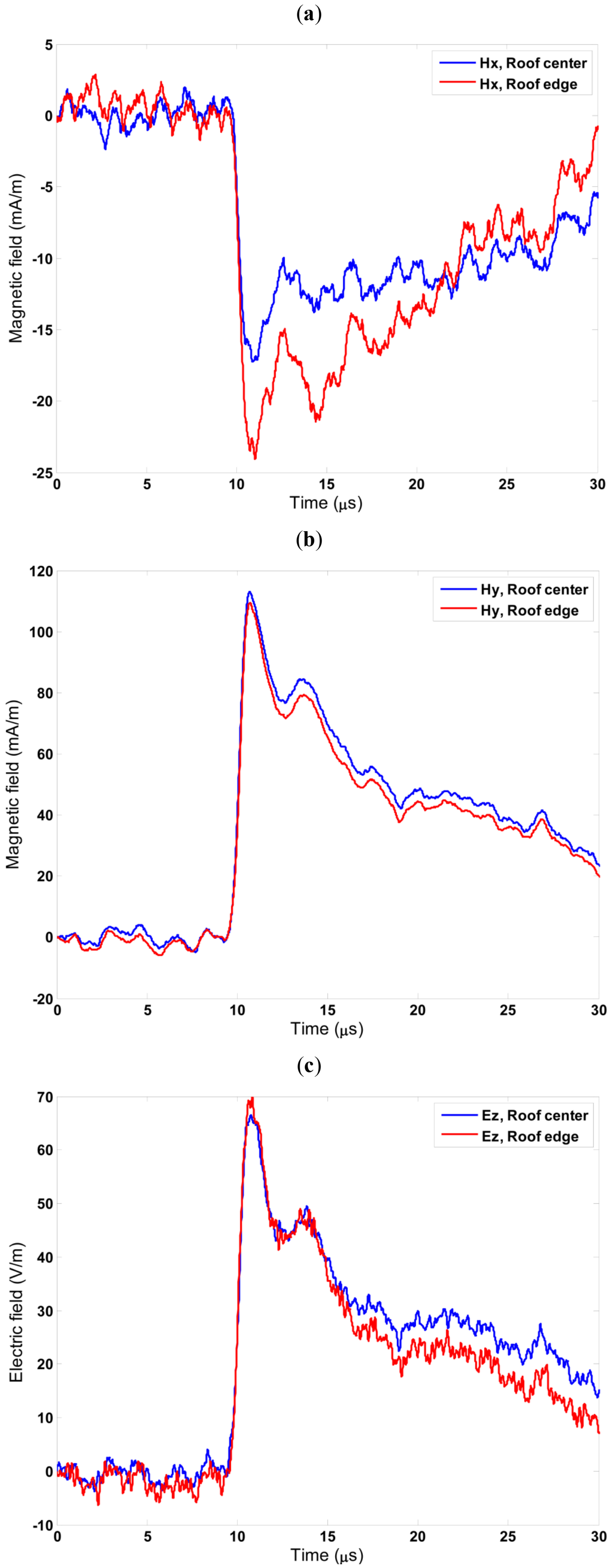


Fig. (5). Setup 2: Electric and magnetic fields recorded on July 20th 2006, 22:50:20 local time. Stroke (3/5). Solid lines: measured waveforms on the roof, dashed line: measured waveforms on the ground. (**a**) H_x, (**b**) H_y, (**c**) E_z.

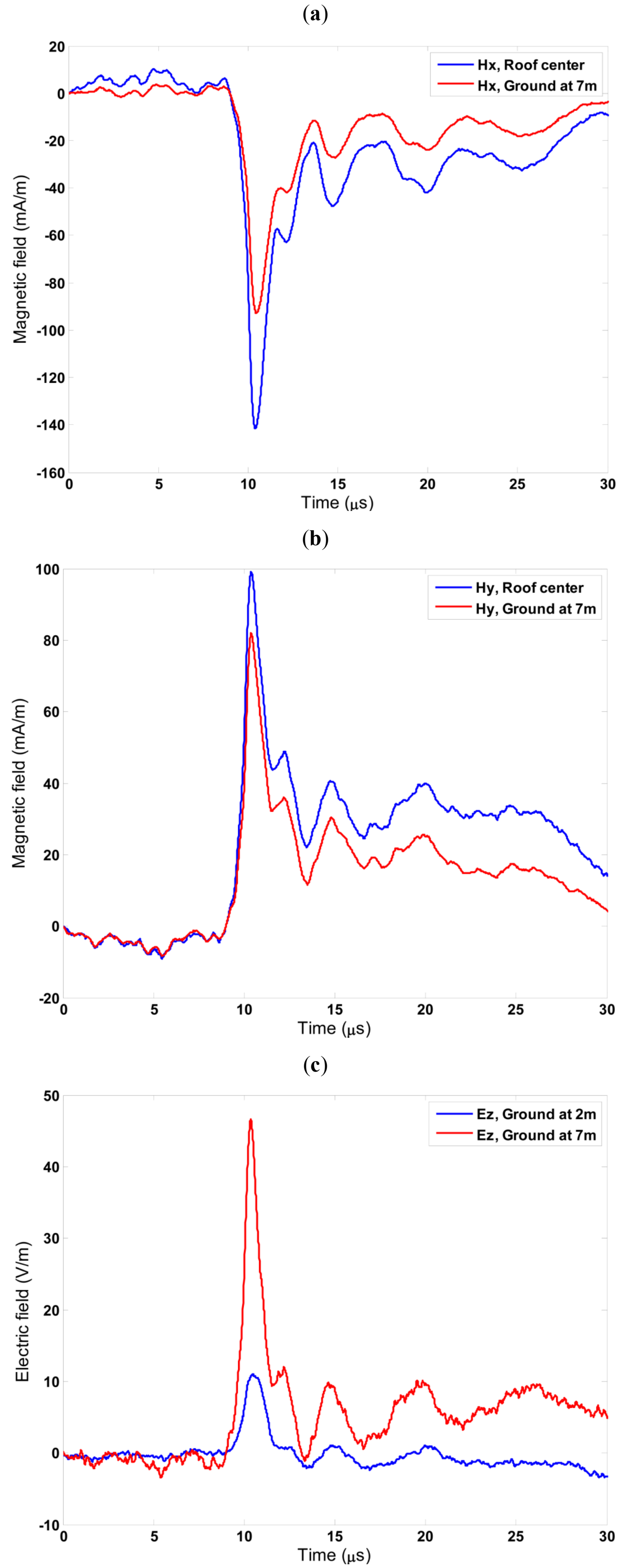


Fig. (6). Setup 3: Electric and magnetic fields recorded on July 1st 2006, 17:15:06 local time. Stroke (3/3). Solid lines: measured waveforms on the roof, dashed line: measured waveforms on the ground. (**a**) H_x, (**b**) H_y, (**c**) E_z.

Table 3. Setup 2: Parameters of the Events Recorded on June 20th and 21st 2006

Flash	Incidence Angle (Degrees)	Event Number	Inter-Event Interval (ms)	E_{Centre} (V/m)	E_{Edge} (V/m)	H_X^{Centre} (mA/m)	H_Y^{Centre} (mA/m)	H_X^{Edge} (mA/m)	H_Y^{Edge} (mA/m)
June 20th 2007, 22:50:20	-171	2/5	172	73.46	69.7	-16.5	116.8	-25.1	111.8
		3/5	134	66.56	70	-17.3	113.1	-24.1	109.5
		5/5	0.2	78.38	83	-19.9	132.2	-29.9	125.9
June 20th 2007, 23:42:48	161	1/2		53.69	57.1	30	84.9	36.3	82.3
June 20th 2007, 23:43:03	-50	1/1		28.97	28.89	-31.8	-27.1	-38.8	-29.2
June 20th 2007, 23:48:40	-48	1/1		27.63	29.4	-29.3	-26	-37.7	-28.5
June 20th 2007, 23:49:57	-60	1/3		93.25	99.5	-121.6	-69.8	-150.2	-76
June 20th 2007, 23:50:23	-59	1/1		52.94	60.21	-63.9	-38.5	-76.9	-45
June 20th 2007, 23:52:33	-51	3/3	103.9	40.51	44.69	-46.5	-37.9	-56.8	-42.7
June 20th 2007, 23:59:42	-48	3/4	56.78	37.18	37.08	-39.9	-35.4	-50	-37.5
June 21st 2007, 00:03:03	-48	1/1		38.45	43.5	-40.3	-36.9	-47.8	-42.4
June 21st 2007, 01:10:49	-170	1/1		53.8	58.14	-16.8	97.6	-22.5	93.6

Table 4. Setup 2: Ratios of Electric and Magnetic Field Peaks and Wave Impedances

Flash	Incidence Angle (Degrees)	Event Number	$\frac{E_{Edge}}{E_{Centre}}$	$\frac{H_X^{Edge}}{H_X^{Centre}}$	$\frac{H_Y^{Edge}}{H_Y^{Centre}}$	$\frac{E^{Centre}}{H^{Centre}}$ (Ω)	$\frac{E_{Edge}}{H_{Centre}}$ (Ω)
June 20th 2007, 22:50:20	-171	2/5	0.95	1.52	0.96	622.7	590.9
		3/5	1.05	1.39	0.97	581.7	611.8
		5/5	1.06	1.5	0.95	586.3	620.8
June 20th 2007, 23:42:48	161	1/2	1.06	1.21	0.97	596.3	634.1
June 20th 2007, 23:43:03	-50	1/1	0.99	1.22	1.08	693.4	691.5
June 20th 2007, 23:48:40	-48	1/1	1.06	1.29	1.1	705.3	750.5
June 20th 2007, 23:49:57	-60	1/3	1.07	1.24	1.09	665.1	709.6
June 20th 2007, 23:50:23	-59	1/1	1.14	1.2	1.17	709.6	807.1
June 20th 2007, 23:52:33	-51	3/3	1.1	1.22	1.13	675.3	745
June 20th 2007, 23:59:42	-48	3/4	0.99	1.25	1.06	697	695.2
June 21st 2007, 00:03:03	-48	1/1	1.13	1.19	1.15	703.7	796.1
June 21st 2007, 01:10:49	-170	1/1	1.08	1.34	0.96	543.2	587.1

examining the last two columns in Table **4** which present the ratio of the electric field peaks on the roof center and on the roof edge to the magnetic field peaks on the roof center. It can be seen that the ratio of the field peaks on the roof ranges from 590 to 807Ω, with a mean value of 686.64Ω and a standard deviation of 77.67Ω. These values indicate that the enhancement of the electric field on the roof is about 1.5 to 2.

3.3. Setup Three

We measured 1 flash occurred on July 1st, 2006 for this configuration and which was identified as a negative cloud-to-ground strike by its field signatures.

Fig. (**6**) presents one typical set of measurements consisting of simultaneous records of electric and magnetic fields recorded on July 20th 2006. Table **5** summarizes parameters for the 2 strokes out of the recorded flash. It can be seen that the vertical electric field at 2m from the building is significantly smaller in magnitude than that measured at 7m from the building, presumably less affected by the building shadowing effect. In agreement with the results obtained for the setup 1, the magnetic field *x*-component at ground level perpendicular to the building façade, H_x, is considerably lower than the same component on the roof. However, it is found for this configuration that the H_y

component at ground level is also lower (to a lesser degree) compared to the same component measured on the roof.

Table **6** presents the ratios of electromagnetic field peaks, as well as the values for the wave impedances. It can be seen that the wave impedance for the field measured at 7m from the building façade is nearly equal to the free space wave impedance. This could be considered as an indication that at this location, electric and magnetic field components are very little affected by the building. On the other hand, the ratios of the electric field at 7m from the building to the magnetic field on the roof center are 261.9 and 269.7Ω for first and second stroke respectively. Assuming that the magnetic field on the roof center is unaffected by the building, this would indicate that both the electric and magnetic fields at 7 m from the building façade are still affected by the shadowing effect, despite the fact that their ratio is close to the free space wave impedance.

4. SIMULATIONS

In the analysis presented in this section, use is made of the Numerical Electromagnetics Code NEC-4 [9], a well-known and widely used computer code based on the Method of Moments for analyzing the electromagnetic response of antennas and scatterers. The building was represented using a very simplified wiregrid parallelepiped structure consisting of 12 wires (see Fig. **7**). Each wire was subdivided into 10 segments and the radius of all wires was 5cm. The incident field used was a plane wave with a waveshape typical of a lightning return-stroke far field and with an angle of incidence corresponding to the event presented in Fig. (**4**) (July 5th 2006, 02:30:20), which corresponds to the setup 1.

The resulting computed electric and magnetic fields are shown in Fig. (**8**). Table **7** presents, for comparison, the ratios of the electric and magnetic field peaks and the wave impedances determined from the measured waveforms and from the simulations. Despite noticeable differences between simulations and measurements, which are believed to be essentially due to the oversimplified model for the building, it can be seen that the computed results are qualitatively in agreement with the observed data and show the same trends.

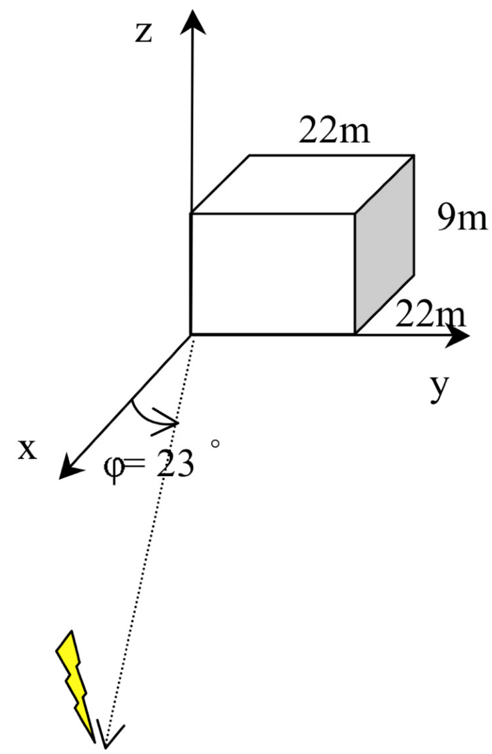


Fig. (7). Wiregrid model for the building and the configuration for the NEC-4 computation corresponding to the event recorded on July 5th 2006, 02:30:20 local time.

Table **8** presents the difference, expressed as a percentage, between the calculated fields in the presence of the building and those obtained without the building. The results confirm (i) the enhancement of the electric field on the roof and (ii) the attenuation of the electric field on the ground. The results also confirm that the H_y component is very little affected by the building whereas the H_x component on the ground is attenuated. The results also indicate an enhancement of the H_x component on the roof, which is in agreement with the experimental results obtained for the setup 2.

Table 5. Parameters of the Events Recorded on July 1st., 2006

Flash	Incidence Angle (Degrees)	Event Number	Inter-Event Interval (ms)	E^{2m}_{Ground} (V/m)	E^{7m}_{Ground} (V/m)	H^{Roof}_{X} (mA/m)	H^{Roof}_{Y} (mA/m)	H^{Ground}_{X} (mA/m)	H^{Ground}_{Y} (mA/m)
July 1st 2007, 17:15:06	-125	1/3		10.6	44.7	-139	99	-93	84.2
		3/3	66.8	11.04	46.62	-141.6	99.2	-92.7	81.9

Table 6. Ratios of Electric and Magnetic Field Peaks and Wave Impedances

Flash	Incidence Angle (Degrees)	Event Number	$\frac{E^{7m}_{Ground}}{E^{2m}_{Ground}}$	$\frac{H^{Roof}_{X}}{H^{Ground}_{X}}$	$\frac{H^{Roof}_{Y}}{H^{Ground}_{Y}}$	$\frac{E^{2m}_{Ground}}{H^{7m}_{Ground}}$ (Ω)	$\frac{E^{2m}_{Ground}}{H_{Roof}}$ (Ω)	$\frac{E^{7m}_{Ground}}{H^{7m}_{Ground}}$ (Ω)	$\frac{E^{7m}_{Ground}}{H_{Roof}}$ (Ω)
July 1st 2007, 17:15:06	-125	1/3	4.22	1.49	1.17	78.0	62.1	356.3	261.9
		3/3	4.22	1.53	1.21	81.3	63.9	376.9	269.7

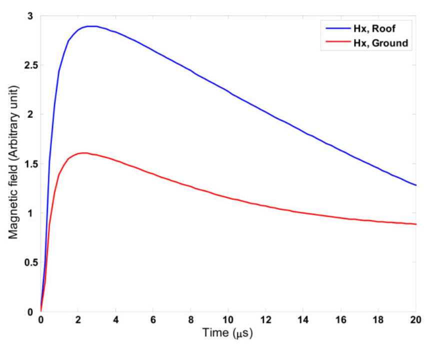
Table 7. Ratios of Electric and Magnetic Field Peaks and Wave Impedances. Comparison Between Measurements and Simulations. Event July 5th 2006, 02:30:20

July 5th 2006, 02:30:20	$\frac{E_{Roof}}{E_{Ground}}$	$\frac{H_X^{Roof}}{H_X^{Ground}}$	$\frac{H_Y^{Roof}}{H_Y^{Ground}}$	$\frac{E_{Ground}}{H_{Ground}}$ (Ω)	$\frac{E_{Roof}}{H_{Roof}}$ (Ω)	$\frac{E_{Ground}}{H_{Roof}}$ (Ω)
Simulation	2.3	1.8	1.0	269.5	550.7	243.3
Measurement	34.7	7.6	1.0	23.3	735.6	21.2

Table 8. Percentage of Difference Between Computed Electric and Magnetic Field Components in the Presence of the Building and with the Building Removed, Leaving Only the Ground Plane

Percentage	E_{Roof}	E_{Ground}	H_X^{Roof}	H_Y^{Roof}	H_X^{Ground}	H_Y^{Ground}
Simulation	47 %	-35 %	27 %	-5 %	-29 %	-6 %

(a)



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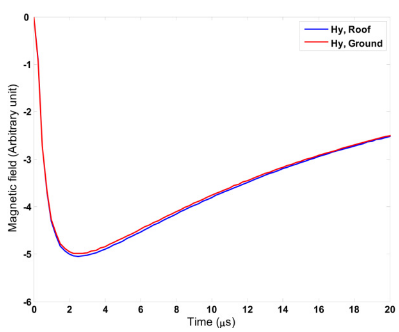

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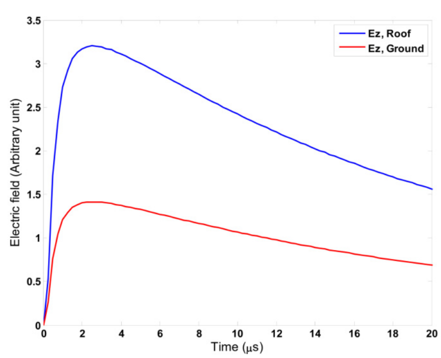

Fig. (8). Calculated electric and magnetic fields corresponding to the single-stroke flash that occurred on July 5th 2006, 02:30:20 local time. Solid lines: calculated waveforms on the roof, dashed line: calculated waveforms on the ground. (**a**) H_x, (**b**) H_y, (**c**) E_z.

5. CONCLUSIONS

We presented experimental waveforms radiated from distant natural lightning recorded during the Summer of 2006. Electric and magnetic field waveforms were measured simultaneously on the roof of a building (the Power Systems Laboratory of the Swiss Federal Institute of Technology, Lausanne, Switzerland) and on the ground at different distances away from it. The fields were recorded using flat plate antennas (for the E-field) and magnetic loops (for the H-field). The results suggest that the measured electric field on the roof of the building could be enhanced by a factor of 1.7 to 1.9, whereas the electric fields on the ground experience a significant reduction by a factor ranging from 5 to 20. Also, it is shown that for a sensor located on the ground close to a building, the magnetic field component perpendicular to the building can experience significant attenuation, presumably due to the effect of the induced currents in the building. The magnetic field on the roof of the building seems not to be significantly affected by the building.

Simulations using the Numerical Electromagnetic Code (NEC-4) were also carried out in which the building was represented using a simple wiregrid model. The simulation results support in essence the findings of the experimental analysis, despite quantitative differences which are ascribed, at least in part, to the oversimplified model of the building.

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